Dear XXXX

I am writing in respect of your recent request of 3 April 2014, for the release of information held by the Civil Aviation Authority (CAA).

Your request:

“Please supply:

1) Helicopter Ditching Survival Aspects, CAA-SRG internal report ref. 9/31/R50-11C-3, September 1989 PLUS any contemporaneous records internal CAA reviews, comments or discussion of the report

2) British Hovercraft Corporation, Study of Float Positioning, BHC draft report no. X/O/3282, November 1985. OR in the event that this cannot be released as proprietary data, please supply records of any contemporaneous internal CAA reviews, comments or discussion of the content.


Our response:

In assessing your request in line with the provisions of the Freedom of Information Act 2000 (FOIA), we are able to provide the information below.

1. This document is no longer held by the CAA as it was disposed of in 2012, in line with the CAA’s disposal policy.
2. As discussed during our telephone conversation on 11 April 2014, this document is held by the CAA. However, the format of this document means that it is not easy to copy. We agreed during our conversation that you would arrange to view this document at Aviation House. Please can we ask that you contact us with the dates you intend visiting the CAA and we will make the document available.

3. Copies of the documents requested in points three to six of your request have been provided.

If you are not satisfied with how we have dealt with your request in the first instance you should approach the CAA in writing at:-

Mark Stevens  
External Response Manager  
Civil Aviation Authority  
Aviation House  
Gatwick Airport South  
West Sussex  
RH6 0YR

mark.stevens@caa.co.uk

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Yours sincerely

Rick Chatfield  
Information Rights and Enquiries Officer
CAA INTERNAL REVIEW & COMPLAINTS PROCEDURE

- The original case to which the appeal or complaint relates is identified and the case file is made available;
- The appeal or complaint is allocated to an Appeal Manager, the appeal is acknowledged and the details of the Appeal Manager are provided to the applicant;
- The Appeal Manager reviews the case to understand the nature of the appeal or complaint, reviews the actions and decisions taken in connection with the original case and takes account of any new information that may have been received. This will typically require contact with those persons involved in the original case and consultation with the CAA Legal Department;
- The Appeal Manager concludes the review and, after consultation with those involved with the case, and with the CAA Legal Department, agrees on the course of action to be taken;
- The Appeal Manager prepares the necessary response and collates any information to be provided to the applicant;
- The response and any necessary information is sent to the applicant, together with information about further rights of appeal to the Information Commissioners Office, including full contact details.
CAA Paper 97010

DEVICES TO PREVENT
HELICOPTER TOTAL INVERSION
FOLLOWING A DITCHING

BMT Fluid Mechanics Limited, Document No. 44117 Report 3

Prepared by: G E Jackson and S J Rowe

CIVIL AVIATION AUTHORITY, LONDON, DECEMBER 1997
Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority, The UK Offshore Operators Association, and the UK Health and Safety Executive. The work forms part of the Authority’s ongoing research programme on the stability of ditching helicopters, instigated in response to Recommendation 10 of the Report of the Helicopter Airworthiness Review Panel (CAP 491).

The CAA concurs with the conclusions of the research. The further work highlighted in respect of the development of the additional emergency flotation systems evaluated during the project is considered to be helicopter type specific; the Authority will seek to encourage and facilitate progress in this area. As regards the investigation of the human factors issues associated with escape from a side-floating helicopter recommended, further generic research is currently planned.

Safety Regulation Group

05 August 1997
Executive Summary

The purpose of this research project was to investigate novel emergency flotation devices intended to prevent the total inversion of ditched helicopters following capsize.

Capsize of ditched helicopters is virtually inevitable in moderate to severe sea-states, and the function of the devices is to ensure that, following capsize, some of the cabin doors and windows remain above the water level, thus affording a less hazardous escape route for the occupants. The devices also prevent the cabin from completely filling with water, and thus should give the occupants more time to escape.

Initially, ten ideas for flotation devices were developed and considered by a panel of specialists from BMT Fluid Mechanics Limited and GKN-Westland Helicopters Limited. These 10 devices were narrowed down to a short list of three which it was considered should be model tested in order to measure their effectiveness. All the three short-listed devices were intended to work by providing additional buoyancy in the area of the upper fuselage and engine cowling.

The three short-listed devices were:

- Foam filled engine/gearbox cowling panels.
- Long tubular flotation units attached to the upper cabin walls.
- Tethered flotation units.

The result of the model tests was that the general effectiveness of the first two of the devices was established, but the third device was found to be ineffective. Most effective were the buoyant engine cowling panels. The second most effective, and certainly worthy of consideration, were the long buoyancy units.

Overall it is concluded that additional emergency flotation of this type can be effective in reducing the risks of escape from a capsized helicopter. They may also play a important role in reducing the perception of these risks amongst passengers. Furthermore, increasing the total quantity and distribution of flotation units on the helicopter has the potential to improve the overall crashworthiness of the emergency flotation system.

Now that the general effectiveness of two of the additional emergency flotation systems has been demonstrated, it is recommended that the further development of these systems should proceed. This should consist of helicopter type-specific design studies which address some of the practical design issues, including a detailed review of the inherent buoyancy in the engine / gearbox compartment, and upper fuselage areas. This will permit more reliable estimates of the buoyancy required in the additional units to be made.

The practical problems posed by passenger escape from a partially inverted helicopter (say at a 150 degree attitude) should also be investigated.
5.6. Tethered Flotation Units ................................................................. 32
5.6.1. Performance in calm water ....................................................... 32
5.6.2. Performance in waves ............................................................. 34
5.7. Results Summary ................................................................. 36

6. Conclusions and Recommendations ........................................... 38

7. References ................................................................................. 41

Appendix A  Panel Meeting Background Briefing .................................. 43
Appendix B  Helicopter Stability ....................................................... 47
Appendix C  Device Marking and Ranking ........................................ 53

Appendix D  Excerpts from: Helicopter Model Tests –
Devices to Prevent Total Inversion, HHTC Model Test Report Assignment TSANR04J,
October 1996 ................................................................. 59
INTRODUCTION

1.1 Objectives

The objectives of the project were as follows:

- To review and develop ideas for devices to prevent total inversion of helicopters following capsize.
- Investigate the design basis for such devices (e.g. quantification of the extent of additional flotation required).
- To list all the device ideas and rank these in order of likely effectiveness and practicability, and develop a short-list of the three most attractive devices worthy of further investigation.
- To perform hydrodynamic model tests on the three short-listed devices in order to demonstrate their effectiveness.

It should be noted that the study was not intended to be specific to any particular helicopter type, and the results are therefore intended to be applicable to any large transport helicopter. However, the study was performed using drawings, specifications and models of the EH101 helicopter (and its earlier precursor, the WG34) provided by GKN-Westland Helicopters Limited.

1.2 Background

Certification of helicopters requires that they should be able to float in a stable attitude on the surface of the sea following a ditching in order to give the occupants sufficient time to escape to the life-rafts. Certain limiting wave conditions are specified. Helicopters certified for operation over the sea are fitted with various additional flotation equipment (normally in the form of inflatable buoyancy units) in order to fulfil these requirements.

The design of helicopters is such that their centre of gravity is high due to the weight of engines and gearboxes located on the cabin roof. Consequently it is unlikely that they can ever be made truly seaworthy to fulfil the stability requirements in more severe sea conditions.

When helicopters do capsize, they invariably turn completely upside down leading to complete flooding of the cabin and immersion of all doors, windows and escape hatches. This complete inversion makes escape from the cabin extremely hazardous.

It has been suggested in the past that one way of improving the situation might be to accept that the helicopter cannot remain upright in the steepest waves, but to try to ensure that a capsize does not result in a complete inversion. It was suggested that additional flotation devices located high up on the fuselage in the vicinity of the engine and gearbox might prevent the helicopter from rotating into the completely inverted condition.

A brief model test was performed by British Hovercraft Corporation in 1985 on a S-76 type helicopter to test this idea, but the results of the test were not completely successful, and no further work was pursued at that time.
In a more recent review of helicopter ditching research performed by BMT [1] it was proposed that further investigation should be made into the concept and, as a result, CAA commissioned the study reported here.

1.3 Study Method

The method adopted for the study comprised two phases.

1.3.1 Phase 1 – Initial Desk Study

The initial phase consisted of:

(a) A literature search for papers/articles describing such devices.

(b) The formation of a working panel consisting of naval architects/ hydrodynamicists and helicopter designers to develop more ideas and rank them.

The desk study was performed by a team of experts drawn from BMT Fluid Mechanics Limited (BMT) and GKN-Westland Helicopters Limited (GKN-WHL), and a total of 10 ideas resulted.

The members of the panel were as follows:

Mr Stephen J Rowe BMT (Panel Chairman)
Dr Robert G Standing BMT
Dr Ian W Dand BMT
Mr Andy Belben GKN-WHL
Mr Simon Clifford GKN-WHL
Mr Mike Loader GKN-WHL

The panel held one all-day meeting at GKN-Westland Helicopters, Yeovil. Following this meeting BMT performed some calculations to determine approximate buoyancy requirements for the proposed devices. Finally the panel members each made their own assessments of the likely effectiveness, practicality and safety of the proposed devices which led to conclusions on which were the most attractive devices to pursue. Three devices were eventually recommended for model testing in the second phase.

Two papers were produced for this panel; a briefing document issued prior to the meeting (reproduced here in Appendix A), and a stability and buoyancy calculation paper (reproduced here in Appendix B).

1.3.2 Phase 2 – Model Tests

In this phase the three devices which had been identified as most promising in Phase 1 were model tested in waves in order to determine their effectiveness in preventing the helicopter from inverting.

The objectives of the model tests were:

- To determine the effectiveness of three novel devices for the prevention of helicopter capsize into an inverted attitude.
- To rank these devices in order of apparent effectiveness.
- To arrive at an estimate of the minimum size/buoyancy requirements for each device.
THE CAPSIZE PROCESS

2.1 General

Helicopters are rather prone to capsize into a completely inverted attitude in waves because their centre of gravity is high. This is due to a concentration of weight on the top of the passenger cabin caused by the engines and gearbox.

Despite the flotation bags, which are installed to ensure a measure of seaworthiness, the metacentric height of the helicopter tends to be quite small, and the range of stability (angle at which the roll righting moment becomes negative) small when compared with a boat of similar dimensions. Once the capsize process has been initiated (usually by a large breaking wave), and the range of stability exceeded, there is nothing to prevent the aircraft from turning into the completely inverted attitude. In this attitude the weight is below the buoyancy and the aircraft is quite stable, but escape for the passengers from the completely flooded cabin is very difficult. The capsize initiation sequence is shown schematically in Figure 1.

![Figure 1](image-url)

**Figure 1 – The nature of capsize of a helicopter by a breaking wave [2].**

For the purposes of this study it was assumed that (i) the helicopter is always likely to capsize in other than very benign wave conditions, and (ii) it is preferable if the capsize process can be halted with the aircraft on its side. With appropriate buoyancy, this side-floating configuration may be arranged to be much more stable than the original upright one, and may offer the occupants a more reliable prospect of escape¹.

The study therefore considered the helicopter floating on its side, and attempted to ensure that this could be made to be a stable attitude.

¹ There are, however, some aspects of the side-floating attitude which do not promote easy escape from the cabin. These are outlined in Section 2.4.
Simple calculations of the EH101 helicopter weights and volumes (described in Appendix B) led to the conclusion that it was necessary to provide additional buoyancy of about 3 m$^3$ at the level of the engine and gearbox. If a 3 m$^3$ volume were to be provided on each side of the cabin, then the immersed side of the helicopter will balance the weight, and the 'high side' buoyancy will assist recovery when immersed by large waves. If the buoyancy were to be placed centrally, then it has been assumed that a total of about 6 m$^3$ would be required.

The 3 m$^3$ buoyancy is approximately equivalent to one of the existing main emergency flotation floats. The displaced weight of 3 tonnes also approximates to the total weight of engines and gearbox, and thus can be thought of as supporting that weight.

If the buoyancy can be placed in a location much higher than the engines (see for example Figure 8 in Section 3.2.7) then less buoyancy need be provided (due to the higher moment arm the buoyancy has about the centre of gravity).

### 2.2 Hydrostatic Objectives

The hydrostatic objectives for permitting the helicopter to float on its side in a stable attitude can thus be summarised as:

- Provision of a total of 6 m$^3$ of additional flotation in the vicinity of the engines/gearbox (or the provision of an equivalent buoyancy moment about the centre of gravity).

### 2.3 Airframe Objectives

Key issues to be considered in the context of installing the additional buoyancy on the airframe are as follows:

- It must be attached at a point where the airframe is strong enough to withstand the applied loads.
- Buoyancy and inflation systems may have a short life if stowed in a hot location (e.g. in close proximity to engines).
- The consequences of accidental in-flight deployment of the flotation system needs to be considered in relation to the aircraft safety (e.g. blocking engine intakes).
- When inflated, the flotation must avoid the engine exhausts, intakes and rotating components, otherwise they may be damaged or destroyed before they can do their job.

### 2.4 Escape from a Side-floating Helicopter

The premise of this work is that it is much easier for a passenger to escape from a helicopter when there is a door or hatch above the water level.

However, although strictly outside the terms of reference of the study, it is worth noting that there are some difficulties that a passenger may experience in escaping from a side-floating helicopter (particularly a large one). Some of these are:

- Inability to reach the door/hatch on the upper side due to large width of cabin (perhaps special provision needs to be made for escape e.g. rope ladders attached to door frame).
- Loss of footing when standing on the cabin wall (windows might pop out).
It is expected that these problems can be solved by detailed changes to the design of the passenger cabin fittings.

In the model testing phase of the work, the motion of the side-floating helicopter was measured and recorded (see Section 5, and Tables 4 and 5 and Figure 36 of Appendix D). It is anticipated that this data will assist any follow-on studies on escape from a side-floating helicopter.
3 DEVICES INITIALLY CONSIDERED

3.1 Literature Survey

The initial task in the study was to perform a literature survey to identify any relevant publications. The search was made using BMT’s own abstracts database, and the European Space Agency Information Retrieval Service (ESA/IRS) host, which provides access to more than 200 online databases in the fields of aerospace and its applications, science and technology, patent and business information. The service allows retrieval of information on specific topics contained in papers, articles, and reports. The main databases searched were:

<table>
<thead>
<tr>
<th>Database name</th>
<th>Publisher</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>National Aeronautics &amp; Space Administration</td>
<td>Aeronautics</td>
</tr>
<tr>
<td>Compendex*Plus</td>
<td>Engineering Information, Inc</td>
<td>Engineering and technology</td>
</tr>
<tr>
<td>European Aerospace</td>
<td>European Space Agency</td>
<td>Aerospace</td>
</tr>
<tr>
<td>NTIS</td>
<td>National Technical Info. Service</td>
<td>Scientific and technical information</td>
</tr>
<tr>
<td>INSPEC</td>
<td>Institution of Electrical Engrs.</td>
<td>Physics, electronics and computing</td>
</tr>
<tr>
<td>NATO-PCO</td>
<td>NATO</td>
<td>Science and engineering</td>
</tr>
<tr>
<td>BMT Abstracts</td>
<td>BMT</td>
<td>Marine technology</td>
</tr>
</tbody>
</table>

These searches failed to find any new information in the public domain on preventing helicopter total inversion following capsize.

3.2 The Devices Proposed

As a result of the panel meeting held in Phase 1, a number of ideas for providing additional floating buoyancy were developed and discussed. These are described in the following sections, and their perceived advantages and disadvantages are listed.

It should be noted that not all these ideas are necessarily original or new, but they were all considered worthy of discussion and consideration in the context of preventing total inversion of helicopters following capsize.
3.2.1 Buoyant foam-filled engine cowling panels

![Diagram of buoyant foam-filled engine cowling panels]

Figure 2 – Buoyant foam-filled engine cowling panels.

The engine cowling panels of the EH101 are currently of honeycomb sandwich construction which possesses a degree of inherent buoyancy due to the air contained in the cell structure. This raises the question of whether these panels could be increased in thickness to provide a useful and practical buoyancy enhancement.

The total surface area of the engine cowlings for the EH101 is 29.5 m² and so, in order to obtain an additional 6 m², it is necessary to increase the thickness of these panels by about 20 cm. The scheme is shown diagrammatically in Figure 2.

3.2.1.1 Advantages
- No additional active flotation systems required.
- Good location from hydrostatic viewpoint.
- Few potential safety problems.

3.2.1.2 Disadvantages
- Panel attachments to airframe will almost certainly need to be made more robust in order to withstand the buoyancy forces.
- May be difficult to provide sufficient buoyancy without excessive increase in external dimensions.
- May be significant weight penalty associated with the additional foam required.
3.2.2 Engine cowling panels with integral buoyancy bags

Figure 3 – Engine cowling panels with integral buoyancy bags.

The thickness of the cowling panels noted in Section 3.2.1 gives rise to the idea that thickened panels might each incorporate self-contained inflating buoyancy bags. The scheme is shown diagrammatically in Figure 3.

3.2.2.1 Advantages
- Good buoyancy location from hydrostatic viewpoint.

3.2.2.2 Disadvantages
- Panel attachments to airframe will almost certainly need to be made more robust in order to withstand the buoyancy forces.
- Need to ensure that accidental inflation of one or more panel units would not endanger the aircraft.
- Need to ensure that bags are not damaged by, for example, being sucked into engine intakes.
- Difficulties associated with the flotation equipment being stored in close proximity to the hot engine and gearbox.
- Complicated inflation system with many components and command wires.
3.2.3 Buoyancy bags inside rear fuselage

Figure 4 – Buoyancy bags inside rear fuselage.

Existing void spaces to the rear of the passenger cabin could be utilised for either permanent or automatically inflating buoyancy. However, it can be seen from Figure 4 that the location of the buoyancy is too low and too far aft to be really effective in preventing a capsise.

3.2.3.1 Advantages
- Makes use of existing largely void space.
- Good environment for storage of the flotation equipment.
- Few practical or safety problems.

3.2.3.2 Disadvantages
- Buoyancy is not well-placed from a hydrostatic viewpoint. Too far aft (giving rise to excessive nose-down attitude) and not high enough. Therefore likely to be ineffective in preventing total inversion.
3.2.4 Buoyancy inside passenger cabin roof

![Diagram of a vehicle with a roof section highlighted for buoyancy]

**Figure 5 – Buoyancy inside passenger cabin roof.**

It is possible that useful space for buoyancy could be provided inside the passenger cabin, perhaps in the space between the luggage lockers. This offers the possibility of a long thin flotation unit which might provide significant water plane area after cabin flooding has occurred. The design of the system would obviously have to ensure that the ability of the passengers to escape from the cabin was not impaired.

3.2.4.1 Advantages

- Few risks to airframe associated with accidental inflation.
- Good environment for storage of the flotation equipment.
- Probably sufficient space available for installation without major airframe or internal trim modifications.
- Longitudinally distributed buoyancy makes it easy to attach at many locations, also gives large water plane area when partially immersed.

3.2.4.2 Disadvantages

- Buoyancy not quite high enough (therefore more buoyancy required).
- Only becomes effective when the cabin has flooded.
- Potentially makes it more difficult to escape from the cabin.
- Potential risk of injury to passengers in event of accidental inflation.
- Inflation of bag may contribute to passenger panic under emergency conditions.
3.2.5 Long buoyancy bags along upper cabin wall

Figure 6 – Long buoyancy bags along upper cabin wall.

In this scheme, shown in Figure 6, the buoyancy is provided in the form of two long buoyancy bags attached to the outside of the upper cabin wall. The system offers the possibility of a large water plane area and permits attachment over a long length of the cabin skin, thus spreading the load over a large area of the structure.

It is believed that such buoyancy might be stowed in a long thin blister of about 200mm chord running along the top of the passenger cabin.

3.2.5.1 Advantages
- Longitudinally distributed buoyancy along a length may make it easy to attach at many locations to the fuselage frames (rather than requiring special ‘hard points’).
- Longitudinally distributed buoyancy can be arranged to provide a large water plane area.

3.2.5.2 Disadvantages
- Buoyancy not quite high enough (therefore more buoyancy required).
3.2.6 Flotation collar under rotor head

Figure 7 – Flotation collar under rotor head.

This system, shown in Figure 7, requires the flotation to be stored in the engine cowling area and to be deployed into the space between the cowling and the rotor. Both these aspects cause practical problems, although the location of the flotation buoyancy is ideal for counteracting a complete inversion capsize. The collar would not be easy to attach in this location and is likely to require considerable modification to the local structure.

3.2.6.1 Advantages
- Good location from hydrostatic viewpoint.

3.2.6.2 Disadvantages
- Difficulties associated with the flotation equipment being stored in close proximity to the hot engine and gearbox.
- Difficulty of attaching to local structure of sufficient strength.
- Probably not sufficient room to accommodate a doughnut of sufficient buoyancy between rotor and engine cowling on some aircraft types.
- Accidental in-flight inflation needs careful study to ensure that device is destroyed without damage to rotor systems or impairment of aircraft control.
3.2.7  Flotation on rotor head

Figure 8 – Flotation on rotor head.

A derivative of the flotation collar described in the previous section is a system shown in Figure 8, where the flotation is carried on the rotor head itself. This is a very favourable location for the buoyancy, because it has a very large moment arm about the aircraft centre of gravity. This means that less buoyancy is required, and indeed the volume required is about half that shown in the other schemes.

Whilst this scheme is obviously attractive from a hydrostatic and hydrodynamic point of view, it clearly raises a number of important practical design issues.

3.2.7.1  Advantages

- Excellent location from hydrostatic viewpoint and therefore very effective at preventing total inversion.

3.2.7.2  Disadvantages

- Difficulties associated with the flotation equipment being mounted on the rotor head.
- The consequences of accidental in-flight inflation need careful study.
Figure 9 – Tethered inflatable flotation units.

The thinking behind this system is to provide buoyancy high up on the side of the cabin whilst arranging for it to be stowed, and some of the forces resisted, at a location low on the fuselage in the region of the existing flotation units. The system must rely for its effectiveness on the buoyancy units being trapped against the cabin wall at the high location shown in Figure 9 as the helicopter rolls onto its side. This may be difficult to guarantee in practice if the helicopter first spends a period of time riding the waves upright. It may also be difficult to ensure that the units are not damaged by chafing against the fuselage and contact with hot exhausts.

3.2.8.1 Advantages
- Potentially good location from hydrostatic viewpoint.

3.2.8.2 Disadvantages
- Need to ensure that the tethered buoyancy bags always take up the correct position high up on the cabin wall, in all wind and wave conditions, and all capsize scenarios (probably needs considerable hydrodynamic model testing to arrive at a reliable design).
- Need to ensure that they are not damaged by contact with structure.
- May be difficult to ensure that accidental inflation does not compromise safety of the aircraft.
- Risk of blocking passenger exits with flotation bags and tethers.
Increased passenger seat buoyancy

Figure 10 – Increased passenger seat buoyancy.

The buoyancy of the cabin seats is quite significant and is roughly equivalent to the additional buoyancy required. However, it is believed that the current seat designs might not ensure that buoyancy remains intact and rigidly attached to the airframe (indeed some parts of aircraft seats are often removable for use a personal flotation by the passengers). Thus modifications to seat design would be required.

Unfortunately, the location of the seats is below the aircraft centre of gravity, and therefore will not assist with preventing total inversion.

3.2.9.1 Advantages
- No changes to airframe.
- Passive system with few practical or safety problems.

3.2.9.2 Disadvantages
- Not high enough in cabin to be helpful in preventing total inversion.
- Only becomes effective when cabin has flooded.
Figure 11 – Dynamic chemical foam in engine spaces.

This scheme is related to those described in sections 3.2.1 and 3.2.2 as it provides additional buoyancy in very close proximity to the engines. The principle is to arrange for a quick acting chemical foam to be generated filling the various voids in the engine and gearbox compartment.

However, it is not clear how much buoyancy would be available from this method. The free space in the engine compartments is not great, and probably varies considerably from one helicopter type to another. The system also has a number of inherent dangers associated with the chemicals being used, and the potentially serious consequences of accidental triggering in flight.

3.2.10.1 Advantages

- Good location from hydrostatic viewpoint.
- System could be more reliable and robust than gas filled bags.

3.2.10.2 Disadvantages

- Not clear that sufficient buoyancy will be created.
- Engine cowling attachments may need to be strengthened.
- Potentially serious consequences of accidental triggering in flight.
- Dangers associated with the chemicals required to generate the foam.
- Triggering the system on the water will presumably lead to shutting down of engines, possibly whilst the pilot still requires control.
3.3 The Devices Ranked

It can be seen from the previous section that all the systems have a number of advantages and disadvantages, and these need to be considered on the basis of their relative merits in order to determine which are the most attractive for further study. A ranking of the devices was therefore produced by means of marking each of the devices out of 10 points for each of the following three aspects:

- **Effectiveness** – How effective is the device likely to be in achieving the objective of preventing total inversion following a capsize?
- **Practicality** – How easy or difficult is it likely to be to incorporate the device into the design of a helicopter?
- **Safety** – Is the device free from additional safety hazards which it poses to the operation of the helicopter?

It was decided to weight the marks for effectiveness by a factor of 1.5 (and the others by 1.0). This weighting was applied to ensure that further study would only be considered for devices that were really effective in their action.

Each of six members of the panel marked the devices independently, and these results were then combined in various ways to produce results representative of the consensus of the panel.

It should first be noted that there was not close agreement between the individual marks and rankings of the different panel members. However, it was clear that the following devices were generally liked;

<table>
<thead>
<tr>
<th>No.</th>
<th>Device</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>Foam filled cowlings.</td>
</tr>
<tr>
<td>5.</td>
<td>Cabin wall floats.</td>
</tr>
<tr>
<td>8.</td>
<td>Tethered flotation units.</td>
</tr>
</tbody>
</table>

Four of the six panel members placed foam filled cowlings in either 1st or 2nd place in their rankings, whilst three members placed cabin wall floats and tethered flotation units in either 1st or 2nd place.

The following devices were generally disliked;

<table>
<thead>
<tr>
<th>No.</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.</td>
<td>Rear fuselage buoyancy.</td>
</tr>
<tr>
<td>10.</td>
<td>Foam-filled engine spaces.</td>
</tr>
</tbody>
</table>

The first two had very poor marks for effectiveness, and the third very poor marks for safety and practicality.

Copies of the spreadsheets showing the markings for the individual panel members and the consolidation are given in Appendix C.
3.4 Phase 1 Conclusions

The three most attractive devices for preventing total inversion following capsize were therefore:

<table>
<thead>
<tr>
<th>No.</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Foam filled cowlings.</td>
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<td>Cabin wall floats.</td>
</tr>
<tr>
<td>8.</td>
<td>Tethered flotation units.</td>
</tr>
</tbody>
</table>

It was considered that each of these devices was worthy of further, more detailed, investigation. It was also considered worth investigating whether a combination of two or more of the devices might be even more beneficial.

The effectiveness of each of these devices first needed to be demonstrated by means of simple model tests, which were performed in Phase 2 of the study.

Finally it was noted that increasing the total quantity and distribution of flotation units on the helicopter had the potential to improve the overall crashworthiness of the emergency flotation system.
4 DEVICES MODEL TESTED

4.1 Model Selection

Although this research study into novel emergency flotation devices is not specific to any particular helicopter type, it was necessary to select a particular helicopter type in order to perform any quantitative study or model test. The phase 1 work described in Section 3 was based on the GKN-WHL EH101 helicopter. For the model testing phase of the work a model of an early EH101 variant known as the WG34 was used. The model (Ref No. M1272) was provided by GKN-WHL and was modified to make it sufficiently similar to the EH101 for the model test work to be fully consistent with the Phase 1 desk study.

A policy decision was taken to ballast and balance the WG34 model as if it were an EH101, and information on the required mass properties and stability behaviour for the EH101 were available from [3]. This reference also contained information about EH101 capsize in waves which could be used to verify that the modified WG34 model behaved in a similar manner in waves. Details of model mass properties together with dimensions of the flotation devices are given in Appendix D.

4.2 Modifications to the Model

Prior to the testing the WG34 model was modified in order to:

- make it visually more like the EH101 (this consisted of replacing the engine cowling assembly and removing half the unusual double tail-plane), and
- make the buoyancy and wave forces on the engine cowling more like those that would be experienced by the EH101.

Emergency flotation systems were constructed and fitted as per the EH101 civil variant (the EH101 naval variant, Merlin, had slightly different float dimensions, particularly in the main floats). The main and forward floats and the additional buoyancy units were constructed from rigid foam and were rigidly attached to the sponsons and fuselage as described in [3]. For all the tests, except some attempts with the tethered buoyant units, the additional buoyancy units were also rigidly attached to the fuselage. Dimensions of the standard flotation units and the novel flotation devices are given in Tables 1 and 2 respectively of Appendix D.

Two weight conditions were chosen for the initial model tests. These were for full fuel load and half fuel load, and were consistent with those for the EH101 for which the capsize tests in [3] had been carried out.

4.3 Main Rotor

It has been noted (Appendix B) that the main rotor potentially provides a large amount of buoyancy, and is positioned in the right place to assist in the prevention of total inversion. However, the rotor is also obviously very prone to damage during ditching, particularly in large waves when it can strike the sea surface before the rotor brake is applied. It was therefore decided that these tests would be performed with no rotor fitted to the model. This would provide the novel flotation devices with a more stringent test.
4.4 Buoyancy of Engine Cowling Internal Area

The inherent buoyancy in the engine cowling of the helicopter is crucial in the behaviour of the capsized aircraft. Unfortunately there is little information on this buoyancy because previous work on helicopter ditching has concentrated on the occurrence of capsize, and not flotation following capsize.

The internal buoyancy of the engine cowling area is not considered during the design of the aircraft and it was found that relevant information on component dimensions and volumes was spread among many sources, making compilation of the details to produce a definitive value very time-consuming. However, a figure of 70% was estimated by GKN-WHL to be sufficiently accurate for the purposes of the present research project. Consequently the model was arranged so that only 30% of the engine cowling volume was free to flood.

It is worth emphasising that if model tests were being used to design additional flotation for a specific helicopter type, then more attention would need to be given to determining the appropriate buoyant volume.

4.5 Additional Flotation Units

4.5.1 General

In order to perform the model tests it was necessary to construct models of the three selected flotation devices:

- Foam filled engine and gearbox cowling panels.
- Cabin wall tubular flotation units.
- Tethered flotation units.

The modelling of these units is described in the following sections.

4.5.2 Buoyant Foam Engine Cowling Panels

The increase in buoyancy was obtained by adding a 20mm (200mm full scale) layer of foam over the outside of the engine cowling. This produced the required 6m$^3$ additional buoyancy. Later in the test this was trimmed down to 5m$^3$ (see Figure 12) by removing a layer of foam from the cowling top.

4.5.3 Long Flotation Units Attached along the Upper Cabin Walls

The long tubular flotation units were attached to either side of the aircraft fuselage, just below the engine cowling. They were originally intended to be used in pairs, one on either side of the aircraft, however, they were also tried singly on just one side. Two sets were constructed of differing total volume: two pairs comprising 6m$^3$ plus 31% (7.9m$^3$), and 6m$^3$ minus 18%(5m$^3$). These are shown in Figure 13.
Figure 12 – Buoyant Engine Cowling Panels (5m³ version)

Figure 13 – Long buoyant flotation units (Set 1 in the foreground)
4.5.4  *Tethered Floating Units*

![Tethered Buoyant Units](image)

**Figure 14 – Tethered Buoyant Units (Set 1 right, Set 2 left)**

The tethered flotation units, shown in Figure 14, were attached to the main and forward emergency flotation units on either side of the helicopter by short cords. This proved to be ineffective due to the movement of the devices, and so they were also tested rigidly attached to the aircraft fuselage above the main flotation units.

Two sets of buoyant flotation units were constructed, one set with a volume totalling 8.3m³, and a second set with a volume totalling 5.6m³.
5

MODEL TEST RESULTS

5.1 General

The model tests were undertaken at HHTC, Haslar, and are reported fully in their report (reference [4]). Excerpts are presented here in Appendix D. As noted earlier, the addition of the novel buoyant devices was not to prevent or modify the tendency of the helicopter to capsize, but rather to alter the attitude of the helicopter following capsize so that the occupants would be able to escape more easily and safely.

Assessments of the effectiveness of the novel devices for the helicopter in the capsized condition in calm water and in waves were mainly visual. The effectiveness was determined by the extent to which the doors and windows were held clear of the water surface following capsize, and were free from severe wave impact. Those configurations deemed successful in calm water were also tested in waves.

Quantitative measurements of static stability were also made on the standard helicopter, and on selected novel devices, by means of roll righting moment tests. The results are presented graphically in Appendix D.

All the wave tests were performed in irregular waves of the JONSWAP spectrum type [5]. Irregular waves were used throughout, as recommended in [1] for capsize model tests on helicopters. The JONSWAP spectrum was used because it is normally considered to be most representative of the waves found in the North Sea.

The series of tests in waves began with the standard aircraft (i.e. the helicopter without any novel additional flotation devices) in order to:

- confirm the capsize behaviour,
- select the wave conditions for the appraisal of the devices, and
- select the mass condition for the appraisal of the devices.

Helicopters drifting freely in the sea will tend to take up a preferred heading to the waves. In the absence of wind, or the deployment of a sea anchor, many take up a beam-on heading, in which they are particularly vulnerable to capsize. Some tend to face the waves and are thus less vulnerable to capsize. The WG34 model showed some tendencies to face into the waves, but for these tests it was decided that the helicopter would be maintained in a beam-on condition in order to maximise the likelihood of capsize or further rotations following capsize.

In order to maintain this beam-on heading, the helicopter model was held by two light lines, one attached to the nose and the other to the tail. The ends of the lines were held by two technicians who maintained the model's position in the testing tank. During a sequence of relatively small waves the model was brought back into position and during the larger waves the lines were left slack, and the model allowed to drift freely. This enabled the model to be generally kept aligned beam-on to the waves, providing a more stringent examination of the additional buoyant devices, whilst trying to ensure the minimum of interference with the free floating behaviour of the model.

In addition to tests to assess the effectiveness of the buoyant devices, some additional tests were carried out on the capsized model to obtain roll motion and acceleration measurements. Most of these tests were carried out in beam waves, but some tests were also undertaken with the helicopter heading into the waves. Data was not collected for all
the wave tests because the roll and acceleration measurements required an umbilical cable attached to the model, and there was concern that this cable might affect the free drift and capsizing behaviour of the model.

5.2 Standard Helicopter

5.2.1 Calm water flotation

To ensure that the helicopter model represented the model used in the capsizing tests given in [3], roll righting moment tests were carried out on the standard helicopter. In these tests the model is heeled to a given angle in calm water (whilst being free to change its floating level and pitch trim) and the applied roll moment is measured by a sensitive transducer.

![Image of a standard helicopter capsized in calm water.](image)

**Figure 15 – Standard helicopter capsized in calm water.**

Figure 37 of Appendix D shows the roll righting moment curve for the standard helicopter compared with that presented for the EH101 model in [3]. The roll righting moment curves agreed well with those originally obtained for the EH101 model by GKN-WHL up to a heel angle of about 30 degrees. However, the curves deviate at higher angles because the original tests included the main rotor on the model. As noted in Section 4.3, the model used for these tests did not include the main rotor.

It can be seen from Figure 15 that when the standard aircraft capsizes the exit doors and windows are all submerged. This is typical of all helicopters following capsizing, and provides the starting point for considering the effectiveness of the novel flotation units.
5.2.2 Performance in Waves

Figure 16 – Standard helicopter in waves.

The standard test helicopter capsized in large breaking waves in a sea-state having a JONSWAP wave spectrum, significant wave height $H_s = 4.3$ m, and peak period $T_p = 6.3$ s. This is a similar wave condition to those used in the initial capsize tests reported in [3] and lies within the range of wave conditions for Sea State 6. It confirmed the capsize behaviour of this configuration and demonstrated that the model was truly representative of the model used in reference [3]. The capsize mechanism was also visually confirmed to agree with those described in earlier reports (summarised in [1]).

To capsize the aircraft, the breaking wave required sufficient height and steepness to cause the down-wave main buoyancy unit to dig into the water. This effect, coupled with the rapid down-wave sway, gave rise to significant drag on the unit, accentuating the roll of the aircraft. With the wave breaking on the side and underneath the aircraft, and the capsize moment being so large, capsize is inevitable. The capsize sequence observed was much as shown schematically in Figure 1.

For the standard helicopter there was little observed difference in the willingness to capsize or the capsize behaviour itself between the two mass conditions, and the half fuel case (helicopter weight 12,839 kg) was chosen for the remainder of the study.

The JONSWAP wave spectrum with $H_s = 4.3$ m and $T_p = 6.3$ s condition was used for the remainder of the tests to rank the effectiveness of the additional flotation devices. However, other, less severe sea conditions, were also used in those tests undertaken to measure the motion responses of the capsized aircraft.

5.3 Long Buoyancy Units Attached along Upper Cabin Walls

Two sets of long buoyancy units were manufactured for the model tests. Set 1 had a total buoyancy (both sides) of 7.9 m$^3$, whilst Set 2 was significantly smaller with a total buoyancy of 4.9 m$^3$. The Set 1 units are shown installed on the model in Figure 17.
5.3.1 Calm water flotation

With the two long buoyancy units of Set 1 fitted, the capsized attitude proved to be a significant improvement compared with the standard aircraft. There was some water in the cabin, but the doors and windows on one side of the aircraft were clear of the water surface.

Owing to the symmetry of the units installed on both sides of the aircraft, there are two stable inverted floating attitudes, one on each side of the aircraft. However, one of these stable attitudes can be removed by installing a unit on one side of the aircraft only. This causes the aircraft to float a little lower in the water, but the single stable calm water attitude looked promising, and it was felt worthy of testing in waves. Righting moment curves for the helicopter fitted with the Set 1 Units are shown in Figures 39 and 40 of Appendix D, comparing two long buoyancy units and a single buoyancy unit with the standard aircraft.

The smaller Set 2 units were clearly much less effective and their static roll righting moment characteristics were not measured.

5.3.2 Performance in waves

The Set 1 long buoyancy units were reasonably successful in keeping the doors and windows on one side of the helicopter clear of the water, although occasionally larger waves would sweep in through the doors and windows.

Figure 18 – Prior to capsize, escape on both sides of aircraft.
Figure 19 – After 1st rotation, escape from port side of aircraft.

Figure 20 – After 2nd rotation, escape from starboard side of aircraft.

As noted in the calm water flotation, these devices exhibited two stable capsized floating attitudes. Initial capsize in waves would place the above water doors and windows down-wave, with a roll rotation of approximately -150 degrees. This seemed to be the less stable of the two conditions, and when hit by another large wave, the model would rotate again through a further roll angle of approximately -60 degrees, so that the "dry" side now faced the oncoming waves. Once in this more stable second attitude, no further changes occurred during the remainder of the test. The sequence, showing the first and second rotation is shown in Figures 18, 19 and 20.

Removal of one of the long flotation units results in only one stable inverted attitude with only a small loss in the observed effectiveness. A single unit could be installed on either side of the aircraft, but for asymmetric cabins would generally be expected to be installed on the side of the fuselage with the main doors.

If the approaching waves were towards the side on which the unit was mounted, after capsize the escape side would face away from the waves. Rotation during capsize would be less than 180 degrees. However, if the waves approached the other side of the helicopter (away from the unit), then after capsize the escape side of the helicopter would be facing the waves. Rotation during this latter capsize would be greater than 180 degrees.

Figures 21 and 22 show the start and end attitudes for a capsize for a helicopter with a single unit mounted on the port side, the same side as the incoming waves. Here, as for all these diagrams, the wave is approaching from the right and the capsize is anti-clockwise.

Figure 21 – One long buoyancy unit on port side, prior to capsize.
Figure 22 – One long buoyancy unit on port side, capsized (in a single rotation).

Figures 23 and 24 show the same start and end attitudes but for a single buoyancy unit mounted on the starboard side of the helicopter, the side facing away from the incoming wave. The capsize rotation is greater than 180 degrees.

Figure 23 – One long buoyancy unit on starboard side, prior to capsize.

Figure 24 – One long buoyancy unit on starboard side after capsize (in one rotation).

The capsized attitude of the helicopter with two Set 1 flotation units is shown in Figure 25.

Figure 25 – Long flotation units (Set 1) capsized in waves, "dry" side facing camera.

When only one Set 1 flotation unit was installed the attitude of the helicopter when capsized was lower in the water when compared with two units – see Figure 26. The doors and windows on one side of the aircraft were still above the water surface, but there was more water in the cabin and more wave impacts over the doors and windows.
The performance of the Set 2 units in waves was much inferior to Set 1. It was clear that these provided insufficient buoyancy, with green water often half way up the doors. The total buoyancy of 7.9m$^3$ of the Set 1 units may therefore be regarded as approximating to the minimum effective size for this device.

![Image](image1)

**Figure 26 – Single Set 1 long flotation unit capsized, "dry" side away from camera.**

5.4 Buoyant Foam Cowling Panels

![Image](image2)

**Figure 27 – Foam filled buoyant cowling panels.**

As with the long buoyancy units, two versions of buoyant cowling panels were tested. Initial tests were performed with a total buoyancy of 6m$^3$, and this was later modified during the tests by removing thickness from the top of the cowling (where it might not be practical due to low rotor clearance), and with the effect of reducing the total buoyancy to 5m$^3$. The static roll righting moment test was only performed on the 5m$^3$ version.
5.4.1 Calm water flotation

The 6m$^3$ buoyant cowling, shown in Figure 27, provided a large improvement on the inverted helicopter attitude compared with the standard aircraft. Figure 28 shows that the doors and windows on one side of the aircraft were kept well clear of the water surface and the cabin was also quite clear of water. The 5m$^3$ buoyant version also showed a similar improvement. Righting moment curves are shown in Figure 38 of Appendix D comparing the 5m$^3$ buoyant version with the standard version. The calm water flotation for this system exhibited the same two stable inverted attitudes as were seen for the long buoyancy units.

![Image of a buoyant cowling](image)

Figure 28 - Foam filled buoyant cowling panels capsized in waves.

5.4.2 Performance in waves

The foam filled buoyant cowling panels were clearly very successful. The device produced a smaller overturn angle (capsize rotation) than for the long buoyancy units, with the doors and windows on one side of the aircraft being kept well clear of green water. It also kept the aircraft cabin mainly clear of water, with the forward end of the helicopter being the more deeply immersed. The reduced buoyancy version (5m$^3$) of the device also appeared to work well, although the aircraft was lower in the water and there was more water in the cabin.

The two stable conditions found in the calm water flotation tests were also in evidence in waves. Behaviour in waves was very similar to that seen for the two long buoyancy units. Since the aircraft capsized away from the incoming waves, the side of the aircraft above the water surface lay on the down-wave or lee side. The aircraft remained in this stable attitude for quite some time until hit by another very large wave (about as large as that required to cause the capsise in the first instance). This would cause the aircraft to rotate again so that the other side of the aircraft was above the water surface and now on the weather side. Once this had occurred no further rotations were observed. This attitude ("dry" side facing the waves) again seemed to be the more stable attitude of the two.
5.5 Buoyant Cowling and Single Long Unit Combination

5.5.1 Performance in calm water

In view of the fact that the buoyant cowling panels had been seen to be very successful, and that a single long buoyancy unit had removed the dual stable floating attitudes, it was decided that these should be tested in combination – see Figure 29.

![Buoyant cowling and single long unit combination](image)

**Figure 29 – Buoyant cowling and single long unit combination.**

A single long bag of the smaller Set 2 was installed on the starboard side of the helicopter in combination with the 6m³ version of the buoyant cowling. The calm water performance showed that the addition of the long unit had removed the bi-stable inverted attitude. Static roll righting moment was not measured for this combination.
5.5.2 Performance in waves

In waves the combination showed the desired properties. The dryness of the access doors was much the same as that observed for the 6m³ buoyant cowling alone, but the addition of the long unit was effective in removing the second capsize rotation.

5.6 Tethered Flotation Units

Two sets of tethered flotation units were manufactured for the model tests. Set 1 had a buoyancy of 2.1m³ for each unit (total of 8.3m³ for the four units in the set). Set 2 was significantly smaller at 1.4m³ each (5.6m³ total).

5.6.1 Performance in calm water

The tethered floating units were attached to the main and forward floats on each side of the aircraft. Figure 31 shows the upright aircraft with the Set 1 tethered units attached. Figure 32 shows the same configuration with the helicopter capsized. It had been intended that, on capsize rotation, the units would become trapped high up against the helicopter cabin, thus providing buoyancy in the desired location. In practice this did not work, and the units were free to float clear of the cabin providing virtually no assistance.

It was decided that the units would instead be strapped to the side of the cabin to restrict this movement – see Figure 33. This condition is shown inverted in Figure 34 (no righting moment curves were measured for this case).

Attaching the tethered units to the aircraft at least allowed the additional buoyancy to be effectively utilised. It can be seen from Figure 34 that the doors and windows on one side of the aircraft were clear of the water surface although the cabin had some water in it.
Figure 31 – Free tethered units in calm water.

Figure 32 – Free tethered units capsized in calm water.
5.6.2 Performance in waves

Despite the unsatisfactory performance of the free tether system in calm water, it was decided to test it in waves. However, not surprisingly, it was found to be ineffective.

Once the Set 1 (8.3 m$^3$) tethered units were secured to the fuselage, the calm water attitude had looked more promising. However, when this condition was subjected to waves the windows and doors were submerged for most of the time and so this device was also considered to be unsuitable. The devices did not seem to provide sufficient waterplane area and roll restoring moment and so proved ineffective in waves. The smaller units, Set 2 (5.6 m$^3$), were not tested.

![Secured tethered units](image)

**Figure 33 – Secured tethered units.**

The shortcomings of this system were clear. In the captive mode the buoyancy was positioned too low to be really effective. In the tethered mode the buoyancy did not deploy into a suitable location to be effective. It was also noted that some of the tethers broke during wave tests, indicating the large shock loads that would also be expected to occur at full scale.
Figure 34 – Secured tethered units capsized.
Results Summary

The results described previously are summarised in Table 1.

<table>
<thead>
<tr>
<th>Conditions:</th>
<th>Calm Water Attitude</th>
<th>Observed Wave Response</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Individual Systems</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buoyant Cowling Panels (6m³)</td>
<td>Excellent – doors and windows on one side of the aircraft well clear of water surface</td>
<td>Excellent</td>
<td>Best of the three systems</td>
</tr>
<tr>
<td>Buoyant Cowling Panels (5m³)</td>
<td>Good – doors and windows on one side of the aircraft clear of water surface</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Long Units Set 1 (7.9m³)</td>
<td>Good – doors and windows on one side of the aircraft clear of water surface</td>
<td>Occasional waves over the doors and windows</td>
<td>Next best</td>
</tr>
<tr>
<td>Long Units Set 2 (4.9m³)</td>
<td>Poor, Windows and doors on one side only just clear of water</td>
<td>Only half the doors and windows clear</td>
<td></td>
</tr>
<tr>
<td>Long Units Single set 1</td>
<td>As double units but just slightly lower in the water</td>
<td>Similar behaviour to double units</td>
<td></td>
</tr>
<tr>
<td>Tethered Units Set 1 (8.3m³) free</td>
<td>Effectiveness is poor</td>
<td>Ineffective</td>
<td>Worst of the three systems</td>
</tr>
<tr>
<td>Tethered Units Set 1 (8.3m³) secured</td>
<td>Good – doors and windows on both sides clear of surface</td>
<td>Ineffective, doors and windows mainly covered by water</td>
<td></td>
</tr>
<tr>
<td>Tethered Units Set 2 (5.6m³)</td>
<td>Not Tested</td>
<td>Not Tested</td>
<td></td>
</tr>
<tr>
<td><strong>Combination</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buoyant Cowling Panels (6m³) plus single long bag (from Set 2)</td>
<td>Excellent – doors and windows on one side of the aircraft well clear of water surface</td>
<td>As for the 6m³ cowling, but with the advantage of no second capsize rotation.</td>
<td></td>
</tr>
</tbody>
</table>

The most effective device tested was the buoyant engine cowling panels. This kept the doors and windows well clear of the water save for the occasional large wave. When the buoyancy was reduced from 6 m³ to 5 m³ there was a slight reduction in observed effectiveness in waves. It is likely that the buoyancy could be reduced further, and still retain a measure of effectiveness.

The second most effective device was the long flotation units mounted on the cabin sides. These were tested with a buoyancy of 7.9 m³ (Set 1) which were quite effective with the doors and windows being kept clear of the water for most of the time. However, when the total buoyancy of the units was reduced to 4.9 m³ (Set 2) the doors and windows were severely blocked by water from the waves, limiting the effectiveness of the device.
The tethered buoyant units proved to be the least effective of the three devices tested. In order to provide any benefit they needed to be attached to the fuselage to prevent movement and maintain their position (this virtually negated one of the key features of this device which was intended to be stowed and deployed on a tether from the same location as the existing main emergency flotation). In calm water the doors and windows were kept above the water, but in waves they were almost continually covered.

The tests showed that the capsized helicopter with buoyant engine cowling panels and the long buoyant units had two stable floating attitudes. In calm water these two attitudes were of equal stability. However, in waves capsizing would initially place the "dry" doors and windows down-wave with a roll rotation of approximately 150 degrees. This down-wave attitude was not completely stable, and when hit by another large breaking wave some time later, the model would rotate again through a further roll angle of approximately 60 degrees, so that the "dry" doors and windows faced the oncoming waves. This second attitude proved to be the more stable of the two, and the model did not rotate again once in this position. A roll time history, recorded during and after a capsise, shows clearly the initial capsise and then later the secondary rotation, and is presented in Figure 36, of Appendix D.

A single long buoyancy unit from Set 1, mounted on one side of the helicopter was tested in waves. The single unit proved to be almost as effective as the two units, but with the helicopter floating slightly lower in the water and with a subsequent increase in the water over the doors from the waves. This configuration was successful in removing the second rotation exhibited by the dual unit.

A single long buoyant unit from Set 2 was also tested in combination with the 6m³ buoyant engine cowling panels. This had the key benefit of combining the effectiveness of the buoyant cowling with the removal of the second capsise rotation afforded by the single long unit.

Separate tests were undertaken where roll (angle) and surge, sway and heave (accelerations) were measured for the capsized helicopter with the buoyant engine cowling panels and the long flotation units. The results from these tests are summarised in Tables 4 and 5 of Appendix D. An example time history of the roll motion during a capsise is presented in Figure 36, also in Appendix D.

These motion measurements may be analysed further in a later study if it is desired to investigate the problems associated with escape from the capsized helicopter in waves.
CONCLUSIONS AND RECOMMENDATIONS

1. The initial desk study phase of the project was aimed at developing ideas for novel flotation devices to prevent the total inversion of a capsized helicopter, and ten ideas for novel flotation systems were developed. Following closer study and analysis of their likely effectiveness, safety and practicability, the list of ten devices was narrowed down to a short-list of three which were model tested in phase 2. The three short-listed devices were:

- Foam filled engine/gearbox cowling panels.
- Long tubular units attached to the upper cabin walls.
- Tethered flotation units.

2. The general effectiveness of the first two of the short-listed devices, the foam filled engine/gearbox cowling panels and the long tubular units attached to the cabin walls was established by the model tests in waves. The third device was found to be ineffective.

3. Most effective of the individual devices were the buoyant engine cowling panels. These devices kept the passenger escape routes (doors and windows) well clear of the water except for the occasional large wave. When the buoyancy was reduced from 6m³ to 5m³ there was some slight reduction in observed effectiveness in waves. It is likely that the buoyancy could be reduced even further, and yet still retain a measure of effectiveness.

4. The second most effective of the devices, and certainly worthy of consideration, were the long buoyant units. These were tested with a buoyancy of 7.9m³ (Set 1) which were quite effective with the doors and windows being kept clear of the water for most of the time. However, when the buoyancy was reduced to 4.9 m³ (Set 2), the doors and windows were severely blocked by water, limiting the effectiveness. Minimum effective buoyancy for this device is therefore represented by Set 1.

5. Whilst these two systems performed well, there was a tendency to exhibit a two stage capsize, with a transition between exposing the port side windows and the starboard side windows above the water level. The second stable attitude proved to be the more stable of the two attitudes and the model did not show a tendency to rotate again. Whilst this second rotation was not a violent transition, and the transition might not occur for many minutes, it is clearly undesirable, and would be disconcerting for those attempting to make their escape from the helicopter at that time. The bi-stable behaviour is caused by the symmetry of the flotation system, and can be removed by providing the additional buoyancy on one side of the helicopter only. This asymmetric configuration of one Set 1 long buoyancy unit was also tested and proved to be almost as effective as the two units, but with the helicopter floating slightly lower in the water and with a subsequent increase in the water over the doors from the waves. It removed the second rotation found with the devices used in pairs. A combination of 6m³ buoyant cowling panels, and single Set 2 long buoyancy unit was also tested and found to successfully combine the favourable performance of the cowling with the removal of the undesirable second capsize rotation.

38
6 The tethered buoyant units were the least effective of the three devices tested. When tethered as originally envisaged, they provided no benefit at all. When rigidly attached to the fuselage in the intended position the doors and windows were kept above the water in calm water, but in waves they were almost continually covered.

7 Some tests were undertaken with measurement of accelerations in three axes at the aircraft centre of gravity for the helicopter with buoyant engine cowling panels and the long flotation units. These data may prove useful to any future study of escape from an upturned helicopter in waves.

8 On the basis of the above it is concluded that the foam filled engine cowling panels and the long tubular buoyancy units are worthy of further development, and recommendations to this effect are made below.

9 Overall it is concluded that additional emergency flotation of this type can be effective in reducing the risks of escape from a capsized helicopter. They may also play a important role in reducing the perception of these risks amongst passengers.

10 It proved difficult to arrive at a completely reliable value for the total internal buoyancy represented by the engine and gearbox, and an estimate of 70% buoyancy was made by GKN-WHL for the work. It is concluded that this issue requires more detailed investigation when the design of such additional flotation progresses further.

The following recommendations are made:

1 Now that the general effectiveness of two of the additional emergency flotation systems has been demonstrated, it is recommended that the further development of these systems should proceed. This should consist of helicopter type-specific design studies which address the following issues:

**Buoyant foam-filled engine cowling panels**

- More detailed investigation of the thickness of the panels required in order to provide the buoyancy, and the consequent impact on helicopter external shape and drag.
- Review of panel attachment strength requirements.
- Review of weight implications of the above.

**Long buoyancy units attached along upper cabin wall**

- Investigation of attachment methods which spread the load and also place the bags at the highest possible location.
- More detailed consideration of the buoyancy volume required given the height achieved.

2 It is recommended that, when the design study progresses further, there should also be a more detailed review of the inherent buoyancy in the engine / gearbox compartment, and upper fuselage areas of the selected helicopter. This will permit more reliable estimates of the buoyancy required in the additional units to be made.
3 It is recommended that the effects of partial flotation failure, and the resistance of the novel devices to water impact (crashworthiness) are also considered.

4 The practical problems posed by passenger escape from a partially inverted helicopter (say at a 150 degree roll attitude) should be investigated. The study should at least consider:

- What special escape provisions need to be made to ensure that the above water doors and windows are accessible to the occupants?
- What modifications, if any, need to be made to life raft stowage and deployment in order to make them accessible from the partially inverted attitude?
- What particular difficulties, if any, are caused by the wave motions of the helicopter in this attitude? (Further analysis of the motions data collected in this project may be of assistance here.)

5 Further design studies should also consider the safety consequences of accidental in-flight deployment of the novel flotation systems.
REFERENCES


Appendix A
Panel Meeting Background Briefing
HELIQUPTER STABILITY FOLLOWING DITCHING

Background and Objectives Paper for Working Group on Devices to Prevent Total Immersion

BMT Project 44035/00
Robert G Standing and Stephen J Rowe
6th June 1994

A.1. Background

Reference [1] highlighted the benefits of a flotation device that would prevent the total inversion of a helicopter following capsize. Such a device would have significant benefits in terms of reducing the risks to occupants attempting to escape from the helicopter following a ditching.

It is understood that only one brief set of model tests has been performed to investigate this concept. These tests, described in Reference [2], were on an S-76 helicopter model with floats attached at engine cowling level. The results from this one set of tests were not a complete success and also seem to have been misinterpreted, and, as a result, the concept of floats to prevent total inversion has not been investigated further.

These tests demonstrated that the helicopter had a stable side-floating attitude, with the top of the craft facing oncoming waves. Unfortunately this condition was reached by a two-stage process. Firstly a large breaking wave rolled the helicopter onto its side, with the helicopter bottom facing the oncoming waves, and then a second breaking wave rolled the helicopter through a further 160° until it was again on its side, but with the top of the helicopter facing the oncoming wave.

The guarantee of a stable side-floating attitude, with an escape door above the surface of the water, should significantly improve the chances of escape, provided the helicopter has suitable doors on both port and starboard sides. The disadvantage of this arrangement, however, is that there is a risk that personnel attempting to escape after the first phase of this process will have the helicopter roll on top of them during the second phase. It is questionable, however, whether this risk is any greater than that associated with making an escape during, or following, a complete inversion, when all exit doors will be below water.

A subsequent CAA internal report (Reference 3) was not encouraging on the subject of cowling floats, emphasizing the risk from ‘continuing roll’ in the direction of the waves. This phrase is considered misleading, and may have discouraged further research on this concept. It implies that the helicopter keeps on rolling away from the waves, whereas the evidence from Reference 2 indicates that the helicopter eventually finds a stable attitude, following the two-stage roll.

There is moreover a possibility that this two-stage roll might be avoided altogether if the cowling flotation size were somewhat greater. The practical problems of installing large floats on the helicopter would, of course, have to be addressed.

The following paper is intended as a preliminary discussion document for a small working group, which will consider and recommend possible ideas to prevent total inversion. This group will contain naval architects (with vessel capsize experience) and helicopter designers (with flotation system experience).
A.2. Objectives

* To consider the possible benefits and disadvantages of cowling floats for the purpose of preventing total inversion.
* To consider and list ideas for alternative devices which might prevent total inversion, their possible benefits and disadvantages.
* To make recommendations for further research or trials on the more promising devices.

A.3. Some Points for Discussion

* Are cowling floats of the type tested in Ref [2] likely to be practical and acceptable?
* Are the costs likely to be acceptable?
* Might larger cowling floats avoid the two-stage roll problem, with its attendant risks to escaping personnel?
* Would larger cowling floats be feasible and acceptable?
* Might an alternative location on the craft be advantageous – while still providing the necessary righting moment?
* What other devices might be effective and feasible?
* Are these alternative devices likely to have significant advantages or disadvantages compared with cowling floats?
* What issues need to be addressed before these questions can be answered, and how should they be addressed?
* What recommendations should be made for further research or trials, and to whom?

A.4. References


Appendix B
Helicopter Stability
B.1. Helicopter Stability

Some buoyancy calculations have been performed for the EH110 helicopter, once ditched and lying on its side in the water. The outcome of these calculations is summarised in the following. However, it should be stressed that the calculations are very simplified and should be checked by more detailed consideration of the helicopter’s damaged stability.

B.1.1. Method

The overall mass distribution was taken from the GKN-WHL data, centre of gravity co-ordinates and overall mass for:

- light condition – no fuel, no payload (given)
- all-up condition – with fuel and payload (given)
- ‘empty’ condition – with maximum fuel but no passengers and crew.

It was assumed that thirty-two 100 kg passengers and two crew were carried, which seemed to tie up with the vehicle specification and the payload figures. It was also assumed that 1200 kg of fuel were on board.

The buoyancy of the vehicle was calculated assuming:

- It was floating on its side with the centre-line (‘bl’) as the waterline.
- ‘Skin’ buoyant volumes were obtained from the surface areas and an assumed 40 mm honeycomb, buoyant, skin thickness.
- Crew and passengers were neutrally buoyant.
- Fuel tanks were intact.

The following conditions were studied:

- Sponson buoyancy bag (underwater) inflated or not inflated.
- Main rotor intact with two blades immersed.
- Main rotor damaged and not contributing to buoyancy.
- No passengers and crew and all passengers and crew.
- Light condition.

The aim was to compare the buoyancy obtained in this way with that required to keep the vessel afloat and to investigate what the relative positions of the centres of gravity and buoyancy tell us about trim, capsiz, etc. Clearly the deductions from this can only be taken so far because we currently have no information about the damaged stability curve (especially its range) and even less about the dynamics of the floating body.
B.1.2. Results Obtained

B.1.2.1 Overall Buoyancy

There appears to be enough inherent buoyancy in the honeycomb skin, fuel tanks and rotors to support the light mass of the helicopter floating on its side. The major part of this comes from the fuel and other tanks in the floor of the cabin, but two immersed blades of the main rotor provide the next most significant amount of buoyancy by far. The estimate suggests they provide almost as much buoyancy as a bag (i.e. about 3m³), so a bag up near the motor/gearbox would be valuable, if only to replace the buoyancy lost if (as is likely) the rotor blades are damaged or broken off during a ditching or during a capsize.

In a high weight condition, the sponson air bag adequately allows for the additional mass and indicates that the vehicle would float higher out of the water than assumed.

B.1.2.2 Buoyancy Distribution

Although there appears to be adequate buoyancy, it is in the wrong place when the vehicle is on its side. The fuel tanks and sponson bag form the main buoyancy components with only the rotor/upper bag and skin to balance them. This means:

- The helicopter floats with its base high out of the water when on its side.
- The capsizing lever between buoyancy and mass is quite large. If the stable range is small, it would probably not take much to capsize the vehicle.
- The sponson bag provides buoyancy low down and so lowers the centre of buoyancy (when the helicopter is on its side) which in turn reduces the metacentric height (GM).
- The sponson bag being set aft, together with the buoyancy (and its lever) of the tail arrangement, causes the position of the longitudinal centre of buoyancy (lcb) to lie aft of the longitudinal centre of gravity (lcg). This causes the nose to sink. In the S-76 model test this was balanced by a nose buoyancy bag, which will have helped in this regard, but made matters worse by putting more buoyancy in the wrong place and increasing the capsizing moment.

The result of this is that, without the rotor/upper bag, the moments to cause capsize are significant. They will cause the vessel to ride with its base high out of the water which, with its nose down, will accentuate weather-cocking and possible rotation in 'yaw' until a more stable state, perhaps with the base away from the wind, is reached.

B.1.2.3 Aftermath of a Capsize

Crew and passenger mass and buoyancy are quite significant parts of the overall values and a calculation was made to see what would happen when passengers left their seats after capsize (assuming they remained strapped in during capsize) and floated around, trying to get out.

If main rotor/upper bag (or ideally both) were in place and providing buoyancy, then with passengers strapped in, the capsizing moment is small, the centre of buoyancy low and the nose-down moment moderate. With no passengers the capsize moment increases slightly, the centre of buoyancy lowers appreciably and the nose sinks more. This suggests that, as the passengers leave, the chances of a capsize increase. However, with main rotor/upper bag in place, the increased chances of capsize are probably fairly modest and could be acceptable.

If no rotor or upper bag are in position, the situation is far worse. The capsize moments are evidently larger from the outset and the nose-down moments are accentuated.
Therefore the value of the upper bag (or the main rotor blades if they are intact) lies not so much in the buoyancy it provides, but where it is placed. Things would be much better if, when the vehicle were on its side, the sponson bag were not underwater at all, deflated or moved, as in device 8, to the vicinity of the engine/gearbox.

Many of these arguments, of course, need the damage stability curve for the helicopter on its side to take them to their logical conclusion. This would then give a feel for how close to capsize the vessel is at any condition, which could be both extrapolated into assessing qualitatively how it would behave in waves and perhaps, give some better idea of what was the best position for more buoyancy.

IAN W DAND
12th August 1994
Appendix C
Device Marking and Ranking
# Devices to Prevent Total Inversion

44035f11.ws  DEVICE RANKING MARKING SYSTEM

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<thead>
<tr>
<th>SC's marks:</th>
<th>Device Description</th>
<th>Effectiveness</th>
<th>Marks (out of 10)</th>
<th>Safety</th>
<th>TOTAL POINTS</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.50</td>
<td>Practicability</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Foam-filled cowlings</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>25.5</td>
<td>2</td>
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</tr>
<tr>
<td>2 Cowl integral float units</td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>22.0</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3 Rear fuselage buoyancy unit</td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>21.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4 Cabin ceiling float</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>17.5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>5 Cabin wall floats</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>29.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6 Collar under rotor head</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>18.5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>7 Rotor flotation unit</td>
<td>8</td>
<td>3</td>
<td>5</td>
<td>20.0</td>
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<td></td>
</tr>
<tr>
<td>8 Tethered flotation units</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>24.0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9 Buoyant seating</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>18.5</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>10 Foam-fill engine space</td>
<td>9</td>
<td>5</td>
<td>3</td>
<td>20.0</td>
<td>6</td>
<td></td>
</tr>
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</table>

### C.4. Average GKN-WHL marks

<table>
<thead>
<tr>
<th>Device Description</th>
<th>Effectiveness</th>
<th>Marks (out of 30)</th>
<th>Safety</th>
<th>TOTAL POINTS Rank</th>
<th>Ave. Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.50</td>
<td>Practicability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Foam-filled cowlings</td>
<td>25</td>
<td>18</td>
<td>26</td>
<td>81.5</td>
<td>2</td>
</tr>
<tr>
<td>2 Cowl integral float units</td>
<td>27</td>
<td>11</td>
<td>16</td>
<td>67.5</td>
<td>5</td>
</tr>
<tr>
<td>3 Rear fuselage buoyancy unit</td>
<td>27</td>
<td>24</td>
<td>26</td>
<td>71.1</td>
<td>4</td>
</tr>
<tr>
<td>4 Cabin ceiling float</td>
<td>27</td>
<td>25</td>
<td>24</td>
<td>89.5</td>
<td>1</td>
</tr>
<tr>
<td>5 Cabin wall floats</td>
<td>27</td>
<td>25</td>
<td>24</td>
<td>89.5</td>
<td>1</td>
</tr>
<tr>
<td>6 Collar under rotor head</td>
<td>25</td>
<td>13</td>
<td>13</td>
<td>63.5</td>
<td>7</td>
</tr>
<tr>
<td>7 Rotor flotation unit</td>
<td>27</td>
<td>7</td>
<td>10</td>
<td>57.5</td>
<td>9</td>
</tr>
<tr>
<td>8 Tethered flotation units</td>
<td>25</td>
<td>22</td>
<td>22</td>
<td>81.5</td>
<td>2</td>
</tr>
<tr>
<td>9 Buoyant seating</td>
<td>11</td>
<td>23</td>
<td>22</td>
<td>61.5</td>
<td>8</td>
</tr>
<tr>
<td>10 Foam-fill engine space</td>
<td>18</td>
<td>14</td>
<td>10</td>
<td>51.0</td>
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</tr>
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</table>

56
### C.5. Average of BMT and GKN-WHL marks

<table>
<thead>
<tr>
<th>Device Description</th>
<th>Effectiveness</th>
<th>Practicality</th>
<th>Safety</th>
<th>TOTAL POINTS</th>
<th>Rank</th>
<th>Ave. Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Foam-filled cowling</td>
<td>47</td>
<td>33</td>
<td>53</td>
<td>156.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2 Cowl integral float units</td>
<td>51</td>
<td>22</td>
<td>33</td>
<td>131.5</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>3 Rear fuselage buoyancy unit</td>
<td>39</td>
<td>44</td>
<td>47</td>
<td>119.5</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>4 Cabin ceiling float</td>
<td>36</td>
<td>44</td>
<td>38</td>
<td>136.0</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5 Cabin wall floats</td>
<td>45</td>
<td>40</td>
<td>43</td>
<td>158.5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>6 Collar under rotor head</td>
<td>50</td>
<td>27</td>
<td>32</td>
<td>134.0</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7 Rotor flotation unit</td>
<td>57</td>
<td>17</td>
<td>31</td>
<td>133.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>8 Tethered flotation units</td>
<td>47</td>
<td>30</td>
<td>46</td>
<td>154.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>9 Buoyant seating</td>
<td>16</td>
<td>51</td>
<td>47</td>
<td>122.0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>10 Foam-fill engine space</td>
<td>42</td>
<td>26</td>
<td>26</td>
<td>115.0</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

#### Alternative Overall Ranking Scheme

<table>
<thead>
<tr>
<th>Number of ranked 1st, 2nds and 3rds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score 3 for a first, 2 for a 2nd, 1 for a third</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device Description</th>
<th>No. 1sts</th>
<th>No. 2nds</th>
<th>No. 3rds</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Foam-filled cowling</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>2 Cowl integral float units</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3 Rear fuselage buoyancy unit</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4 Cabin ceiling float</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>5 Cabin wall floats</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6 Collar under rotor head</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>7 Rotor flotation unit</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>8 Tethered flotation units</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>9 Buoyant seating</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>10 Foam-fill engine space</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix D
Excerpts from: Helicopter Model Tests –
Devices to Prevent Total Inversion,
HHTC Model Test Report Assignment T5ANR04J,
October 1996
Standard Buoyancy Devices

The ‘standard’ emergency flotation unit sizes were manufactured to dimensions given by GKN-WHL. The following table summarises the unit parameters and the under-cowling buoyancy as modelled:

### Table 1 Standard emergency flotation

<table>
<thead>
<tr>
<th>Unit</th>
<th>Prototype</th>
<th>Model</th>
<th>Prototype</th>
<th>Model</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (m)</td>
<td>Length (m)</td>
<td>Diam. (m)</td>
<td>Diam. (m)</td>
<td>Volume (m³)</td>
<td>Volume (m³)</td>
</tr>
<tr>
<td>Forward</td>
<td>1.83</td>
<td>0.183</td>
<td>1.07</td>
<td>0.107</td>
<td>1.64(each)</td>
<td>0.00164</td>
</tr>
<tr>
<td>Main</td>
<td>2.38</td>
<td>0.238</td>
<td>1.42</td>
<td>0.142</td>
<td>3.77(each)</td>
<td>0.00377</td>
</tr>
</tbody>
</table>

It should be noted that it was assumed that 70% of the volume under the engine cowlings represented buoyancy volume. This was GKN-WHL’s estimate of the volume taken up by engines, transmission and other equipment.

Novel Buoyancy Devices

The equivalent prototype volume (after correction for this excess weight) is given in the following table, which summarises the dimensions and volumes of all the devices.

### Table 2 – Buoyancy of Novel Flotation Devices Tested

<table>
<thead>
<tr>
<th>Device</th>
<th>No Off</th>
<th>Prototype</th>
<th>Model</th>
<th>Prototype</th>
<th>Model</th>
<th>Prototype</th>
<th>Model</th>
<th>% over 6 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Length (m)</td>
<td>Length (m)</td>
<td>Diam. (m)</td>
<td>Diam. (m)</td>
<td>Volume (m³, each)</td>
<td>Volume (m³, each)</td>
<td></td>
</tr>
<tr>
<td>Long Units(Set 1)</td>
<td>2</td>
<td>6.20</td>
<td>0.620</td>
<td>0.90</td>
<td>0.090</td>
<td>3.94</td>
<td>0.00394</td>
<td>31.5</td>
</tr>
<tr>
<td>Long Units(Set 2)</td>
<td>2</td>
<td>5.55</td>
<td>0.555</td>
<td>0.75</td>
<td>0.075</td>
<td>2.45</td>
<td>0.00245</td>
<td>-18.3</td>
</tr>
<tr>
<td>Tethered Units(Set 1)</td>
<td>4</td>
<td>2.00</td>
<td>0.200</td>
<td>1.20</td>
<td>0.120</td>
<td>2.08 **</td>
<td>0.00226</td>
<td>38.7</td>
</tr>
<tr>
<td>Tethered Units(Set 2)</td>
<td>4</td>
<td>2.00</td>
<td>0.200</td>
<td>1.00</td>
<td>0.100</td>
<td>1.39 **</td>
<td>0.00157</td>
<td>-7.3</td>
</tr>
<tr>
<td>Buoyant Cowling</td>
<td>1</td>
<td>Thickness (m)</td>
<td>0.200</td>
<td>0.020</td>
<td>6.20</td>
<td>0.00620</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Reduced Buoyant Cowling</td>
<td>1</td>
<td>Thickness (m)</td>
<td>0.200</td>
<td>0.020</td>
<td>5.10</td>
<td>0.00510</td>
<td>-15.0</td>
<td></td>
</tr>
</tbody>
</table>

** Equivalent Volume corrected for over-weight model units

**Model Mass Properties**

Two mass conditions were specified for the tests, which were as follows:

1. Full Load Condition – 14290 kg
2. Half Fuel Condition – 12839 kg

The mass properties for the two conditions are given in Table 3.
Table 3 – Helicopter Mass Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Full Load Condition</th>
<th>Half Fuel Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Required</td>
<td>Achieved</td>
</tr>
<tr>
<td></td>
<td>Prototype</td>
<td>Model</td>
</tr>
<tr>
<td>Displacement (kg)</td>
<td>14290</td>
<td>13.94</td>
</tr>
<tr>
<td>XCG (m)</td>
<td>8.385</td>
<td>0.839</td>
</tr>
<tr>
<td>YCG (m)</td>
<td>-0.0076</td>
<td>-0.001</td>
</tr>
<tr>
<td>ZCG (m)</td>
<td>2.675</td>
<td>0.268</td>
</tr>
<tr>
<td>( k_{xx} ) (Roll) (m)</td>
<td>1.503</td>
<td>0.150</td>
</tr>
<tr>
<td>( k_{yy} ) (Pitch) (m)</td>
<td>3.271</td>
<td>0.327</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement (kg)</td>
<td>12839</td>
<td>12.53</td>
</tr>
<tr>
<td>XCG (m)</td>
<td>8.295</td>
<td>0.830</td>
</tr>
<tr>
<td>YCG (m)</td>
<td>-0.0085</td>
<td>-0.001</td>
</tr>
<tr>
<td>ZCG (m)</td>
<td>2.843</td>
<td>0.284</td>
</tr>
<tr>
<td>( k_{xx} ) (Roll) (m)</td>
<td>1.501</td>
<td>0.150</td>
</tr>
<tr>
<td>( k_{yy} ) (Pitch) (m)</td>
<td>3.350</td>
<td>0.335</td>
</tr>
</tbody>
</table>

*** Best that could be achieved without compromising ZCG

Motion Results

The origin for the acceleration measurements was the geometric centre of the MRU unit. The coordinates of this point, defined from the same origin as the helicopter centre of gravity are as follows:

**Origin of Acceleration Measurements**

(\(X = 7.705\))
(\(Y = 0\))
(\(Z = 3.758\))

The Summary Motion Data is given in Table 4 and Table 5. The axis system and sign convention is given in Figure 35.
### Table 4 – Motion Statistics – Beam Seas

#### BEAM SEAS $H_s = 2.0 \text{ m}$, $T_o = 5.8 \text{ s}$ WAVE CONDITION B

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>ROLL (deg)</th>
<th>HEAVE ACCEL. (m/s²)</th>
<th>HEAVE SMM</th>
<th>SWAY ACCEL. (m/s²)</th>
<th>SWAY SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>703</td>
<td>Set 1 bags on both sides</td>
<td>6.22</td>
<td>1.04</td>
<td>5.74</td>
<td>0.27</td>
<td>0.84</td>
</tr>
<tr>
<td>704</td>
<td>Set 1 bag, port side, upwave</td>
<td>4.82</td>
<td>0.94</td>
<td>5.09</td>
<td>0.17</td>
<td>0.45</td>
</tr>
<tr>
<td>709</td>
<td>Set 1 bag, port side, downwave</td>
<td>7.25</td>
<td>0.84</td>
<td>4.44</td>
<td>0.33</td>
<td>1.03</td>
</tr>
<tr>
<td>801</td>
<td>Buoyant Cowling</td>
<td>5.32</td>
<td>1.11</td>
<td>6.29</td>
<td>0.32</td>
<td>1.01</td>
</tr>
<tr>
<td>1006</td>
<td>&quot; (reduced Volume)</td>
<td>5.11</td>
<td>1.07</td>
<td>6.13</td>
<td>0.31</td>
<td>0.87</td>
</tr>
</tbody>
</table>

#### BEAM SEAS $H_s = 2.9 \text{ m}$, $T_o = 6.04 \text{ s}$ WAVE CONDITION E

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>ROLL (deg)</th>
<th>HEAVE ACCEL. (m/s²)</th>
<th>HEAVE SMM</th>
<th>SWAY ACCEL. (m/s²)</th>
<th>SWAY SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>702</td>
<td>Set 1 bags on both sides</td>
<td>8.03</td>
<td>1.30</td>
<td>8.36</td>
<td>0.32</td>
<td>1.01</td>
</tr>
<tr>
<td>705</td>
<td>Set 1 bag, port side, upwave</td>
<td>6.56</td>
<td>1.21</td>
<td>7.61</td>
<td>0.23</td>
<td>0.66</td>
</tr>
<tr>
<td>708</td>
<td>Set 1 bag, port side, downwave</td>
<td>9.24</td>
<td>1.08</td>
<td>6.54</td>
<td>0.44</td>
<td>1.62</td>
</tr>
<tr>
<td>802</td>
<td>Buoyant Cowling</td>
<td>7.06</td>
<td>1.38</td>
<td>8.91</td>
<td>0.43</td>
<td>1.53</td>
</tr>
<tr>
<td>1005</td>
<td>&quot; (reduced Volume)</td>
<td>6.86</td>
<td>1.36</td>
<td>8.85</td>
<td>0.43</td>
<td>1.36</td>
</tr>
</tbody>
</table>

#### BEAM SEAS $H_s = 4.3 \text{ m}$, $T_o = 6.32 \text{ s}$ WAVE CONDITION F

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>ROLL (deg)</th>
<th>HEAVE ACCEL. (m/s²)</th>
<th>HEAVE SMM</th>
<th>SWAY ACCEL. (m/s²)</th>
<th>SWAY SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>701</td>
<td>Set 1 bags on both sides</td>
<td>9.64</td>
<td>1.46</td>
<td>10.96</td>
<td>0.55</td>
<td>2.11</td>
</tr>
<tr>
<td>706</td>
<td>Set 1 bag, port side, upwave</td>
<td>8.11</td>
<td>1.37</td>
<td>9.51</td>
<td>0.32</td>
<td>1.06</td>
</tr>
<tr>
<td>707</td>
<td>Set 1 bag, port side, downwave</td>
<td>10.18</td>
<td>1.25</td>
<td>9.32</td>
<td>0.53</td>
<td>2.38</td>
</tr>
<tr>
<td>803</td>
<td>Buoyant Cowling</td>
<td>8.77</td>
<td>1.51</td>
<td>11.26</td>
<td>0.55</td>
<td>2.64</td>
</tr>
<tr>
<td>1004</td>
<td>&quot; (reduced Volume)</td>
<td>8.50</td>
<td>1.49</td>
<td>11.49</td>
<td>0.50</td>
<td>1.97</td>
</tr>
</tbody>
</table>

63
Table 5 – Motion Data Statistics – Head Seas

### HEAD SEAS  \( H_s = 2.0 \, \text{m}, \, T_o = 5.8 \, \text{s} \)  WAVE CONDITION B

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>PITCH (deg)</th>
<th>HEAVE ACCEL. (m/s^2)</th>
<th>HEAVE SMM</th>
<th>SURGE ACCEL. (m/s^2)</th>
<th>SURGE SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>904</td>
<td>Set 1 bags on both sides</td>
<td>3.72</td>
<td>0.64</td>
<td>3.19</td>
<td>0.21</td>
<td>0.56</td>
</tr>
<tr>
<td>908</td>
<td>Set 1 bag, port side</td>
<td>3.64</td>
<td>0.62</td>
<td>3.10</td>
<td>0.23</td>
<td>0.65</td>
</tr>
<tr>
<td>1001</td>
<td>Buoyant Cowling (reduced Vol.)</td>
<td>4.18</td>
<td>0.79</td>
<td>4.06</td>
<td>0.20</td>
<td>0.50</td>
</tr>
</tbody>
</table>

### HEAD SEAS  \( H_s = 2.9 \, \text{m}, \, T_o = 6.04 \, \text{s} \)  WAVE CONDITION E

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>PITCH (deg)</th>
<th>HEAVE ACCEL. (m/s^2)</th>
<th>HEAVE SMM</th>
<th>SURGE ACCEL. (m/s^2)</th>
<th>SURGE SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>903</td>
<td>Set 1 bags on both sides</td>
<td>5.35</td>
<td>0.87</td>
<td>5.01</td>
<td>0.29</td>
<td>0.92</td>
</tr>
<tr>
<td>907</td>
<td>Set 1 bag, port side</td>
<td>5.12</td>
<td>0.84</td>
<td>4.92</td>
<td>0.33</td>
<td>1.11</td>
</tr>
<tr>
<td>1002</td>
<td>Buoyant Cowling (reduced Vol.)</td>
<td>5.89</td>
<td>1.01</td>
<td>5.96</td>
<td>0.29</td>
<td>0.88</td>
</tr>
</tbody>
</table>

### HEAD SEAS  \( H_s = 4.3 \, \text{m}, \, T_o = 6.32 \, \text{s} \)  WAVE CONDITION F

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>HELICOPTER CONDITION</th>
<th>PITCH (deg)</th>
<th>HEAVE ACCEL. (m/s^2)</th>
<th>HEAVE SMM</th>
<th>SURGE ACCEL. (m/s^2)</th>
<th>SURGE SMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>905</td>
<td>Set 1 bags on both sides</td>
<td>7.03</td>
<td>1.10</td>
<td>7.88</td>
<td>0.35</td>
<td>1.26</td>
</tr>
<tr>
<td>906</td>
<td>Set 1 bag, port side</td>
<td>6.65</td>
<td>1.06</td>
<td>7.54</td>
<td>0.40</td>
<td>1.53</td>
</tr>
<tr>
<td>1003</td>
<td>Buoyant Cowling (reduced Vol.)</td>
<td>7.54</td>
<td>1.19</td>
<td>8.37</td>
<td>0.35</td>
<td>1.17</td>
</tr>
</tbody>
</table>
Figure 35 - Helicopter motions sign convention.
Figure 36 - Typical capsize time history (showing two rotations)

Helicopter with 2 Long Buoyancy Bags (Set 2)

Hs = 4.3 m, To = 6.3 s

Roll Angle (°)

Time (s, prototype)
Righting Moment Curves

A series of righting moment measurements with successful additional buoyancy devices were performed. These are plotted in Figure 37, Figure 38, Figure 39, and Figure 40.
Comparison of Measured Data & Westland Data for Helicopter with standard buoyancy bags
Light Condition

Figure 37 – Roll righting moment – Standard helicopter.

Heel Angle (deg)

- Model as tested – Westland EH101 Data
Comparison of Normal cowling & Buoyant cowling (reduced buoyancy)
Light Condition

Heel Angle (deg)

Moment (kNm)

Buoyant Cowling
Normal Cowling

Figure 38 - Roll righting moment - Comparing buoyant cowling with standard helicopter.
Figure 39 - Roll Righting moment – Comparing 2 Long Buoyancy bags with Standard Helicopter.
Comparison of 2 Long Buoyancy bags & a single Long bag on port side

Light Condition

Figure 40 - Roll righting moment - Comparing single long buoyancy bag with standard helicopter.

- 2 long Bags (Set 1)
- Single Long Bag (Set 1) Port side

Heel Angle (deg)

Moment (kNm)
CAA PAPER 95010

HELIICOPTER FLOAT SCOOPS

Prepared by  Mr. Stephen J Rowe
Checked by    Dr. Robert G Standing
Approved by   Dr. Melvyn E Davies

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Executive Summary

Earlier review work on helicopter ditching concluded that there was a clear benefit to be obtained from fitting scoops to helicopter flotation equipment. The static and dynamic effect of the scoops on the helicopter motions seemed to improve the resistance to capsize performance of most helicopters by about 1 sea state number.

The present study was performed by BMT with the assistance of Westland Helicopters Limited (WHL) in order to consolidate the present state of the art regarding float scoops and specifically to estimate the cost implications of fitting scoops to a typical large transport helicopter.

An outline design for float scoops was conducted for the Agusta/Westland EH101 civil transport helicopter. The increased float forces resulting in the addition of float scoops were estimated, and these loads compared with design calculations for the original helicopter in order to establish the structural and cost implications for the helicopter structure, floats and the float fixings.

The work has again highlighted the need for a better understanding of the dynamic motions of a helicopter in steep (and perhaps breaking) waves. Lack of detailed understanding of the helicopter behaviour limits the precision of any estimates of the forces experienced by emergency floats, whether they include scoops or not.

BMT’s estimates of the dynamic forces experienced by the floats with and without scoops indicated that the magnitude of these forces depends crucially on the zero-crossing period of the sea state selected for analysis, and depending on the selection of this period, might lead to forces larger or smaller than the simple static load assumptions currently used in the helicopter certification process.

In the cases studied, the addition of the scoops to the floats increased these forces by between 12% and 17%.

Using a conservative assumption of an increase in forces between 25% and 50%, it was estimated that the cost of the helicopter airframe might increase by about 1%, and the cost of the flotation bags themselves by 10%. This would be expected to increase the total cost of the helicopter by about 0.28%. The small weight penalty associated with the float scoops was estimated to lead to a possible reduction in payload revenue of about 0.25%.
Contents

1 Introduction
   1.1 Objectives
   1.2 Method
2 Conclusions
3 Benefits of Float Scoops
4 Helicopter Selection and Float Scoop Design
   4.1 Helicopter Selection
   4.2 Float Scoop Design
5 Float and Scoop Loads
   5.1 Existing Float Forces
   5.2 Estimation of Additional Scoop Forces
   5.2.1 Dynamic forces on stationary float
   5.2.2 Dynamic forces on stationary scoop
   5.2.3 Dynamic forces on a moving float
6 Float Scoop Installation Cost Estimation
7 Discussion
8 References

Appendix A Examples Results from BHC X/O/3257 (April 1986)
   A.1 General
   A.2 Sikorsky S-61N
   A.3 Sikorsky S76
   A.4 AS-332L Super Puma

Appendix B Summary of BHC Report X/O/3257 (April 1986)

Appendix C Calculation of Drag and Inertia Forces
   C.1 Wave Particle Velocities and Accelerations
   C.2 Drag and Inertia Forces
   C.3 Additional drag due to scoop
1 INTRODUCTION

A key finding of earlier review work performed by BMT Offshore Limited (BMT) on helicopter ditching [1] was that there seemed to be a clear benefit from fitting scoops to helicopter emergency flotation equipment. On average it seemed to increase the severity of the sea-state at which capsize occurred by about 1 sea state number.

It was believed that the reason why float scoops had not been taken up by the industry might be the lack of published information on their benefit. Consequently the main aim of this short study was to prepare a document on float scoops that can be published in order to promulgate their benefits.

Whilst a number of model tests had been performed on helicopters fitted with flotation scoops [2] this work had not been pursued through to design. It was believed that the main reason why work on scoops was not continued was difficulty in estimating the additional forces introduced into the helicopter structure by the floats.

The present study was performed by BMT with the assistance of Westland Helicopters Limited (WHL) in order to consolidate the present state of the art regarding float scoops.

The objectives of the current study were therefore:

1.1 Objectives

• To confirm whether difficulties with estimation of float forces was the reason for lack of continuation with work on the design of float scoops.

• In collaboration with WHL, to perform a short design study for emergency float scoops. The main output of the study being an estimate of the cost of fitting scoops to a helicopter.

• To summarise the benefits and costs of float scoops in a report.

1.2 Method

An outline design for float scoops was conducted for a specific helicopter type. The increased float forces resulting in the addition of float scoops was estimated, and these loads compared with the original design calculations for the helicopter in order to establish the implications for the helicopter structure, floats and the float fixings.

2 CONCLUSIONS

2.1 It has been established that the reasons why float scoops have not been pursued by helicopter designers in general (and WHL in particular) are:

• Difficulties in estimating the additional flotation loads.

• Lack of demand for float scoops from customers and from certification bodies.

References are listed in Section 8 on page 14.
2.2 Despite this, it has been established from model tests that the fitting of scoops to existing helicopter flotation equipment results in an improvement in the resistance to capsize of most helicopters by about 1 sea state number. (In the southern North Sea this might approximately halve the probability of capsize following any random ditching incident from 26% to 14%.)

2.3 A short design study on fitting scoops to a large modern civil transport helicopter, the Agusta/Westland EH101, has found that:

2.3.1 Dynamic vertical forces estimated on the floats in waves obtained using a simplified dynamic analysis are broadly consistent with the static force assumptions made in the design by WHL.

2.3.2 The estimation of the vertical dynamic forces in a more precise manner is hampered by uncertainties in the water particle velocities and accelerations in steep (possibly breaking) waves, and by difficulties in the non-linear responses of the helicopter to these waves. These difficulties could be at least partly removed if a non-linear simulation of the floating helicopter were to be developed.

2.3.3 The selection of a wave period for the dynamic analysis is crucially important to any dynamic analysis of the float forces. Because of the relatively short natural roll period of helicopters, a period should be selected which is towards the steeper end of realistic waves expected for the area of flight operations.

2.3.4 The main effect of the scoops will be to increase the dynamic vertical components of the loads experienced by the floats in waves.

2.3.5 In the cases studied, adding scoops to the main floats of the EH101 increased the vertical forces by between 12% and 17% depending on the wave period assumed.

2.4 Whilst no specific model tests have been performed for the float scoops assumed for the EH101 in this study, one can be fairly confident that the same benefits in terms of resistance to capsize would accrue for this type.

2.5 In order to safely cover the scoop force increases estimated, and to allow for possible changes in the size and design of scoops, it was decided to estimate costs for a range of increases in the float loads of between 25% and 50%.

2.6 Based on the above range of increase in the flotation loads, a short design study was performed on the float scoops and the modifications likely to be required to the airframe to accommodate them. This study found that the cost of the helicopter airframe was likely to increase by about 1%, and the cost of the flotation bags themselves by 10%. This is expected to be reflected in an increase in the total cost of the helicopter of about 0.28%.

2.7 There will also be some increase in the weight of the airframe as a result of the structural modifications and flotation system modifications. This was estimated to be in the region of 25kg, which might typically equate to a cost of about 0.25% in terms of lost payload revenue.

2.8 The increased helicopter capital and running costs identified above are relatively modest. The benefits of this investment will be felt in terms of a significantly reduced overall risk of capsize when forced to ditch in the sea.
3 BENEFITS OF FLOAT SCOOPS

Scoops or water pockets have been used on inflatable life rafts for many years. Once these scoops have deployed and filled with water, they add weight to the craft and improve its resistance to capsize.

In 1986 [2] BHC performed a series of wave tank tests on models of nine different helicopter types in order to investigate the effect of adding scoops to the emergency floats. Overall they noted that the addition of the scoops showed an improvement in the helicopter resistance to capsize in irregular waves for most of the helicopter types tested.

Appendix A reproduces some example results from [2]. Sketches are shown of the flotation units and scoops fitted to types S-61N, S76 and AS332L. Also shown are the static stability curves of the three helicopter types demonstrating the increase in the peak righting moment that results from fitting scoops, and the effect on wave height and steepness of the capsize threshold that is achieved in regular waves. Improvement in the irregular wave capsize threshold was in most cases about 1 sea-state number. However, the S-61N was an exception, showing virtually no change in performance in waves, even though the static stability curves showed a marked increase in peak righting moment. A tabular summary of the results of [2] is reproduced from [1] in Appendix B.

In reviewing this work, reference [1] noted that the stabilising effect of the scoops is probably due to a number of different static and dynamic physical effects; the improvement in static stability that the scoops produce (due to the weight of the water in the scoop being lifted out of the water), the additional dynamic roll inertia, and the additional roll damping that scoops produce. All these effects will play their part, but it is not clear which are the most important.

If one takes the example of a helicopter which just capsizes in sea state 4 without scoops but survives up to sea state 5 with scoops, then the probability of a capsize following a ditching in the southern North Sea would be significantly reduced. Sea state 4 is exceeded for 26% of the time throughout the year, whilst sea state 5 is exceeded for 14% of the time. The probability of capsize will therefore be reduced by about half from 26% to 14%.

4 HELICOPTER SELECTION AND FLOAT SCOOP DESIGN

4.1 Helicopter Selection

The helicopter type selected for this study was the civil version of the Agusta/Westland EH101. The reasons for selecting this helicopter were:

- It is an example of a large modern transport helicopter.
- EH101 is being certified according to current CAA ditching rules (as at 1991).
- Owing to the current certification process on EH101, WHL can access design calculations relatively easily.
4.2 Float Scoop Design

As no design existed for float scoops for the EH101, it was necessary to design some that were broadly consistent with those used in the BHC model tests [2] for the other helicopter types which demonstrated an improvement in resistance to capsize of about 1 sea state number.

An analysis of the float scoop sizes used in those model tests was performed and the volume of the scoops expressed as a percentage of the individual float volume and the total flotation volume (a number of the helicopter types did not have the scoops added to all their floats). It should be emphasised that this was not a precise analysis as information on float volumes and dimensions was not to-hand for all the helicopter types. However, the results of the analysis are summarised in the following table:

<table>
<thead>
<tr>
<th>Float Scoop Volumes – BHC Work</th>
<th>44035sv1.ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>(units are mm scaled from drawing)</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Float Vol</td>
</tr>
<tr>
<td></td>
<td>mm³</td>
</tr>
<tr>
<td>Bell 412</td>
<td>330,260</td>
</tr>
<tr>
<td>Bell 2145T</td>
<td>1,925,168</td>
</tr>
<tr>
<td>Bell 212</td>
<td>343,470</td>
</tr>
<tr>
<td>BK 117</td>
<td>565,487</td>
</tr>
<tr>
<td>W30-300</td>
<td>443,065</td>
</tr>
<tr>
<td>W30-100</td>
<td>444,388</td>
</tr>
<tr>
<td>S-61N</td>
<td>182,605</td>
</tr>
<tr>
<td>S76</td>
<td>313,961</td>
</tr>
<tr>
<td>AS 332L</td>
<td>317,050</td>
</tr>
</tbody>
</table>

Mean: 23% 19%
Stdev: 7% 10%
Min: 11% 7%
Max: 33% 33%

It can be seen from the above that the scoops fitted for these experiments varied in volume from 11% to 33% of the volume of the float to which they were fitted, and in total varied from 7% to 33% of the total flotation volume. The mean value in each case was 23% and 19% respectively.

On the basis of the above, it was decided to design a main float scoop for the EH101 which amounted to 28% of the main float volume. This was achieved by arranging an EH101 main float scoop with a radius 1.5 times the float radius, running for the full length of the float, and subtending an 80° arc. Figure 1 shows the scoop arrangement selected for the study (dimensions in metres). Figure 2 shows the location of the floats on the EH101.
Figure 1  Scoops assumed for the EH101 main floats

Figure 2  Float locations on EH101
5 FLOAT AND SCOOP LOADS

5.1 Existing Float Forces

The load cases considered for the emergency floats of the EH101 in its certification [3] basically consider the following conditions:

(i) drag in the fore-aft direction, due to the craft's forward speed, after the craft has ditched, but while it is still slowing down, and while the floats are inflating,

(ii) drag and pressure gradient loads in the fore-aft direction, after the craft has come to rest, with the craft head to waves, with the floats fully inflated,

(iii) buoyancy forces in the vertical direction, calculated as if the craft is at rest in still water, but with the floats fully immersed.

Load case (i) above will be unaffected by the presence of scoops. Scoops will only be deployed once the craft has come to rest, and can be designed to ensure that they lie flat against the float while it is moving forwards.

The scoops will face upwards, and so will have relatively little effect on fore-aft loads, other than a small change in the presented area of the float. This effect will be small, and so load case (ii) will also be largely unaffected by the presence of scoops.

Load case (iii) is the only one likely to be affected by the addition of scoops. Dynamic loads are not considered in the WHL standard load case (iii), which assumes instead that there is enough conservatism already in calculating static buoyancy forces with the floats fully immersed.

5.2 Estimation of Additional Scoop Forces

As noted above, the action of the scoops will be to increase the forces experienced by the float attachment points in the vertical axis only. However, the forces generated by the scoops will be dynamic, and not directly comparable with the static buoyancy force assumed by WHL. It is therefore necessary to examine the dynamic forcing on the float and scoop.

The EH101 main float is a cylinder of nominally 1.4m diameter and 2.7m long. The totally immersed buoyancy force on this float is 41.4kN, and this is the force used in the WHL design.

5.2.1 Dynamic forces on stationary float

The dynamic forces exerted by a water wave on a submerged body are usually considered to arise from two components:

- a drag force (in phase with the wave particle velocity), and
- an inertial force (in phase with the water particle acceleration).

The limiting sea state mentioned in the British Civil Airworthiness Requirements (BCAR) [4] is sea state 6. The BCAR paper defines sea state 6 as a significant wave height of between 4m and 6m, and WHL in their float load estimates [3] have
taken the upper limit significant wave height of 6 m, which also according to \([4]\) approximately corresponds to a maximum wave height of 9.6 m.

If the float is taken to be stationary and fully immersed in a 9.6 m regular wave with a period of \(T = 8\) s (i.e. a steepness of about \(1/10\)), and if normal assumptions are made about the drag coefficient and inertia coefficient of the cylindrical float, then the magnitude of the two vertical force components can be shown to be\(^2\):

- **drag force** \(27.0\) kN
- **inertial force** \(25.0\) kN

Because the drag and inertial force components are \(90^\circ\) out of phase with each other, the resultant maximum dynamic force is given by the square root of the sum of the squares of these two numbers:

- **total resultant dynamic force** \(36.8\) kN

In order to arrive at the total maximum vertical force experienced by the float attachments, the static buoyancy force due to the immersion of the floats (i.e. the weight of the helicopter) must be added also. If it is assumed that the float is 50% immersed (approximating to the helicopter floating at or near its maximum weight), then this static force will be \(20.7\) kN which leads to a total maximum force of:

- **total maximum vertical force** \(57.5\) kN

### 5.2.2 Dynamic forces on stationary scoop

The main effect of adding the scoop to the float will be to increase the vertical projected area of the float and the total vertical drag force on the scoop.

For the scoop held stationary in the same wave considered above, the additional drag force due to the scoop is estimated to be:

- **additional drag due to scoop** \(15.5\) kN

If the inertial component remains the same as above, then the new total resultant dynamic force on the float and scoop is given by \([(15.5 + 27)^2 + (25)^2]^{1/2}\):

- **total resultant dynamic force** \(49.3\) kN

and if the static buoyancy force is again added the total maximum vertical force becomes:

- **total maximum vertical force** \(70.0\) kN

This represents an increase of about 22% on the maximum force estimated in section 5.2.1 above.

However, these calculations using the effects of a **regular wave acting on a fixed float** represent a gross simplification of the reality. The following section therefore extends this simple analysis to deal with a helicopter responding with roll motions in irregular waves.

\[^2\] Example calculations of the velocities and accelerations in the wave, and the resulting force components are given in Appendix C.
5.2.3 *Dynamic forces on a moving float*

In reality the float is not being held stationary in the waves. The helicopter responds with the waves, and to some extent tries to follow the water particle motions of the waves. If it follows the motions of the waves then the forces on the floats will be reduced. If, on the other hand, the motions get out of phase with the waves (as they will at the roll resonance wave period) then the forces on the floats will be larger.

In order to estimate the dynamic forces experienced by the moving float it is necessary to have a knowledge of the motions of the helicopter in the waves and, in order to properly take account of the effects of roll resonance, this should be for irregular waves.

An accurate theoretical assessment of the helicopter motions in realistic steep waves is hampered by the following uncertainties:

(i) Uncertainty in the wave particle velocities and accelerations in a steep (possibly breaking) irregular wave.

(ii) Non-linear motion responses of the helicopter to the waves.

(iii) Uncertainty of the drag coefficient and inertia coefficient experienced by the float and scoop when partly immersed in the water.

Of these, the first two are probably the more important, and a proposal [5] has been made for the development of a more detailed mathematical model to address this, but this work has not yet been commissioned.

A simplified and linearized assessment of the helicopter motions has therefore been utilised (using BMT's NMIWAVE program) to arrive at an estimate of the helicopter's roll motion, and consequently the relative motions between the float and the water particles in the wave.

A wave with a significant wave height of 5m was assumed. This is the mean of the range of wave heights suggested by [4], and based on the tank tests described in [2], also seems to be a reasonable design goal.

However, the selection of a suitable wave zero crossing period is also important because of the potentially resonant response of the helicopter in roll. Figure 3 shows the joint probability of significant wave height and zero crossing period at a location in the North Sea [6].
Figure 3 Joint probability of significant wave height and zero crossing period

It can be seen that any particular significant wave height can occur with a zero-crossing period over quite a range of values. And the steepness of the waves will be dependent on this period.

Figure 4 shows the distribution of periods for three different significant wave heights in the region of interest (i.e. selected sections from Figure 3). (It should be noted that these relationships are different for every ocean location, and so the data selected here can only be considered as indicative for the purposes of these float scoop force calculations.)

On the basis of the above, two periods were selected; $T_z = 7s$ and $T_z = 8s$. The $T_z=7s$ value roughly corresponds with the steepest waves that one might expect at this wave height, whilst the $T_z = 8s$ value is a steepness which is more likely to be experienced in practice.
Variation of Period with Wave Height

![Graph](image)

**Figure 4** Variation of zero-crossing period with wave height

The most probable total maximum vertical forces experienced are summarised in the following table:

<table>
<thead>
<tr>
<th>Vertical Float Loads</th>
<th>$T_z = 7s$</th>
<th>$T_z = 8s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float only</td>
<td>52.3 kN</td>
<td>39.6 kN</td>
</tr>
<tr>
<td>Float plus scoop</td>
<td>61.4 kN</td>
<td>44.3 kN</td>
</tr>
<tr>
<td>Percentage increase due to scoops</td>
<td>17.4%</td>
<td>11.9%</td>
</tr>
</tbody>
</table>

These forces include the drag and inertial components of the vertical dynamic load, and 50% of the static buoyancy force, and are the maximum values most likely to be experienced in a total exposure of 200 waves (i.e. about 20 minutes).

In view of the gross simplifications involved in the above calculations, it would be wrong to read too much into the differences between these values and the value of 41.1 kN assumed in WHL's static force estimates. The difference is not significant when taken in context with the inherent inaccuracies in the procedure used to estimate these dynamic loads. However, in relative terms it can be seen that the presence of the scoops adds between 12% and 17% to the total maximum vertical forces experienced by the float.

In view of the uncertainty in the estimation of these float load increases it was decided to conservatively carry forward a float load increase of between 25% and 50% to the remainder of the study for the estimation of the consequential airframe and running costs.
FLOAT SCOOP INSTALLATION COST ESTIMATION

The compilation of cost estimates for aircraft modifications is an arduous process and it is impossible to arrive at accurate figures without a considerable amount of preliminary design activity.

However, it has been estimated that the cost of the structural modifications required to the airframe to cope with the additional float loads, and to provide stowage space for the additional bulk of the floats, would not be particularly sensitive to the actual increase in those loads (be it 25% or 50%). The number of components would remain the same, and the manufacturing effort would be largely unchanged.

On this basis it has been estimated that the structural modifications might lead to an increase in the cost of the airframe of about 1%. This cost is likely to be much the same for a new design, or for the modification of an existing design.

The addition of the scoops to the floats is likely to increase the manufacturing cost of the floats themselves by about 10%. However, a retrofit of the scoop system to an existing helicopter would almost certainly require the complete replacement of the float units.

Given that the total additional airframe costs are about 1%, and given that the airframe represents about 28% of the total cost of the helicopter, it can be deduced that the scoops will add about 0.28% to the total capital cost of the helicopter.

The scoops system will also add weight to the helicopter, and all other things being equal, this additional weight will represent a loss of maximum payload capacity. It is estimated that the float scoop modifications will add about 25kg to the weight of the helicopter.

Estimates of seat revenue for a medium civil helicopter operating a typical route suggest that, if every flight was previously operated up to maximum weight, then the loss of revenue due to the additional weight of the scoops system would be in the region of 1%. However, it is probably that for most operators fewer than 25% of flights would be operated at maximum weight and therefore the true cost is likely to be less than 0.25%.

Overall the above cost and revenue variations seem very small, and would be easily swamped by other variations in helicopter types, routes and operational conditions.

DISCUSSION

The clear benefit of fitting scoops to the emergency floats of a helicopter is a general increase in the sea state at which capsize is likely to occur. This leads to a reduction in the capsize risk for any given random ditching incident. The actual level of reduction of risk depends on the helicopter type and on the weather climate in the operational area, but as an example, a helicopter whose capsize boundary is increased from sea state 4 to sea state 5 by the addition of scoops will have its probability of capsize approximately halved from 26% to 14% if it were operating in the southern North Sea area.
The cost of adding scoops to a helicopter will mainly consist of three elements:

- the additional cost of the float units themselves with the scoops added, and
- the cost of any modifications required to the helicopter structure in order to resist the additional forces transmitted by the scoops, and
- any revenue penalty associated with an increase in weight.

Certification calculations performed for the float forces by WHL consider both horizontal and vertical components of the float forces in order to check the strength of the floats and their attachment points to the airframe. It can generally be assumed that scoops could be designed such that the horizontal components of these float forces are not significantly changed. However, the vertical components of these forces will be changed by the addition of scoops, and indeed, it is these vertical force changes that give rise to the greater resistance to capsize of a helicopter fitted with them.

The vertical forces experienced by the floats (whether fitted with scoops or not) are difficult to estimate reliably. Currently the vertical forces on the floats themselves are estimated by WHL as the static buoyancy force experienced if the float is fully immersed. However, in reality the floats experience dynamic forces which are a function of wave drag loads, wave inertial loads, and drag and inertial components resulting from the motions of the helicopter as it responds the action of the waves. Such forces are difficult to estimate in steep (and perhaps breaking) waves, and where the float is only partly immersed. Better estimates of the forces could be made if there existed a non-linear computer simulation model of the floating helicopter, but to-date such a model has not been developed.

However, in the knowledge that the process is prone to significant inaccuracies, this project has made estimates of the dynamic float forces using a linearized motions analysis (BMT's NMIWAVE program). The forces were estimated in irregular waves for a 5m significant wave height which is in the region of the limiting sea state indicated by the BCAR [4] requirements. The results of the calculations emphasised the importance of the selection of a zero-crossing wave period because the two values chosen for the calculations showed very different vertical float forces.

The EH101 helicopter chosen for the current investigation has a natural roll period at around 3 seconds, and any waves occurring at these periods will lead to dynamic magnification of the roll motions and larger dynamic float forces. (This roll natural period is also presumably typical of other helicopters of this size.)

The steeper wave spectrum with a zero-crossing period at \( T_z = 7s \) has significantly more energy near to the natural roll period than the \( T_z = 8s \) case also used in the calculations. Particle velocities and accelerations near the water surface are also greater in the \( T_z = 7s \) wave. Consequently the dynamic forces on the floats are higher for this case. The \( T_z = 7s \) case estimated a total probable maximum vertical float force which was about 25% higher than the static buoyancy force assumed by WHL. The \( T_z = 8s \) case, however, indicated forces closely agreeing with the static buoyancy assumption.
It must be emphasised that the accuracy of these dynamic force estimates is severely limited by the shortcomings identified above, and consequently it should not be assumed that the WHL statically based vertical design force is necessarily inadequate. The dynamic estimates do, however, clearly illustrate the importance of the wave period selected for any dynamic analysis.

In the North Sea a $T_z = 8s$ might be commonly experienced accompanying a significant wave height of 5m. $T_z = 7s$ would be a more unusual occurrence, and would be close to the steepest sea state that might be experienced at this height. However, if this steepest case results in the largest float forces it is arguable that it should be the basis of a dynamic forcing design process.

The total vertical forces have been estimated including both dynamic and static components. The dynamic component includes both drag forces (in phase with fluid velocities) and inertial components (in phase with fluid accelerations). The static component is equivalent to the part of the weight of the helicopter which is supported on the floats. For the purposes of these estimates it has been assumed that the main floats are 50% immersed (roughly equivalent to floating at maximum weight for the EH101).

The addition of the scoops resulted in the probable maximum vertical force on the floats increasing by 17% for the $T_z = 7s$ case and by 12% for the $T_z = 8s$ case. However, in order to be conservative in the remainder of the cost study, it was decided to use two vertical force increases of 25% and 50%.

The requirement to stow the larger floats, and the need to resist greater float forces in the helicopter structure lead to an estimated increase in the cost of the airframe of about 1%. This might be expected to lead to an increase in the total cost of the helicopter of about 0.28%.

The additional weight of the float system is estimated to be about 25kg. If all other design and operational parameters for the helicopter remain the same, this theoretically represents a reduction in the maximum payload that can be carried, which in turn represents a reduction in revenue earning capacity. An accurate estimate of this reduced earning capacity cannot be made without consideration of a particular route structure and operating profile. However, with various assumptions made here it has been conservatively estimated to be about 0.25% of revenue. It should be emphasised, however, that this weight increase is very small and is probably of the same order as weight differences between individual aircraft of the same type in a helicopter fleet.

Overall it must be said that the costs of installing scoops have been estimated in a conservative way, and nevertheless have been found to be very small.

The emergency flotation equipment of a helicopter is obviously only brought into use on the rare occasions when a major failure has already occurred leading to the ditching on the water, but the potential benefits from the scoops in reducing the likelihood of capsize occurring before the occupants can escape to the relative safety of the liferafts is an important tangible benefit.
REFERENCES

1. BMT Offshore Ltd., 'Review of helicopter ditching performance', Report on Project 44011/00 for the Civil Aviation Authority, Release 2, 7 July 1993 (Confidential to CAA).

2. BHC Report No. X/0/3257, April 1986, Study of Fitting Scoops to Emergency Floats (Confidential to CAA).


Appendix A  Examples Results from BHC X/O/3257 (April 1986)

A1  GENERAL

Example results are presented in the following reproduced from Ref [2] for three of the nine helicopter types tested: S61N, S76 and AS332L.

In each case the following are shown:

• A sketch of the helicopter showing the location of the flotation units.
• A detailed sketch and/or photograph showing the scoops added to the flotation units.
• A static stability curve showing the increase in the peak roll righting moment which results from the addition of scoops.
• A graph showing the change in the regular wave height at which capsize occurs when the float scoops are added.

These results (and those for the other helicopter types not reproduced here) lead to the following main conclusions:

(a) All helicopters show a marked increase in static stability in terms of the peak righting moment when scoops are added.

(b) Most helicopters show an increase in the wave height at which capsize occurs, both in regular and irregular waves. The exception was the S-61N which showed no noticeable improvement in either type of wave.

A.2  SIKORSKY S-61N
(See overleaf)
Figure 8/1  Sikorsky S-61N Helicopter
EMERGENCY FLOAT AND SCOOPS

FRONT ELEVATION

SIDE ELEVATION

Figure 8/2  Sikorsky S61-N Helicopter
VIEWS OF WATER SCOOPS

Figure 8/3 Sikorsky S61-N Helicopter
VARIATION OF RIGHTING MOMENT WITH ROLL ANGLE

SIKORSKY S-61N HELICOPTER  TEST WEIGHT - 18000 lb

Figure 8/4  Sikorsky S61-N Helicopter
STABILITY WHEN FLOATING IN REGULAR WAVES

SIKORSKY S-61N HELICOPTER

TEST WEIGHT ~ 18000 lb

Figure 8/5  Sikorsky S61-N Helicopter
Figure 8/15 Sikorsky S76
FORWARD FLOAT AND SCOOP

FRONT ELEVATION

SIDE ELEVATION

Figure 8/16  Sikorsky S76
Figure 8/17  Sikorsky S76
VIEWS OF WATER SCOOPS

FORWARD FLOATS

MAIN FLOATS

Figure 8/18  Sikorsky S76
VARIATION OF RIGHTING MOMENT WITH ROLL ANGLE

TEST WEIGHT - 70371 lb
C.G. OFFSET - 0.8 in. TO STARBOARD

SIKORSKY S-76 HELICOPTER

---- ORIGINAL TEST RESULTS

--- Figure 8/19 Sikorsky S76 ---
STABILITY WHEN FLOATING IN REGULAR WAVES

SIKORSKY S-76 HELICOPTER  TEST WEIGHT = 7037 lb

Figure 8/20  Sikorsky S76
Figure 9/1  AS-332L Super Puma
Figure 9/3  AS-332L Super Puma
FLOAT AND SCOOP
FRONT ELEVATION

SIDE ELEVATION

Figure 9/4 AS-332L Super Puma
VARIATION OF RIGHTING MOMENT WITH ROLL ANGLE

DOORS CLOSED

TEST WEIGHT ~ 4610 Kg

ROLL ANGLE - DEGREES

RIGHTING MOMENT

lb. ft. x 10^-6

SCOOPS ON

SCOOPS OFF

Figure 9/5  AS-332L Super Puma
STABILITY WHEN FLOATING IN REGULAR WAVES

DOORS OPEN —— —— TEST WEIGHT - 8,600 Kg
DOORS CLOSED ——

Figure 9/10  AS-332L Super Puma
<table>
<thead>
<tr>
<th>Helicopter Type</th>
<th>Weights</th>
<th>Float Position Variant</th>
<th>Computer Models</th>
<th>Regular Wave Tests</th>
<th>Irregular Wave Tests: Static H/3/fp</th>
<th>Comments</th>
</tr>
</thead>
</table>
| B-412           | 3476 kg     | Scoops fitted to main and rear floats. | Various         | 1:10 scale:        | S4 2.40m/6.5s  
S5 3.58m/6.80s  
1:28 scale:  
S5 2.80m/7.47s  
S5 3.94m/9.43s  
S6 4.40m/9.17s  
S7 6.06m/11.21s  
(with and without wind) | Both 1:10 and 1:28 scale models used. Concluded that scoops cause marginal improvement of limiting steepness of regular wave before capsize (from about 1.85 to 1.8). Improvement of about 1 sea-state in irregular waves. But note the wide range of conditions called Sea-state 5. |
| B-214ST         | 4184 kg     | Scoops fitted to outside of main floats. | Various         | 1:10 scale:        | S4 2.40m/6.54s  
S5 3.58m/6.80s  
1:26 scale:  
S5 2.85m/7.19s  
S5 3.79m/9.08s  
S6 4.41m/9.09s  
S7 6.35m/11.60s | Both 1:10 and 1:26 scale models used. At 1:10 scoops improved regular wave boundary from 1.75 to 1.85. Larger model seemed less stable (in larger waves) and showed less difference. General improvement with scoops in irregular waves (not clear that results from the two models consistent though). NOTE two very different 'sea-state 5's referred to in the text for 1:26 scale model. |
| B-212           | 3636 kg     | Scoops fitted outside each float. | Various         | S4 ??              | S5 3.58m/ ??  
(with and without wind) | 1:10 scale physical model. General improvement in stability with the addition of scoops. (Some tendency to adopt a more head to wave direction with scoops?) Removal of the doors reduced stability slightly. |
| 8K-117          | 1700 kg     | Scoops fitted to twd floats only. | Various         | S4 2.17m/6.62s  
S5 2.79m/6.08s  
(with and without wind) | 1:8 scale physical model. Marked increase in dynamic stability in regular waves at the lighter weight. Little difference at the heavier weight. In irregular waves improved about 1 sea-state at both weights. |
<table>
<thead>
<tr>
<th>Helicopter Type</th>
<th>Weights</th>
<th>Float Position Variant</th>
<th>Computer Models</th>
<th>Regular Wave Tests</th>
<th>Irregular Wave Tests, Sea H1/3/Fp</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>W30-300</td>
<td>7273 kg</td>
<td>Scoops fitted to rear floats only. Also tests with one float compartment deflated.</td>
<td>Various</td>
<td>S4 2:40m/6 54s S5 3:58m/6 80s (with and without wind)</td>
<td></td>
<td>1:10 scale physical model. Scoops increase stability in regular waves. Marginal improvement in irregular waves. Effect of scoops much more marked with the doors open and one float compartment deflated.</td>
</tr>
<tr>
<td>W30-100W/200</td>
<td>4432 kg 5818 kg</td>
<td>Scoops fitted on both fwd and rear floats.</td>
<td>Various</td>
<td>S4 2:40m/7? S5 3:58m/7? (still air only)</td>
<td></td>
<td>1:10 scale physical model. Clear improvement with scoops in regular waves. Increase of about 1 sea-state in irregular waves.</td>
</tr>
<tr>
<td>S-61N</td>
<td>8182 kg</td>
<td>Scoops fitted to floats. Also tests with one float removed.</td>
<td>Various</td>
<td>S4 2:17m/6 62s S5 2:79m/6.08s (still air only)</td>
<td></td>
<td>1:8 scale physical model. Very little effect caused by the floats although static stability was increased.</td>
</tr>
<tr>
<td>S-76</td>
<td>3199 kg</td>
<td>Scoops fitted to all floats.</td>
<td>Various</td>
<td>S4 2:17m/6 62s S5 2:79m/6.08s (with and without wind)</td>
<td></td>
<td>1:8 scale physical model. Scoops improve behaviour in regular wave considerably (roll motion said to have been &quot;damped&quot;). Helicopter also less vulnerable in breaking irregular waves. Improved about 1 sea-state. Scoops had little effect on weather cocking behaviour.</td>
</tr>
<tr>
<td>AS-332L</td>
<td>4610 kg 8600 kg</td>
<td>Scoops fitted to main floats.</td>
<td>Various</td>
<td>S4 2:17m/6 62m S5 2:79m/6.08s</td>
<td></td>
<td>1:8 scale physical model. Significant improvement in stability boundary in regular waves. Also improvement in irregular waves. Improvement in weatherwaving.</td>
</tr>
</tbody>
</table>
Appendix C  Calculation of Drag and Inertia Forces

C.1 Wave Particle Velocities and Accelerations

The fluid dynamic forces exerted by a water wave on a submerged body are usually considered to arise from two components:

- a drag force (in phase with the wave particle velocity), and
- an inertial force (in phase with the water particle acceleration).

The instantaneous elevation of a regular (Airy) wave with a height (peak to trough) of $H$ and a period $T$ is given by:

$$
\zeta = \frac{H}{2} \sin \omega t
$$

where:

$\omega$ = angular velocity in radians = $2 \pi / T$

$t$ = time

Differentiating this, the instantaneous velocity and acceleration of the water particles at the surface are given by:

$$
u = \dot{\zeta} = \frac{H}{2} \omega \cos \omega t$$

$$
a = \ddot{\zeta} = \frac{H}{2} \omega^2 \sin \omega t$$

Thus the maximum velocity at the surface of a wave is given by $H\omega/2$ and the maximum acceleration by $H\omega^2/2$.

In the example regular wave considered in section 5.2.1 where $H = 9.6$ m and $T = 8$s;

- Maximum velocity = $9.6/2 \times 2\pi /8 = 3.77$ m/s
- Maximum acceleration = $9.6/2 \times (2\pi/8)^2 = 2.96$ m/s/s

It can be seen from the above equations that the velocity in the wave is a $\cos$ function and the acceleration in the wave is a $\sin$ function. Consequently the maximum values do not occur at the same time, but 90° out of phase.
C.2 Drag and Inertia Forces

Drag force and inertia force are described in terms of a drag and inertia coefficient as follows:

\[ C_d = \frac{D}{\frac{1}{2} \rho u^2 A} \]

where:

- \( C_d \): Drag Coefficient
- \( D \): Drag force
- \( \rho \): Density of water (1025 kg/m³ for sea water)
- \( u \): Water particle velocity
- \( A \): Projected area

\[ C_m = \frac{l}{\rho V a} \]

where:

- \( C_m \): Mass Coefficient
- \( l \): Inertia force
- \( V \): Immersed volume
- \( a \): Water particle acceleration

If we are considering a helicopter emergency float which has a diameter of 1.397 m and a length of 2.687 m, then the horizontal projected area and the volume are respectively:

\[
A = 1.397 \times 2.687 = 3.75 \text{ m}^2 \\
V = 2.687 \times \pi \times 1.397^2 / 4 = 4.12 \text{ m}^3
\]

For a cylindrical body such as the float the drag coefficient and the inertia coefficient are normally taken to be:

- \( C_d = 1.0 \)
- \( C_m = 2.0 \)

These coefficients are for a fully immersed cylinder. In the case of the helicopter float it is only partially immersed (about 50%). There is no established reliable information about drag and inertia coefficients for partially immersed cylinders, and so we shall assumed that the forces are the same as if it were fully immersed. Consequently we shall use the full volume and full projected area to produce the drag and inertia forces exerted on the cylinder held stationary in the waves as follows:

\[
D = 1.0 \times 0.5 \times 1025 \times 3.77^2 \times 3.75 = 27.32 \text{ kN} \\
l = 2.0 \times 1025 \times 2.96 \times 4.12 = 25.00 \text{ kN}
\]
As noted in the previous section the maximum velocity in the wave occurs at a time 90° out of phase with the maximum acceleration. Therefore the maximum drag force will occur 90° out of phase with the maximum inertia force. Consequently the maximum value of the resultant force that will be experienced as a result of both components is given by the square root of the sum of the squares:

\[ F = \sqrt{(27^2 + 25^2)} = 36.80 \text{ kN} \]

**C.3 Additional drag due to scoop**

The actual additional drag due to the scoop is quite complex, depending on the shape of the scoop, and the velocity of the (accelerated) flow around the float and other 'interference' effects. However we can make an approximate estimate for this drag in a similar manner to the above if we have a drag coefficient for it. This time it is assumed that the drag coefficient for the scoop alone is similar to that for a semi-circular channel with its concave face to the flow. For this case Hoerner (Fluid Dynamic Drag, chapter III, section 7, figure 33, p. 3-17) gives \( C_d = 2.3 \).

The horizontal projected area of the scoop (from Fig [2]) is approximately:

\[ (1.043 - 1.397/2) \times 2.687 = 0.925 \text{ m}^2 \]

and the drag force on the scoop is:

\[ D_s = 2.3 \times 0.5 \times 1.025 \times 3.77^2 \times 0.925 = 15.5 \text{ kN} \]

Thus the total drag force on the float and scoop is:

\[ 15.5 + 27.0 = 42.5 \text{ kN} \]

and the new resultant dynamic force is

\[ F = \sqrt{(42.5^2 + 25^2)} = 49.3 \text{ kN} \]
CAA PAPER 2001/10

HELICOPTER DITCHING RESEARCH – EGRESS FROM SIDE-FLOATING HELICOPTERS

D W Jamieson, I J Armstrong and S R K Coleshaw

REPORT PREPARED BY CENTRE FOR HEALTH AND SAFETY SCIENCES, RGIT LIMITED, ABERDEEN AND PUBLISHED BY CIVIL AVIATION AUTHORITY, LONDON, SEPTEMBER 2001
Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority and the UK Health and Safety Executive. The work was instigated at RGIT Limited in response to the conclusions and recommendations of earlier research performed for CAA by BMT Fluid Mechanics Limited. This earlier work was commissioned by CAA as part of its ongoing research programme on the stability of ditched helicopters in response to recommendations made in the HARP Report (Report of the Helicopter Airworthiness Review Panel - CAP 491), and was published as CAA Paper 97010 in December 1997.

The earlier research addressed the hyrodynamic aspects of providing a post capsize side-floating attitude. The work covered in this paper comprised an investigation of the human factors issues associated with escape from a side-floating helicopter. This was accomplished by comparing escape from both fully inverted and side-floating helicopters in a series of helicopter underwater escape trainer trials using 30 naive subjects.

The CAA and HSE concur with the conclusions of the research, and consider the results to weigh heavily in favour of providing a post capsize side-floating attitude. Consequently, the CAA now plans to proceed with a design study to address the practical issues associated with the provision of the modified emergency flotation systems required. In view of the nature of these issues, the study will focus on a specific helicopter type.

Safety Regulation Group

27 June 2001
Management Summary

RGIT Limited were contracted by the Civil Aviation Authority (CAA) to develop an appropriate technique and associated training procedures for egress from side-floating helicopters, and determine the overall benefit/disbenefit of the scheme by comparison with egress from a fully inverted helicopter. This report describes the results of this work.

A review of accident reports and relevant research was undertaken to identify the main issues associated with helicopter underwater escape. Particular attention was paid to the Super Puma, due to it’s high usage in the North Sea. An examination of an operational Super Puma was carried out in order that the risks of egress would be realistically assessed and to ensure that the helicopter simulator closely resembled its configuration in the trials.

Practical trials were carried out using a helicopter underwater escape trainer (HUET) as a simulator. The helicopter simulator was modified so that it came to rest at an angle of 150° after capsize. Buoyancy bags were fitted above the window exits on one side to simulate the proposed flotation system.

Initial work was performed using training staff as subjects who were able to use their knowledge and experience to determine best practice and develop new escape procedures. Carefully controlled feasibility trials were performed in which all possible means of escape from the side-floating helicopter simulator were explored. A risk assessment was then carried out to ensure that the risk of injury from such an escape would be kept to an acceptable, minimum level. From the feasibility trials, escape procedures were developed.

Thirty naïve subjects were recruited to evaluate escape from the side-floating helicopter simulator following capsize through an angle of either 150° or 210° and to compare it with escape from the fully inverted helicopter simulator following a capsize of 180°. Psychological and physiological measurements were taken at various intervals during the trials to measure the subjects' performance and levels of anxiety. Subjects also rated their perception of the difficulty associated with each escape. Each trial was filmed from inside the simulator and from the pool-side in order to measure escape times and assess ease of escape. The different escape procedures were compared in order to assess the relative advantages and disadvantages of each.

The results showed that the majority of subjects preferred escape from the side-floating helicopter and found it to be easier. This was reflected by the fact that subjects were significantly more satisfied with how they coped with the side-floating escape. In escape from the fully inverted simulator, difficulty caused by disorientation, breath-holding, locating and using the exit were more prominent than was the case in the side-floating exercises. This was especially true when subjects were required to make their way across the cabin to escape. In the side-floating escapes, subjects had some difficulty releasing the harness when seated on the upper side of the simulator. These problems were not thought to outweigh the advantages of escape from a side-floating helicopter.
Contents

1 INTRODUCTION 1
  1.1 Background 1
  1.2 Aims and Objectives 3
  1.3 Review of Accident Reports and Research 3
    1.3.1 Overview 3
    1.3.2 Findings of Accident Review and Escape Research 4
    1.3.3 Life-rafts 12
    1.3.4 Helicopter Escape: Fully Inverted Compared to Side Floating 13
    1.3.5 Helicopter Underwater Escape Training 14

2 FEASIBILITY TRIALS 16
  2.1 Method 16
    2.1.1 Preparation of the helicopter simulator 16
    2.1.2 Protocol 16
  2.2 Results 18
  2.3 Discussion 19
  2.4 Development of Capsize Scenarios 20

3 NAIVE SUBJECT TRIALS 21
  3.1 Method 21
    3.1.1 Overview 21
    3.1.2 Subject recruitment 22
    3.1.3 Experimental trial programme 22
    3.1.4 Management and analysis of data 24
  3.2 RESULTS 26
    3.2.1 Background 26
    3.2.2 Perceived worry 27
    3.2.3 Difficulty ratings after the trials 28
    3.2.4 Post trial evaluations 34
    3.2.5 Physiological correlates of stress 36
    3.2.6 Psychological stress 38
    3.2.7 Escape and submersion times 38
  3.3 Discussion 40
    3.3.1 Overall preference 40
    3.3.2 Comparison of escape difficulty 40
    3.3.3 Breath holding and escape times 41
    3.3.4 Stress 42
    3.3.5 Confidence 42
    3.3.6 Problems of escape from a side-floating helicopter 43
    3.3.7 Wave action 44
    3.3.8 Life-raft deployment 44
CONCLUSIONS

4.1 Overall Preference
4.2 Ease of Escape
4.3 Above-Water Exits
4.4 Harness Release
4.5 Overall Benefits

RECOMMENDATIONS

REFERENCES

APPENDIX 1 REVIEW OF HELICOPTER ACCIDENTS
APPENDIX 2 WITNESS REPORT
APPENDIX 3 CABIN CONFIGURATION OF SUPER PUMA
APPENDIX 4 VIEW INSIDE HELICOPTER SIMULATOR AT 150°
APPENDIX 5 QUESTIONNAIRES
APPENDIX 6 EXAMPLE OF HEART RATE TRACE
List of Tables

Table 1  Possible escape procedures tested in the feasibility trials  17
Table 2  Most common issues identified from feasibility trials  18
Table 3  Escape procedures tested in naïve subject trials  23
Table 4  Average height and weight of subjects  27
Table 5  Subjects’ background  27
Table 6  Subjects’ rating of capsize difficulty  28
Table 7  Significant differences between difficulty ratings  34
Table 8  Subjects’ confidence in helicopter transport  35
Table 9  Subjects’ satisfaction with coping in the trials  35
Table 10  Subjects’ confidence to cope with a real helicopter ditching after each trial  36
Table 11  Mean heart rates before, during and after the trials  36
Table 12  Mean salivary cortisol values  37
Table 13  Mean urinary cortisol values  37
Table 14  Mean STAI scores  38
Table 15  Mean escape times from the trials  39
Table 16  Mean submersion times  39
List of Figures

Figure 1  Subjects’ perceived worry before first trial  28
Figure 2  Subjects’ rating of difficulty factors in the fully inverted cross-cabin capsize  30
Figure 3  Subjects’ rating of difficulty factors in the side-floating cross-cabin capsize  30
Figure 4  Subjects’ rating of difficulty factors in the fully inverted same-side capsize  32
Figure 5  Subjects’ rating of difficulty factors in the side-floating same-side capsize  32
Figure 6  Subjects’ rating of difficulty factors in the fully inverted reverse capsize  33
Figure 7  Subjects’ rating of difficulty factors in the side-floating reverse capsize  33
INTRODUCTION

1. Background

In one year (1991) offshore helicopter operators in the UK sector of the North Sea flew over two million passengers on over 300,000 flights. Over the preceding seven year period, in excess of 2 million flights were made carrying nearly 15 million passengers. During this time there were two accidents resulting in passenger fatalities. In these accidents a total of 51 passengers were killed, 45 of these being in the Chinook accident in November 1986. It is obvious that the only satisfactory record is one in which no fatal accidents occur at all, however these figures do indicate that a high level of safety and passenger awareness exists (Bycroft, 1992). Between 1992 and 1999 there was one further fatal accident in the UK sector in which 11 died (AAIB, 1993).

As part of a Helicopter Underwater Escape Training (HUET) workshop in 1996, Shell UK Exploration and Production set some high safety targets for helicopter travel (Clark, 1996). By the year 2000 they hoped to have reduced the fatal accident rate to 5 per one million flying hours, with a further reduction to 2 per one million flying hours by the year 2005 (equivalent to the projected commuter airline standard at that time). Shell hoped to achieve these targets through a range of safety improvements and an aviation research programme, including flotation aids for helicopters. Currently, flotation systems are mounted low down and must be manually activated.

The capsize boundaries for the helicopter types which operate in the North Sea region lie in the range of Sea State 4-5. Studies of wave climate along six North Sea helicopter routes (BMT, 1997) have shown that if helicopters were to ditch in the winter months there is a significant risk of the sea state being greater than 6. Damage to the helicopter or malfunction could also lead to capsize in more moderate seas. Generally the worst case scenario can be assumed, as Rayack (1986) suggested by stating: ‘When a helicopter crashes in the water, it almost always rolls over. The sea begins to rush in, and the cabin fills with turbid water, oil, fuel and debris. Within a minute – even in as few as 20 seconds – the helicopter will often begin to sink to a depth from which no one can survive’.

The Helicopter Airworthiness Review Panel (HARP) Report, published in 1984, stated that: ‘The frequency of forced landings is such that a high probability of survival of all occupants is essential. To achieve this, the helicopter must have adequate buoyancy, stability, practicable means of escape and effective life-raft equipment. Buoyancy needs to be assured in order to provide the pilot with ditching as an acceptable option, and there are strong arguments in favour of deployment of flotation bags before contact with the water. The need for stability is emphasised by the very limited practicability of escape from a capsized helicopter. The conditions on which the stability of the helicopter should be demonstrated must take account of realistic wind speeds accompanying severe sea states’.

Recommendation 10 of the report (HARP, 1984) identified ditching stability as an area which required improvement. Helicopters have a limited range of stability due to their weight distribution. This means that in moderate to severe conditions the likely outcome is capsise, and without flotation, is often followed rapidly by sinking. In 1995, the CAA’s Report of the Review of Helicopter Offshore Safety
and Survival (RHOSS) emphasised the need for helicopters to remain afloat long enough for survivors to escape. Improved flotation systems were recommended.

The Civil Aviation Authority (CAA) is currently investigating options for improving the potential for escape from a ditched helicopter. The solutions entail the positioning of additional flotation devices high on the fuselage in the vicinity of the main rotor gearbox and engines. The aim of these flotation systems is to prevent total inversion of the helicopter following capsize and retain an air space within the cabin. The provision of an air space within the cabin would remove the time pressure of escape and ensure that some of the potential exits and escape routes remain above the water level, facilitating egress.

Model tests have been carried out (Jackson and Rowe, 1997) to investigate the different flotation systems and configurations. These systems were intended to prevent the total inversion of a ditched helicopter following capsize. The most efficient and stable flotation system proved to be an asymmetric configuration with a combination of a buoyant cowling panel and a single buoyant unit placed along one side of the fuselage (Jackson and Rowe, 1997).

The model tests demonstrated that this asymmetric configuration resulted in the helicopter inverting to an attitude of 150° from the vertical, and remaining stable in that attitude. It may have rolled through an angle of 150° or 210°, depending upon whether the wave hit the helicopter model on the side with or without the buoyant unit. The asymmetric configuration removed the potential for a two stage capsize which would be possible with a symmetric system. Clearly this event is undesirable as it may occur while people are trying to make their escape after the first capsize.

The provision of a definite air gap in the cabin and a number of exits which are above the water surface, combined with appropriate egress training to cope with this flotation angle and scenario will, in theory, improve the individual’s ability to successfully egress from a capsized helicopter. However, in order to properly assess the chances of survivors escaping from a helicopter after capsize, it was necessary to have extensive knowledge of the problems which they might encounter.

This being the case, a number of factors needed to be considered such as the jettisoning of exits and the position of windows in relation to seats. A helicopter on its side creates specific issues for consideration. The angle of flotation and degree of buoyancy have significant effects on both the position and angle of the seating. Release from the harness was also a potential problem.

Jackson and Rowe (1997) suggested that there is limited evidence in the literature to show whether occupants could escape from a side-floating helicopter. Rice and Greear (1973) suggested that when a helicopter sinks on its side, the escape hatches are beneath and above the occupants. Some survivors have actually dived down under the sinking aircraft because the opposite hatch was unreachable, approximately 8 feet up. The new EH101 helicopter (EH Industries) includes a rope ladder, built into the side window seal so that survivors can pull themselves up towards the window if necessary. However, following a ditching into the sea and capsize, it might still prove difficult to reach up and release the window and rope ladder. Escape from the windows may thus depend upon design, the size of the cabin, and the flotation angle of the helicopter. Issues like
these help to illustrate the importance of assessing the feasibility of escape from a helicopter floating on its side.

1.2 Aims and Objectives

The overall aim of the project reported here was to study the human factor issues related to egress from a side-floating helicopter.

The main objectives of the study can be summarised as follows:

1. To develop an appropriate technique and associated training procedures for egress from side-floating helicopters;

2. To determine the overall benefit/disbenefit of the scheme by comparison with egress from fully inverted helicopters.

An important first step towards a feasible solution was to carry out a thorough review of all available information relating to the problems facing individuals having to effect an underwater escape from a helicopter. This was considered important in helping to ensure the success of the practical phase of the work. There were two parts to this review. The first part was to study Air Accident Investigation Branch reports; the second part complemented this by looking at papers in the literature on helicopter escape research.

The next step was to develop a generic procedure for egress from a side-floating helicopter which was as simple and safe as possible and achievable. It was considered important to assess the subjects’ perceptions of the difficulty associated with escape from a side-floating helicopter in order to accomplish this.

A further objective was to ensure that any generic procedure developed would be appropriate to the wide range of helicopters currently in use offshore (there are currently 42 different configurations). Training for passengers thus needs to be representative of the ‘norm’ building up general knowledge and levels of confidence. The intent was to provide the helicopter passenger with the skills and ability to cope in a real ditching, whatever the helicopter configuration.

1.3 Review of Accident Reports and Research

1.3.1 Overview

The Accidents Investigation Branch (AIB), and later Air Accidents Investigation Branch (AAIB), reports and bulletins (1977 – 1999) on accidents involving helicopters landing in the sea with and without capsize were reviewed. Information relating to egress was extracted and analysed. Of particular interest were those accidents involving Super Puma helicopters since this is one of the most commonly used helicopters operating in the North Sea. (The underwater escape trainer used in the trials was also configured to represent a Super Puma – Sections 2 and 3 refer).
The following accidents were reviewed in detail:

- Sikorsky S.61N helicopter, G-BBHN, in the North Sea, North East Of Aberdeen, on 1 October 1977 (AIB, 1978)
- Bell 212 G-BIJF, in the North Sea, o/south east of the Dunlin Alpha platform, on 12 August 1981 (AAIB, 1982)
- Boeing Vertol (BV) 234 LR, G-BISO, in the East Shetland Basin of the North Sea, on 2 May 1984 (AIB, 1987)
- Bolkow BO 105D, G-AZOM, 5½ nm due east of Skegness, Lincolnshire, on 24 July 1984 (AIB, 1985)
- Aerospatiale AS 332L, Super Puma G-BKZJ, 35 nm east-north-east of Unst, Shetland Isles, on 20 May 1987 (AAIB, 1988)
- Sikorsky S-61N, G-BEID, 29 nm north east of Sumburgh, Shetland Isles, on 13 July 1988 (AAIB, 1990a)
- Sikorsky S61N, G-BDII, near Handa Island off the north-west coast of, Scotland on 17 October 1988 (AAIB, 1989)
- Sikorsky S61N, G-BDES, in the North Sea 90 nm north east of Aberdeen, on 10 November 1988 (AAIB, 1990b)
- AS 332L Super Puma, G-TIGK, in North Sea 6 nm South West of Brae Alpha Oil Platform on 19th January 1995 (AAIB, 1997)

Summaries of each of the above accidents, with particular reference to evacuation and escape, are given in Appendix 1.

As well as reviewing accident reports, efforts were made to interview witnesses from helicopter ditching accidents in order to gain a better understanding of the issues involved with evacuation and escape. One such witness report is contained in Appendix 2.

The results of the accident review were then related to the results from studies of helicopter escape, sourced from the scientific literature.

**Findings of Accident Review and Escape Research**

From the accident review it was possible to identify six critical stages which could determine the success of an individual’s attempted egress from a helicopter when
forced to land in the sea. The outcome of a particular stage may be influenced by a number of factors, including the outcome of the previous stages.

1.3.2.1 Stage One – Impact of Helicopter with the Sea

The force of impact of the landing is very important in terms of an occupant’s chances of egress and is largely affected by the type of landing. In the report of the Review of Helicopter Offshore Safety and Survival (RHOSS; CAA, 1995) landings are classified as either a ditching or a crash. A ditching is used to describe the event when a helicopter makes a controlled descent, with some measure of warning, into a ‘non-hostile’ sea. A crash includes all uncontrolled or inadvertent impacts with the water, controlled descents into a hostile sea and the case of a helicopter falling off a helideck. These definitions are used for the remainder of this review.

As a general rule, the more controlled the landing, the more favourable the outcome for the occupants of the aircraft in terms of their chances of egress. A good example is the controlled landing of AS 332L Super Puma G-TIGK in the North Sea in January 1995 (AAIB, 1997). Despite heavy seas the landing was executed successfully and the helicopter remained upright enabling the passengers and crew to board a helirraft without injury.

The forced landing of Bolkow BO 105D G-AZOM in July 1984 (AIB, 1985) could not be controlled so effectively. The pilot had intended to ditch but lost control during the descent, resulting in the aircraft crashing into the water while still rotating. As a result, one of the floats detached and the aircraft rolled onto its side, which made it more difficult for the pilot to escape.

In the worst case scenario the accident occurs without warning, with the helicopter impacting the water with considerable force. On such occasions, helicopter passengers will not have time to prepare for the emergency. Analysis of military helicopter accidents clearly indicates that pre-crash warning could, at best, be measured in seconds (Haywood, 1993). The fact that helicopters are operating at such low altitudes means that the occupants must depend on the basic crashworthiness of the aircraft for survival (Shanahan and Shanahan, 1989).

An accident involving a crash happened to AS 332L Super Puma G-TIGH in the East Shetland Basin in March 1992 (AAIB, 1993). The commander allowed the aircraft to descend unnoticed until collision with the sea was inevitable. Five of the seventeen occupants were unable to escape from the helicopter before it capsized and sank, probably because they had so little time to react, even though post-mortems indicated that the impact would not have incapacitated them. In other accidents, such as that to Sikorsky S61N G-BEWL at Brent Spar in July 1990 (AAIB, 1991), the force of impact incapacitated some occupants to the degree that escape was virtually impossible. The AAIB report recommended that upper torso restraint should be installed in new and existing UK helicopters to help lessen impact injuries, thus providing an individual with a greater chance of escape.

Whilst the proposed new flotation system would not have any effect on the impact with the sea, the system would provide additional available buoyancy, allowing some redundancy. This would reduce the likelihood of the helicopter sinking on impact with the water.
1.3.2.2 Stage Two – Stability of Aircraft Upon Entering Water

The desired outcome is that a helicopter will remain afloat in an upright attitude long enough for the occupants to complete a successful evacuation. In reality it is likely that the helicopter will capsize and start to sink. Of the 11 accidents reviewed involving helicopters landing on the sea, seven aircraft capsized. Furthermore, six of these capsizes were very rapid, occurring within 1 or 2 minutes of impact with the sea. One of the aircraft sank almost immediately after capsize and another remained afloat for only 15 to 20 minutes.

From the evidence provided by accident reports the pattern which emerges is that the majority of helicopters will capsize very soon after striking the sea with the possibility of fairly rapid sinking. This is clearly influenced by how the helicopter impacts upon the sea and the subsequent damage to the hull. The commander had managed to execute a very controlled landing in three (AIB, 1987; AAIB, 1987; AAIB, 1990a) of the four accidents when a capsize did not take place (the other was a severe crash resulting in immediate sinking of the aircraft [AAIB, 1991]). In two of these three accidents the weather conditions were favourable, suggesting that this is another factor which influences whether a helicopter capsizes or not. Finally, the effectiveness of the flotation gear and whether the commander has time to deploy it will impact upon the stability of the helicopter in the water. Once again, the flotation gear is more likely to be deployed effectively and keep the helicopter upright if the pilot is able to carry out a successful controlled ditching.

The aim of the side-floating system is to mitigate the consequences of a capsize. This is achieved by providing a post-capsize floating attitude with at least one set of exits above the water surface, which should increase the time available for escape and increase the overall ease of escape.

1.3.2.3 Stage Three – Unfastening of Safety Belt

Once an aircraft has come to rest on the sea, if an individual has followed their training then their next task is to open their safety belt. There is evidence that this does not always happen easily and some may be unable to release their seat belts (Ryack et al., 1976; Ryack et al., 1986). An example of this occurred after the accident to Bell 212 G-BIJF in August 1981 (AIB, 1982). The accident involved collision with the sea followed by rapid capsize. One of the passengers had considerable difficulty in freeing himself from his safety belt, only managing to extend it enough so he could wriggle free. The effort of this took its toll on the man who was unable to help himself upon egress from the aircraft which caused him to drift away and drown. Subsequent examination of the safety belt in question showed it to be in working order. The report recommended that: ‘the opening and adjustment mechanisms on safety belt release buckles be designed to avoid similarities in their operation’. This measure might help to ensure that such buckles are always operated in the right direction at the first attempt, which is clearly crucial in an accident such as the one to G-BIJF. However, the CAA did not accept this recommendation. In the ‘Follow-up action to accident reports’ published subsequent to this accident (CAA, 1987a), the CAA point out that the great majority of seat belts are released by operating the mechanism from left to right but that in some cases this is not possible due to practical constraints.
In the accident to Sikorsky S61N G-BDES in November 1988 (AAIB, 1990b) three passengers reported some difficulty releasing their lap strap buckle although they were able to escape without serious injury.

Clearly any problems and delay in releasing a safety belt may seriously diminish the chances of an individual escaping from an aircraft. This will be affected by familiarisation with and ease of use of the buckle, the condition of the buckle and possibly the orientation of the wearer. This has possible implications for the side-floating configuration, where the victim may be strapped into the seat at an angle of about 150° to the vertical following capsize.

It should also be noted that in the accident to Super Puma G-TIGH in 1992 (AAIB, 1993) one passenger's escape was impeded by the cord of his headset becoming wrapped around his neck. The benefit of cordless headsets is suggested in the RH OSS report (CAA, 1995).

1.3.2.4 Stage Four – Reaching an Exit

The next critical stage is to reach an exit. It should be remembered that the chances of survival at this point have already been affected by the extent of injury and incapacitation from the helicopter’s impact with the sea, the orientation of the helicopter and the ease and speed of release from the safety belt. In particular, heavy impact or a rapid capsize may have moved or damaged some of the cabin fittings, turning them into obstacles.

This happened in the accident to Sikorsky S61N G-BBHN in October 1977 (AIB, 1978) when cabin floorboards and baggage compartment doors became detached. It was recommended that: ‘the cargo door on S.61N helicopters should be modified so that it can be locked in the open position to facilitate an emergency evacuation’. A further recommendation was that: ‘under floor baggage locker doors, floor covering and panels should be tightly secured to prevent their becoming detached after a capsize’.

In the report on the accident to Boeing Vertol 234 LR G-BISO in May 1984 (AIB, 1987) underwater escape was discussed. Based on interviews with helicopter ditching survivors, a US Army report (see AIB, 1987) found that reaching and operating exits, disorientation and dark, were major factors in escape. Underwater escape tests completed by the Royal Navy suggested that the maximum number of trained personnel likely to escape from one hatch was four. In addition, tests conducted by the Royal Air Force Institute of Aviation Medicine showed that the minimum dimensions of an aperture through which a 95th percentile male could escape, while wearing standard survival clothing used by North Sea passengers, was 17 inches by 14 inches. The AIB (1987) suggested that consideration should be given to the possibility of modifying some windows to provide additional exits of such minimum dimensions. It was recommended that the Civil Aviation Authority conduct a review of the number and type of exits required for all public transport helicopters. The CAA’s response to this was to require that all suitable openings in the passenger compartment which are 17’ by 14’ or larger be designated as an escape route and capable of being opened. In addition, that larger persons do not occupy seats adjacent to windows smaller than approximately 19’ by 17’ down to the minimum acceptable size of 17’ by 14’ (CAA, 1987b).
From this, it is clear that the number of escape exits available and exit size, will have a direct affect on an individual's chances of escape. Seat position was identified by Bohemier and Morton (1996) as another factor which might improve or impede egress. The RHOSS report (CAA, 1995) considered it to be important that each passenger should have easy access to one clearly identified exit and noted worthwhile efforts to alter cabin design and seating configuration in order to optimise this.

The ditching of Sikorsky S-61N, G-BEID in July 1988 (AAIB, 1990a) was caused by fire in both engines which led to the cabin filling with noxious thick smoke. Clearly this made it more difficult for occupants to find an exit and slowed egress. In this case passengers and crew were able to evacuate successfully but had they less time, the effects of the smoke may have been more crucial in terms of their chances of survival.

The rapid inrush of water is another factor which might severely hamper an individual's attempts to reach an exit. This has been identified by a US army report (see AIB, 1987) as the major difficulty encountered when trying to escape from a helicopter landing in the sea and is supported by several authors (Ryack et.al., 1976; Ryack et.al., 1986; Rice & Greear, 1973; Muir, 1996). There is also evidence from the AAIB reports that this is indeed one of the most crucial factors determining chances of escape. The accident to AS 332L Super Puma G-TIGH in 1992 (AAIB, 1993) provides a stark illustration of this. The helicopter crashed into the sea causing rapid water ingress into the cabin. It is likely that four of the five passengers who did not escape from the helicopter before it sank were in some way overcome by this rush of water before they were able to make their escape. Breath holding time possible in the conditions was estimated at less than 20 seconds.

Another example is provided by the accident to Sikorsky S61N G-BDII in October 1988 (AAIB, 1989) involving capsize. The winch operator was considerably hampered by the inrush of water through the open starboard cargo door although he managed to escape. The winchman, who had been sitting halfway down the fuselage, was washed by a succession of waves, emanating from the open forward exits, towards the rear of the aircraft. He was eventually trapped in a small air pocket in the tail section of the inverted aircraft, from where his attempts to reach one of the jettison mechanisms for the rear port emergency exit were frustrated by his own natural buoyancy and the air trapped in his immersion suit. This latter point constitutes another problem which may hamper attempts to reach an exit in an inverted helicopter full of water. The winchman was eventually rescued by the commander who opened the rear port door from outside the aircraft.

Some of the perceived benefits of the side-floating helicopter are that one set of exits will be above the water surface after capsize, and, that a large air gap will be maintained within the cabin. This will allow the victim to surface within the cabin air gap and reduce the need for the individual to make an immediate escape following capsize. Once the head is above the water surface, the individual can take a breath, overcome any disorientation, locate the nearest exit and then make an escape.
1.3.2.5 Stage Five – Opening an Exit

Upon reaching an exit it will probably be necessary for the individual to jettison the potential escape exit. This will usually have to be done by touch rather than sight due to poor visibility. This final challenge may be too much for those who are at the limit of their breath holding ability or who have been injured in the accident. According to Brooks et al (1994), these individuals will form part of the 25-35% mortality rate associated with helicopter ditching accidents, suggested by military helicopter accident statistics.

Exits may already have been jettisoned if the crew are able to initiate an automatic unlatching control. This will depend on whether the crew have enough time to react or if they remember under the stress of bringing a helicopter to land in rough seas. This added responsibility upon crew members was noted by Hognestad (1993) and is certainly another factor which may affect egress. As an example, in the accident to Sikorsky S-61N G-BEID in 1988 (AAIB, 1990a) the crew did not manage to activate the automatic control for one of the exits which slowed egress from the aircraft, although everyone eventually escaped unharmed.

It may also be the case that the helicopter’s impact with the sea has broken or dislodged some exits due to the distortion of the airframe. In this case occupants may be able to make use of the exits without having to open them.

Assuming exits have still to be opened, there are a number of problems which may face those trying to do so. If the helicopter is upside down this will present particular difficulties for anyone trapped inside. The jettison mechanism may be difficult to locate due to the fact it will almost certainly be underwater. This was the case in the accident to Sikorsky S-61N G-BDII in October 1988 (AAIB, 1989) when the winchman had great difficulty in getting to the jettison mechanism for the rear port door. Not only did his buoyancy make it difficult to progress under the water but upon reaching the exit, the mechanism was visually obscured by a curtain of bubbles illuminated by the emergency lights. Poor visibility can often prevent people from even finding escape hatches and egress routes (Ryack et al, 1976; Ryack et al, 1986; Bohemier & Morton, 1996).

A further problem with locating and operating an exit after the inversion of a helicopter is caused by disorientation (Ryack et al, 1976; Ryack et al, 1986; Rice & Gereear, 1973). The problem of disorientation was highlighted in the accident to Sikorsky S61N G-BDES in November 1988 (AAIB, 1990b). The commander was forced to execute an immediate landing into a fairly hostile sea which was followed by rapid capsize. After capsize, neither pilot was able to locate the jettison handle for their emergency exit from an inverted position under water. One factor which probably contributed to this was identified from research into disorientation of subjects inverted under water. Tests were carried out in an intact S61 cockpit to establish why neither pilot could locate the operating handle for his emergency exit. Results indicated that when a pilot in the left hand seat reaches for the side escape exit operating handle his hand would naturally fall between the collective lever and his seat. This raises the possibility that the collective lever would obstruct the attempts of a pilot to reach the emergency exit operating handle. This problem may be exacerbated by the weight of the inverted pilot raising him from his seat. The effect of raising the pilot two inches from his seat is to put the emergency handle near the limit of normal reach. Research into disorientation of subjects inverted under water had demonstrated that their
perception of the vertical could be seriously in error. Any one or a combination of these factors probably explain why neither pilot was able to locate their emergency exit operating handle. This being the case, it is possible that crew of an aircraft who are inverted under water may reach to the wrong place for a jettison handle, or find that the lever is beyond their normal reach.

A design issue raised by the RHOSS report (CAA, 1995) concerns the lack of standardisation in the operation of emergency exits. Although there is little evidence from the accident reports that this has hampered egress, research has shown that operating controls for escape hatches may be problematic. In controlled simulated training, trained subjects failed to correctly operate controls for escape hatches and required assistance to egress in 3.5% of escapes (Brooks et al, 1994). Jettison levers may appear to operate in the ‘right direction’ and be ergonomically well designed in terms of size, shape and location for emergency ground egress. However, their operation may become much more difficult in an inverted position underwater due to a person’s disorientation and inherent buoyancy. Brooks et al also found that due to poor depth perception and magnification effects underwater, combined with disorientation, individuals required great eye-hand co-ordination to execute physical actions more than 25cm ahead of their finger tips when they were seated with the elbows flexed.

Lack of uniformity in the placement and operation of the levers is a potential problem. Theriault found that of 35 helicopter types, there were 23 different mechanisms positioned in many different places relative to the seated pilot or passenger (Theriault, 1998). As Brooks et al (1994) stated, solutions require both standardisation and improvement to design since the inconsistency can only serve to increase the difficulty of escape.

It has been identified that the design of an emergency exit may inhibit it being opened after a helicopter has landed in the sea. As early as 1987, the crew of AS 332L Super Puma G-BKZH (AAIB, 1988) elected not to ditch after technical failure because they were aware that the Super Puma cabin doors cannot be jettisoned when the aircraft is inverted. British International Helicopters confirmed this when they undertook practical tests in 1990 which showed that the Super Puma sliding doors are very unlikely to jettison if the aircraft is other than upright (Bailey, 1990). This is due to the fact that the design of the emergency release mechanism for these doors relies on gravity to release a portion of the sliding door track. The AAIB report (1988) relating to the accident to G-BKZH in 1987 recommended that the door design of the Super Puma should be reviewed, which the CAA agreed to undertake in its reply. However, the same design was involved when Super Puma G-TIGH (AAIB, 1993) crashed into the sea in 1992.

In the report on the accident to the aforementioned Super Puma (AAIB, 1993) the issue of this aircraft’s cabin door jettison was discussed. The report concludes that the inability of the cabin doors to jettison unless the aircraft is in a near vertical position cannot be viewed as acceptable for the wide range of impacts where the helicopter is likely to remain erect for a very short period. It is also suggested that the benefit of opening a relatively large aperture, for personnel escape and perhaps life-raft deployment should not be ignored.

Somewhat contrary to this, the RHOSS report (CAA, 1995) found it difficult to envisage circumstances in which it would be practicable to use a main exit when the fuselage is not upright and therefore did not consider there to be any need for
the CAA to reconsider the operating parameters for cabin door release mechanisms. However, there is evidence of instances when a helicopter capsized but did not sink immediately in which attempts were made to open a cabin door (AIB, 1978; AAIB, 1989; AAIB, 1990b). From this, it seems there are situations when it may be beneficial for cabin doors to open when a helicopter is not upright.

Further vindication of this point comes from the accident to Super Puma G-TIGK in 1995 (AAIB, 1997). The aircraft was upright but rolling in the sea and the inherent buoyancy of one of the doors prevented it from falling vertically, causing the upper locating arm to fail. It was thought that the fractured end of the floating door punctured the lower chamber of one of the helirafts. In conclusion, it appears that the need to open a cabin door in a non upright helicopter is not unlikely and could be beneficial. As such, the design of cabin doors perhaps requires further attention.

Once open it is preferable that the door remains open (see AIB, 1978). All non-jettisonable doors of emergency exits must now have a means of securing them in the open position (Document BCAR 29.809[j]; see CAA, 1992) and a provision has been made to deal with the issue of properly securing items which, if unsecured, might obstruct escape in the event of a helicopter ditching (CAA, 1987b).

Other factors which may prevent or hamper the successful opening of an exit include an obstacle on the outside of the door or part of an individuals clothing inhibiting the mobility they require to open the exit. An example of the former was observed in the accident to Bolkow BO 105D G-AZOM in 1984 (AIB, 1985) when the aircraft rolled onto its side and a detached flotation bag lay beneath the commander’s door making it impossible to open. The latter was illustrated after the accident to Sikorsky S61N G-BDES in November 1988 (AAIB, 1990b) when one passenger reported he could not grip the fabric tag attached to the window rip-out beading until he had a survival glove. The AAIB (1990b) recommended that the CAA give further consideration to the problems of escape from inverted helicopters when approving helicopters for offshore operations, given the likelihood of rapid capsize following ditching. The CAA fully accepted this recommendation (CAA, 1990) and undertook to consider what further action could be taken in determining future escape facility standards.

When the side-floating configuration is considered, one set of exits will be above the water, allowing time to operate the release mechanism without undue panic.

1.3.2.6 Stage Six – Using an Open Exit to Make a Safe Escape

Having successfully reached and opened an escape exit there is a reasonably good chance that egress from the helicopter to the sea will be achieved. In this critical final stage, it is important that an individual’s personal safety equipment is not so bulky or buoyant as to impede progress, and is designed to present the least possible risk of snagging (CAA, 1995). Also, a few incidents have been noted in this review which emphasise the fact that nothing should be taken for granted at this stage of escape.

In the accident to Bell 214 ST G-BKFN in 1986 (AAIB, 1987) the aircraft was forced to ditch but remained upright and all passengers and crew were eventually
rescued safely. However, one of the passengers entered the sea inadvertently as a result of slipping off a flotation bag, and subsequently found himself drifting towards the still turning tail rotor. The individual was able to arrest the situation but clearly this final stage of egress was far from ideal. The AAIB report suggests that the addition of a non-slip surface to the float bag could have prevented this from occurring.

The accident to AS 332L Super Puma G-TIGK in January 1995 (AAIB, 1997) highlighted a situation whereby an open exit could not be used. The aircraft had alighted on the sea and remained upright with both cabin doors being ejected and a helirraft being deployed from each. Passengers on the left side of the aircraft were having difficulty since the helirraft was blowing up against the open door on this side, making boarding very difficult. Fortunately the helirraft on the right side of the helicopter was available for all to board but this situation clearly slowed egress.

Finally, the rapid inrush of water is probably the most important factor which might prevent egress through an open exit. This has been reported by survivors of helicopter crashes at sea and was emphasised during the accident to Sikorsky S61N G-BDIl in October 1988 (AAIB, 1989) when the winch-man was washed away from the open starboard cargo door and the winch operator had considerable difficulty overcoming the water as it entered the cabin.

In-rushing water should not be a problem with the side-floating helicopter. Oncoming waves may be a concern, but this situation is little different to the upright-floating helicopter. The design of the new flotation system should aim to ensure that the top of the inverted exits are close to the water surface, allowing an easy escape to the sea. The victim should not have to climb up to the exit. If a flotation unit is fitted along the outside of the cabin, the victim may have to clamber over the unit, but this poses little risk of injury or difficulty.

1.3.3 Life-rafts

Life-raft evacuation from a ditched helicopter has been very problematic for survivors as a result of heavy sea states and the condition of the ditched helicopter. Problems which have been encountered include; total loss of the raft because the helicopter rolled on top of it; puncture through friction on the fuselage or tail rotor strike; the raft being blown on to its side against the fuselage and impossible to right; survivors having difficulty in boarding; the line or painter securing it to the helicopter cut by a sharp edge; and a liferaft which is difficult or impossible to launch (Brooks et al, 1997; Brooks et al, 1998).

Although not directly a recommendation of the HARP report (CAA, 1984), the launching of a life-raft and life-raft evacuation was suggested for further research. Following these suggestions, offshore helicopter operators performed a number of actions to improve life-raft deployment and reliability. Bailey (1990) stated that 'the sharp edges and projections which in the past had punctured life-rafts were covered or reprofiled. A new life-raft, the RFD helirraft was developed. This was very much tougher than previous rafts and thus puncture resistant. A drawback was that the canopy was difficult to erect in a rough sea or strong wind. Nevertheless, it was and is a great advance on earlier models'. A number of operators took the step of mounting life-rafts externally on the Super Puma. The possible puncture of liferafts by damaged structure or sharp projections was again
highlighted in 1997 (AAIB, 1997), when the AAIB recommended that action be taken to prevent door mounting arm failures.

Whilst work has been done to examine the options for life-raft evacuation from a ditched but non-inverted surface floating helicopter, (see Brooks et al 1997), the issue of life-raft deployment from a capsized helicopter appears to be absent from the research and only features in two of the AAIB reports reviewed for this study. In the accident to G-BBHN in 1977 (AIB, 1978), after capsize the co-pilot experienced difficulty moving the stowed life-raft towards the cargo door due to obstacles in his way. With the water level rising it became more important for the co-pilot to concentrate on opening the cargo door, which he managed with assistance, but only when neck deep in water with little breathing space above. In the accident to G-BDII near Handa Island (AAIB, 1989), the commander, who had already escaped from the aircraft, opened the rear port exit which allowed the winchman to escape from an air pocket in the tail section. The winchman had already removed the life-raft from this exit in his efforts to escape and was then able to retrieve it for use.

These cases illustrate the impracticability of deploying a life-raft from a capsized helicopter when an individual may only have a matter of seconds to make their escape. In the accident to G-BBHN in 1977 (AIB, 1978), the co-pilot was forced to abandon his attempt to deploy the life-raft in order to make his escape. In the accident to G-BDII (AAIB, 1989) the life-raft was deployed, but only because it could be accessed from outside the aircraft.

**1.3.4 Helicopter Escape: Fully Inverted Compared to Side-Floating**

From the review of helicopter accidents and related research it has been established that a helicopter which has been forced to land on the sea in high sea states, is likely to capsize and then sink. This fact makes it extremely important to establish which floating position after capsize gives the best chance of escape.

Common sense suggests that if a helicopter is floating on its side, this would be easier to escape from than a fully inverted aircraft due to the fact that the exits on one side of the helicopter would be above the water. There is also likely to be a larger air pocket within the cabin. Despite this, there may also be disadvantages of the side-floating position. One such disadvantage may be the release of the harness at an angle of about 150°. Such an angle is likely to create an uneven load on the harness buckle, which might make it more difficult to release. This is not a problem specific to the side-floating position, but one which may be exacerbated by the proposed flotation angle. Harness release has caused problems in at least one accident (AIB, 1982) and such problems are not uncommon during helicopter underwater escape training. Evidence from the review indicates that in many respects, escape from a side-floating helicopter would probably be easier than escape from a fully inverted one.

The review has shown that problems trying to reach exits are a major factor in escape. While waves could still provide a problem, 'inrushing' water will not affect exits which are above the water surface. The problems of underwater escape, particularly in poor visibility are well known, with speed and ease of escape being critical. Military research has shown that a maximum of only four people are likely to escape from any one exit. It is easy to see why this would be the case if occupants are trapped underwater and must rely on holding their
breath to locate an exit, escape and reach the surface. However, if a helicopter is on its side, breath-hold time is likely to be less critical and passengers can wait their turn in the air pocket, before using an above water exit. The problems of locating an underwater exit can be avoided, increasing the chances of escape. The accessibility of the exits above the water will depend upon the angle of flotation and the flotation depth.

Substantial evidence has been presented which shows that the operation of an exit jettison mechanism presents a considerable barrier to an individual attempting to escape from a fully inverted helicopter. If a helicopter came to rest on its side after capsize in a stable flotation position, the problem of operating exit jettison mechanisms may be much less severe. Occupants would have more time and could better orientate themselves, making it more likely that they could release the exit.

The external mounting of a life-raft may be the only realistic way that it can be used following the capsize of a helicopter to the fully inverted position. However, if a helicopter rests on its side after a capsize, the resulting air pocket may allow more time for a life-raft to be located and deployed. Rice and Greear (1973) have suggested that when a helicopter floats on its side, the escape hatches above the occupants may be unreachable, approximately 8 feet up. If this was the case it would be extremely difficult for a life-raft to be taken to the outside but, again, this could depend upon flotation angle and depth.

It may be concluded that many of the potentially life-threatening problems associated with reaching and opening exits in a fully inverted helicopter would be less severe if the aircraft was floating on its side. It is also probable that life-raft deployment may be more feasible from a side-floating helicopter.

1.3.5 Helicopter Underwater Escape Training

At the time of this report, the United Kingdom Offshore Operators Association (UKOOA) are responsible for developing and reviewing the guidelines for emergency training provided to offshore workers. It is then the role of the Offshore Petroleum Industry Training Organisation (OPITO) to develop training standards to meet the requirements of the UKOOA guidelines (Ramsay, 1996). The training providers are accredited by OPITO to provide courses which meet these standards. Although helicopter underwater escape training (HUET) is not mandatory for all aircrew and passengers involved in flying over water in helicopters, the offshore industry does impose HUET training on its workforce.

Helicopter underwater escape training has been emphasised repeatedly in the literature as important for preparing occupants of helicopters on what actions to take in the event of a ditching. As Haywood (1993) states: ‘the importance of timely emergency egress post crash, whether on land or at sea, is equally important. The hazards in each crash scenario, whilst obviously different (fire, water), nevertheless necessitate early egress from the wreckage to facilitate survival. In both scenarios survival beyond two minutes, post crash, is unlikely. The importance, therefore, of adequate safety or survival training (including briefings) cannot be over emphasised’.

In a real ditching, noise, poor light conditions, inrushing of water, oil, petrol and debris, may all cause confusion and hamper escape. Training is carried out under
safe and calm conditions. Hognestad (1993) stated that: 'simulators play a powerful role in the transfer of learning. Recreating potentially hazardous situations in a controlled environment offers the participant the ability to practice skills in a safe setting, free to make what would otherwise be tragic errors. By creating an environment as closely as possible to what could actually be expected to present in a given situation, the desired skills and knowledge can be reinforced through drill and practice.'

The military believe that it is imperative that personnel are trained to cope with the physical, physiological and psychological stress of helicopter emergency egress in order to maximise what little time is available in the event of an accident (Haywood, 1993). Both Haywood (1993) and Hytten (1989b) believe that the training develops a positive response outcome, nurtures the survival instinct or will to survive and improves the individual’s ability to cope with the stress of an emergency situation. The practical involvement provides clarification and confirmation of specific briefing points but, much more importantly, the physical experience will generate confidence. Coping is developed through repetition of controlled action in the training. Such a high level of training is not thought to be appropriate for the offshore workforce who may range in age from 18 to 70 years, who may not be physically fit and generally, only use helicopters to travel to work.

Research has shown that close physical fidelity (i.e. faithfulness to the real condition) is not necessarily required for the effective transfer of training from the helicopter simulator to the real situation (Summers, 1996). Task analysis should be performed to identify what skills and knowledge must be transferred to ensure effective learning and positive outcomes in the event of a real incident. Summers (1996) states that: 'skill learning does not require complete physical correspondence between the simulator and operational environments. What is needed is psychological or operational simulation rather than purely physical simulation'.

There is evidence to support the philosophy that HUET training improves the survival chances of those who ditch in a helicopter. As far back as 1973, Rice and Greear stated that: 'many of the individuals who have egressed from underwater helicopters indicated that helicopter simulator training markedly enhanced their chances of survival. Successful escape from a submerged, inverted aircraft may depend largely upon reflexive action, which can best be learned in a realistic underwater egress trainer'.

Statistics presented by Ryack et al (1986) showed that fewer than 8% of those who had received underwater escape training died in ditchings with capsizes, compared to more than 20% who had not received such training. This led him to believe that proper training would markedly reduce the number of such fatalities. A study of survivors of a Norwegian Army helicopter crash in the winter of 1988/89 (Hytten, 1989) highlighted the important role that helicopter simulator training had played for all survivors. It was reported that training had been decisive for successful escape, in particular helping to keep survivors calm and causing reflex conditioned behaviour. More recent studies have re-emphasised the critical role that training can have in preparing both crew and passengers for an emergency ditching (Bohemier & Morton, 1996; Haywood, 1996).

One disadvantage of HUET training is that it may cause anxiety. However, studies of offshore workers undergoing HUET training showed that repeated training
reduced feelings of anxiety. Heart rates of trainees undergoing their first, basic HUET were relatively higher than those undergoing refresher training (Harris, Coleshaw and MacKenzie, 1996). The heart rates which were elicited during the HUET exercises were found to be comparable, if not lower, than those that might be expected during moderate manual external work offshore.

2 FEASIBILITY TRIALS

2.1 Method

2.1.1 Preparation of the helicopter simulator

The helicopter simulator was customised to represent a Super Puma. Changes were made to make the escape process as realistic as possible, allowing comparison with escape from a real helicopter.

A visit was made to Bristow Helicopters Limited in Aberdeen, where measurements were taken from an operational Super Puma. These measurements included window dimensions and distances to exits. Following the visit it was possible to confirm that the seating arrangement in the helicopter simulator matched the rear and forward seats in a Super Puma cabin and that the distances from the seats to the exits were similar in both (Appendix 3).

In addition, aluminium window frames were fitted to the helicopter simulator which were of the same or very similar dimensions to Super Puma windows. Perspex push-out windows were fitted so that subjects would have to complete the action of pushing out a window during escape. Velcro rip-cords were attached to the window frames to simulate the rip cord on a real helicopter window, allowing the subjects to carry out an action required during a real escape.

Yacht fenders were used to simulate the proposed helicopter flotation system in order to assess their effect on the difficulty of escape. Two fenders of the appropriate size were attached securely to the port side of the helicopter simulator, one above each window.

A practical method was needed to ensure that the helicopter simulator would reliably come to rest at the desired side-floating position following capsize. The required capsize angle was achieved by application of the drum brake. A block was attached at the appropriate point on the drum rail so that the helicopter simulator would reliably come to rest at the same desired angle on each capsize. This angle was 150° from the vertical. The depth of submersion of the helicopter simulator was controlled by the operator.

To enable simulation of a reverse capsize, the block on the drum rail was moved, allowing a controlled capsize through 210°.

2.1.2 Protocol

The helicopter simulator was set up prior to the feasibility trials, with the flotation bags and window frames attached. The helicopter simulator was then capsized with no personnel on board to check that the correct angle could be achieved. Once the helicopter simulator was in the side-floating position at around 150°
from the vertical, training staff boarded the cabin to observe the angle of seats and predict the effect this would have on occupants who were strapped inside. They were allowed to explore the possibilities of escape and potential difficulties. Appendix 4 shows a view inside the cabin at 150°. Sources of potential risk of injury to someone escaping were also noted at this stage. The training staff were encouraged to identify any aspects of the escape which could cause problems.

Training Officers were used for the feasibility trial for safety reasons. All were qualified divers and so were comfortable inside the helicopter simulator and able to assess the potential problems. An escape route was agreed before each capsize for the training staff to test. The possible escape scenarios which were tested are listed in Table 1.

**Table 1 – Possible escape procedures tested in the feasibility trials**

<table>
<thead>
<tr>
<th>Seat position</th>
<th>Angle of roll</th>
<th>Escape route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starboard</td>
<td>150°</td>
<td>Underwater escape through starboard exit</td>
</tr>
<tr>
<td>Starboard</td>
<td>150°</td>
<td>Rise to air pocket then underwater through starboard exit</td>
</tr>
<tr>
<td>Starboard</td>
<td>150°</td>
<td>Rise to air pocket then out through port exit (above water)</td>
</tr>
<tr>
<td>Port</td>
<td>150°</td>
<td>Rise to air pocket then underwater through starboard exit</td>
</tr>
<tr>
<td>Port</td>
<td>150°</td>
<td>Rise to air pocket then out through port exit (above water)</td>
</tr>
<tr>
<td>Starboard</td>
<td>210°</td>
<td>Underwater escape through starboard exit</td>
</tr>
<tr>
<td>Starboard</td>
<td>210°</td>
<td>Rise to air pocket then underwater through starboard exit</td>
</tr>
<tr>
<td>Starboard</td>
<td>210°</td>
<td>Rise to air pocket then out through port exit (above water)</td>
</tr>
<tr>
<td>Port</td>
<td>210°</td>
<td>Rise to air pocket then underwater through starboard exit</td>
</tr>
<tr>
<td>Port</td>
<td>210°</td>
<td>Rise to air pocket then out through port exit (above water)</td>
</tr>
</tbody>
</table>

Information was gathered in the form of comments from the training staff as well as photographs and video recordings. The findings were used for two purposes. Firstly, a risk assessment was constructed to identify any part of the escape procedure which carried an unacceptable risk of injury. The modifications to the helicopter simulator, i.e. the window frames and flotation bags, were taken into account when assessing the safety requirements. A work assessment record was completed which included the scoring of hazards on a matrix to produce a quantitative measure of risk. This was used to determine whether the level of risk was acceptable. Any procedure which was thought to carry excessive risk was either amended to make it safer or completely discarded. Secondly, the results from the feasibility trials were used to help select a number of escape procedures which could be tested against corresponding escapes from a fully inverted helicopter.

On completion of the feasibility trials, escape procedures were agreed and protocols were drawn up. In helicopter underwater escape training it is considered important for trainees to build up a clear mental picture of egress, where the different actions form a pattern. Emphasis was therefore placed upon the development of ‘generic’ procedures which could be broken down into a
series of simple steps performed in a particular order. This was taken into account when developing procedures for escape from a side-floating helicopter.

2.2 Results

In total, 7 different subjects provided feedback from 5 different trial sessions in which escape from the side-floating helicopter simulator was tested. All subjects were experienced RGIT staff. Table 2 shows the most commonly identified issues and the number of subjects who raised them.

Table 2 – Most common issues identified from feasibility trials

<table>
<thead>
<tr>
<th>Problem issues</th>
<th>Number of reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficulty locating exit due to a person’s angle in the seat</td>
<td>2</td>
</tr>
<tr>
<td>Release problem with harness due to uneven weight distribution</td>
<td>3</td>
</tr>
<tr>
<td>Shoulder strap of harness twisting around neck area</td>
<td>2</td>
</tr>
<tr>
<td>Fall with force from upper seat</td>
<td>6</td>
</tr>
<tr>
<td>Which escape route to take when on lower side of helicopter simulator?</td>
<td>3</td>
</tr>
<tr>
<td>Difficulty going from air pocket to underwater exit</td>
<td>2</td>
</tr>
<tr>
<td>Difficulty getting foot purchase to pull through window on upper side</td>
<td>3</td>
</tr>
<tr>
<td>Better to exit window backwards</td>
<td>3</td>
</tr>
<tr>
<td>Disorientation worst in 210° roll</td>
<td>2</td>
</tr>
<tr>
<td>Bumping head</td>
<td>1</td>
</tr>
<tr>
<td>Escapee kicking to assist escape, presenting hazard</td>
<td>2</td>
</tr>
</tbody>
</table>

The major immediate concern for the trials was that when an occupant in an upper seat released their harness, their legs fell with considerable force toward the person in the lower seat on the opposite side of the cabin. It was concluded that individuals coming up from the lower seats would be at serious risk of injury from the forceful leg swing of people releasing from the upper seats. Furthermore, it was felt that someone might kick their legs to help them pull through an upper window which might injure occupants behind them. (This latter point was also true of current underwater escape procedures). Whilst this was a potential problem for the trials and future training, it was not thought likely to have any impact in the outcome of a real accident.

The issue of which escape route to take from an underwater seat was also raised. It was suggested that, in such a position, an individual might be inclined to make an immediate underwater escape from the exit next to them instead of first going to the air pocket. Going to the air pocket and then making an underwater escape was found to be problematic due to inherent buoyancy.
The four point harness caused two concerns. Firstly, it was predicted that an uneven load on the buckle might make it more difficult to release than normal. This was confirmed in practice on three occasions. Secondly, it was observed that once the harness had been released, a shoulder strap had the tendency to get caught around the neck of someone twisting to get clear of the harness and rise to the air gap. This was found to be due in part to the method of retracting the harness on release; the retraction system used in the simulator exerted less force than the system used in operational helicopters.

The issue of hand and footholds was raised. It was felt that handholds might be useful for maintaining contact with an exit whilst at an angle, and that footholds would be useful for an individual to push themselves through an exit on the upper side of the aircraft. On the subject of exiting from the upper side, it was noted that the safest method of leaving the exit would be to sit on the window ledge and then push backwards into the water. This method allowed the subject to present their back to any potential oncoming waves, and keep the face pointing upwards, reducing the potential risk of drowning from further head immersion.

As a final point, it was reported by two subjects that the 210° capsize caused the greatest disorientation of any of the side-floating exercises. The subjects said that this was because of the extra roll, which came unexpectedly after the helicopter simulator had gone through 180°, increasing the sense of disorientation.

**Discussion**

The results of the feasibility trial were used to develop the procedures and protocols for the comparison trials using naïve subjects.

The risk assessment resulted in a restriction to the number of naïve subjects who would be allowed to escape from the helicopter simulator at any one time. It was decided to restrict this number to two, both sitting on either the starboard or port side of the helicopter simulator. This would ensure that a subject in an upper seat would not fall down onto a subject in an underwater seat, risking injury.

Issues relating to the harness caused some concern. These were given due consideration during the naïve subject trials to assess whether harness release affected the reported ease of escape. Further work is needed to determine the best system of buckle release for a side-floating helicopter.

Hand and footholds close to windows and exits deserve consideration for future designs of helicopter. They are likely to ease the process of escape, particularly in real situations in which the occupant has released the seat harness before reaching a window or exit. In such cases, the individual would need some leverage to push out a window. Hand and footholds could help to provide leverage.

The additional disorientation identified by the trained staff during the 210° capsize may be explained by the experience of the staff who were habituated to the more normal 180° roll by repeated regular exposure. The degree of roll was likely to be much less obvious to a naïve subject.
2.4 Development of capsize scenarios

The escape procedures following capsize which were chosen for the side-floating trial were those in which subjects would take advantage of the perceived benefits of escape from a side-floating helicopter, namely the air pocket and the fact that exits are above the water on one side. As a result, it was decided that in escapes from the side-floating helicopter simulator, subjects should always rise to the air pocket before escaping from an above water exit, irrespective of where they were sitting.

A series of exercises was developed which would allow side-floating escape to be compared to conventional fully inverted escape. The first exercise simulated a surface ditching, allowing all occupants to evacuate through the cabin door into a helirraft. The second exercise was a slow immersion without capsize when the helicopter simulator slowly sank and occupants escaped from the underwater windows and door. The capsize exercises were developed to include escape from seats on each side of the helicopter simulator. In each case, subjects were required to exit through a port side window. They also included a reverse roll capsize, with subjects escaping from the nearby port window. This was thought to provide a representative coverage of the possible escape scenarios.

The first capsize selected was subjects sitting on the starboard side followed by a 150° roll and then escape through one of the above-water port windows. This was known as a ‘cross-cabin escape’. Subjects would have to release from their harnesses, surface in the air gap and then escape through the opposite above-water exit. The second capsize was the same except that subjects sat on the port side, labelled the ‘same-side escape’. This would involve the subjects having to release from a seat which rested mostly above water after the capsize, falling down from the air gap into the flooded cabin and then escaping by the above-water exit next to their seat. The third and final capsize chosen was subjects sitting on the port side, a reverse 210° roll capsize and then escape through the nearby above-water port exit. This was included to simulate a wave striking the side of the aircraft which does not have the added buoyancy and was called ‘reverse capsize escape’. It should be noted that, in this case, the helicopter still came to rest at 150° but had to roll through 210° to get there.

Each of the side-floating escape procedures was matched to a corresponding fully inverted escape procedure in terms of using the same seat, the same direction of roll and the same target exit for escape. By controlling these factors, it was more valid to attribute any differences between the escapes to the floating angle of the helicopter simulator and the corresponding escape procedure. The capsizes were ordered so that they had a small increase in difficulty each time, in a way that would build up the confidence of a subject. The procedures were incorporated into a draft lesson plan and multi-media briefing. The lesson plan was reviewed to assess its suitability for use by naïve passengers and amended accordingly before implementation within the naïve subject trials.
3 NAÏVE SUBJECT TRIALS

3.1 Method

3.1.1 Overview

To assess the benefits or disbenefits of escape from the side-floating helicopter, trials were carried out using naïve subjects who had no pre-conceived views or experience of helicopter escape. Thirty subjects were recruited, each subject completing two trials. In one, three escapes were carried out from a fully inverted helicopter following a 180° capsize. In the other, the subjects carried out three escapes from a side-floating helicopter following capsizes of either 150° or 210°. Ethical approval for the study was obtained from Grampian Research Ethics Committee.

It was considered desirable to record objective as well as subjective measures of performance during the trials. Subjects were required to complete a questionnaire before and after each trial, which asked them to rate their perception of the difficulty associated with each escape.

Physiological and psychological measurements were taken at various intervals during the trials to assess the subjects' levels of anxiety. Cortisol production has been shown to increase in response to demanding and stressful situations (Bohnen et al, 1991; Harris et al, 1996; Selye, 1980). Cortisol in saliva provides an acute measure of stress, an increase in cortisol concentration reflecting physiological activation within the previous 20 to 90 minutes. Samples of saliva were collected at intervals throughout each trial. Cortisol levels in urine provide a chronic measure of stress and the psychological status of the subject. Samples of urine were collected early in the morning (overnight sample) on the day of each trial.

Anxiety levels were measured using Spielberger et al’s (1983) State/Trait Anxiety Inventory (STAI) to provide an indicator of subjectively experienced stress. The STAI was chosen due to its wide recognition in the scientific literature and its applicability over a wide range of stressors (see Harris, 1995; Harris et al, 1996).

It is well established that heart rate is related to the metabolic requirements of the body (Anastasiades & Johnston, 1990). There is also evidence of a relationship between heart rate and stressful situations, heart rate increasing with anxiety (Fuller, 1992; Hodges & Spielberger, 1966). Subjects were fitted with heart rate monitors (Polar), providing a continuous record of heart rate throughout each trial. Data was later down-loaded onto computer. In order to separate the effects on heart rate of physical effort and anxiety, activity records were completed for each subject, providing precise times when subjects were carrying out activities such as sitting, walking or swimming.

Each trial was filmed from the pool-side to allow escape time to be measured accurately by stopwatch. Underwater cameras were used to record the escapes and provide evidence of any problems experienced by the subjects.
3.1.2 Subject recruitment

A total of 30 subjects were recruited from 3 age ranges (18 – 29, 30 – 39, 40 – 49 years) with ten subjects from each category. An upper age limit of 50 years was set for medical ethics reasons. The subjects were to be predominantly male and cover a range of body heights and builds. This was intended to represent the profile of the offshore population as far as possible. Recruitment took the form of distributing a poster to advertise the need for volunteers and spreading information about the study verbally. The recruitment criteria were that subjects had to be reasonable swimmers and not have any previous experience of helicopter underwater escape training. Potential volunteers were issued with written information describing the study and had a chance to discuss the study with one of the research team. If they were happy to take part they were required to provide written, witnessed consent and fill in a medical screening form.

3.1.3 Experimental trial programme

Each subject completed one trial with egress from the capsized and fully inverted helicopter simulator using current training procedures (the control condition) and one trial with egress from the side-floating helicopter simulator using the new procedures. Only two subjects at a time were allowed in the helicopter simulator for a side-floating capsize, seated one at each end, to reduce the risk of injury. Consequently, in order to make valid comparisons, only two subjects were in the helicopter simulator at any one time for capsize to the fully inverted position.

The order of carrying out the trials was randomised so that half of the group used the fully inverted (control) procedures first, and the other half used the new side-floating procedures first. This was done to remove any order or training effects which might affect subjects’ preferences and perceptions of difficulty. The two trials were separated by at least a week but by no more than a month. All trials were started at roughly the same time of day.

An initial briefing was completed at least a day before the trial itself. Subjects were provided with written information about the trials and asked questions before filling in a consent form. They also completed Spielberger’s state and trait anxiety questionnaires (Spielberger et al, 1983) and supplied a saliva sample to provide control measures of their anxiety. They were also given a sample bottle in order to take a urine sample on the morning before their first trial.

When subjects arrived for a trial they were seated in a warm room and checks were made that they had received written information, given consent, and had completed and passed a medical screening procedure. The trial programme was then explained.

Subjects provided the first saliva sample after washing out their mouth with water. Next, ‘Polar’ heart rate monitors were fitted. This involved subjects putting on a chest band transmitter and a wrist watch monitor to receive and store the signal. Subjects were instructed to start their monitors in synchronisation with each other. At the same time a member of the research team started a stopwatch and recorded the time. This enabled heart rate recordings to be linked to events in time recorded on activity sheets. The final part of the initial session was for subjects to complete a pre-trial evaluation questionnaire assessing how
each individual thought they would perform during the trials, i.e. their perceived efficacy. Before their first trial they were also asked to fill in some background information such as swimming ability and physical fitness.

Subjects were then transferred to a classroom for a multi-media briefing to train them in the helicopter escape techniques which they were due to undertake. After the briefing, a second saliva sample was taken. Subjects were then taken to the RGIT Environmental Tank where they donned a helicopter immersion suit and a lifejacket over jeans, shirt, jumper and socks. Training shoes were worn over the immersion suit and subjects wore a safety helmet. Finally, just before starting the HUET exercises, subjects gave a pre-trial saliva sample and completed a pre-trial state anxiety questionnaire.

The escape procedures tested in the naïve subject trials are shown in Table 3. They are displayed in the order in which they were undertaken in the trial, i.e. with a small increase in difficulty each time. It should be noted that it was the corresponding capsizes in terms of position of seating, direction of roll and target exit that were compared.

<table>
<thead>
<tr>
<th>Table 3 – Escape procedures tested in naïve subject trials</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Escape procedures after 180° capsizes to fully inverted position</th>
<th>Escape procedures after 150°/210° capsizes to side-floating position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Surface evacuation</td>
<td>1. Surface evacuation</td>
</tr>
<tr>
<td>2. Partial submersion, port seats leaving by port windows</td>
<td>2. Partial submersion, port seats leaving by port windows</td>
</tr>
<tr>
<td>4. Escape After Reverse roll – 180° reverse fast capsize, port seats leaving by port windows</td>
<td>4. Same-side Escape – 150° fast capsize, port seats leaving by port windows</td>
</tr>
<tr>
<td>5. Cross-cabin Escape – 180° fast capsize, starboard seats leaving by port windows</td>
<td>5. Escape After Reverse roll – 210° reverse fast capsize, port seats leaving by port windows</td>
</tr>
</tbody>
</table>

During the trials, the timing of events was carefully recorded. This included making notes on escape success and recording escape time. This was supplemented by a video record of the exercises from the pool-side and from two underwater cameras mounted inside the helicopter simulator. Both underwater cameras were mounted on the starboard side, one at roof level and one at floor level.

Once all escapes had been completed the subjects left the pool and provided another saliva sample as well as completing the post-trial state anxiety questionnaire. They then showered and changed before proceeding back to the classroom. In the final part of the trial, subjects were required to complete a post-trial evaluation questionnaire, rating each capsize in terms of the difficulty to escape. Subjects were also asked questions about their confidence before and after the trials and how satisfied they were with the way they had coped in the
exercises. After this, subjects gave the final saliva sample of the trial and removed the heart rate monitor which signalled the end of a trial.

3.1.4  

Management and analysis of data

3.1.4.1 Heart rate

After each trial, the heart rate data stored by the wristwatch receiver was downloaded onto computer via an interface. Data was transferred into a software package where it was saved as a file. The software package provided several options for analysing the heart rate data. Heart rates were plotted over the course of each trial. The sampling rate was once every 5 seconds.

Heart rate averages were calculated for particular periods of time. Of interest in this study was the level of heart rate before each trial, during the exercises and after a trial had finished. A pre-trial average was taken over a 5 minute period before subjects went to the pool-side. This was selected by visual inspection of each heart rate graph and by identifying a 5 minute period of steady state resting heart rate. An average heart rate was also taken for the critical phase of each partial submersion exercise and each capsize exercise. The start of these sampling periods was marked at 10 seconds before the helicopter simulator started its descent, running until the subject’s head was clear of the water. The time period thus varied between subjects but covered the same activities. Once subjects had completed the trial, a resting post-trial average was taken using the same rationale employed for the pre-trial average.

Statistical comparisons were made between average heart rates in the side-floating and fully inverted exercises. Paired sample t-tests were used to test if there were any differences in subjects’ heart rates before, during and after the escape exercises, depending on the type of trial, and any differences between trials. Heart rate was tested for any effects of age using a one way analysis of variance (ANOVA).

3.1.4.2 Urinary and salivary cortisol

Urine samples were brought to each trial by the subjects, who had taken them on that morning. The samples were immediately placed in a freezer. As described in 3.1.3, a control saliva sample was taken a day before the first trial. Further samples were taken on the day of each trial; on arrival, after the briefing, immediately before entering the pool, immediately after leaving the pool and at the end of proceedings. Saliva samples were frozen directly after each trial. All samples were given a unique identifier which included the subject number, whether it was their first or second trial, the type of trial, the time the sample was taken and the date.

After the trials had been completed, it was necessary to decide which of the saliva samples that subjects provided over the course of a single trial should be analysed to provide the most meaningful results. To this end, all the serial saliva samples from three subjects were analysed and the results were plotted in graph form. This indicated that the biggest difference in cortisol was between the first saliva sample of the trial (on arrival) and the one taken immediately on leaving the pool after the subject had completed the escape exercise.
Consequently, it was decided that the samples taken at these two times would be analysed for all subjects in both trials as well as the control sample taken at least a day before the first trial. This meant that five saliva samples were analysed for each subject as well as their two early morning urine samples.

Samples were sent to a qualified professional for analysis using a standardised immunoassay kit (DRG Instruments), providing a quantitative measurement of cortisol (Haeckel, 1990). This biochemist was not told the code used to identify individual samples and was therefore blind to the timing, and relevance, of each sample.

The values of salivary cortisol were compared using paired sample t-tests to determine if the level of cortisol before and after the escape exercises was significantly altered depending on the trial. The same test was used to compare the control samples and those taken during the trials. In addition, the levels of cortisol found in this study were compared to those reported from other populations.

3.1.4.3 State / trait anxiety questionnaires

Subjects completed the Spielberger (1983) state and trait anxiety questionnaire during the initial briefing. They then repeated the state questionnaire before and after the escape exercises in each trial. The questionnaires were scored according to a template. This provided one trait anxiety score and five state anxiety scores for each subject.

The state anxiety scores from the side-floating trial were statistically compared to those from the fully inverted trial. The state anxiety scores from before and after each pool session were assessed using paired sample t-tests to assess whether subjects' were significantly more anxious in one trial compared to the other. The same test was used to compare the control scores with those from during the trials. Levels of state and trait anxiety taken from this study were compared to those reported elsewhere in the literature.

3.1.4.4 Perceptions of difficulty, confidence and coping

These were measured by way of pre-trial (perceived efficacy) and post-trial evaluation questionnaires which each subject completed. Before the first trial subjects were asked about their general confidence in helicopter transport. Before each trial subjects were asked to rate how confident they were about escape in the exercises. After each trial they were asked to re-assess their level of confidence, to rate how satisfied they were with the way they coped in the session and to rate how they felt they would cope in a real helicopter ditching.

Subjects were also asked about the general difficulty of each capsize escape and to rate 10 factors in terms of how difficult they were. These included disorientation, releasing the harness, finding the exit and getting snagged. Each answer was given a score along an ordinal scale which made it possible to statistically compare the perceptions from the side-floating trials with those from the fully inverted trials. Copies of first and second trial questionnaires are given in Appendix 5.
A Wilcoxon Matched-Pairs Signed-Ranks test was used to compare the difficulty scores given to the side-floating escapes with those given to the corresponding fully inverted escapes. Similarly, this test was used to compare the confidence and coping scores from each trial.

3.1.4.5 Escape and submersion times

Escape times were always taken from when the floor of the helicopter simulator made contact with the water to when subjects surfaced outside the simulator with their mouth clear of the water. This time was recorded by stopwatch and checked using the video footage.

Submersion times were taken from the video footage of the trials. This came from a pool-side camera and two underwater cameras inside the helicopter simulator. The separate footage was edited so that the three different synchronised views could be seen at the same time on one screen. This made it possible to accurately judge the time from when a subject took a breath to when they surfaced.

For submersion time in the partial submersion, the time was taken from when subjects took a breath before being submerged to when they surfaced outside the helicopter simulator with their mouth clear of the water. The same was true for the fully inverted capsizes. In the side-floating capsizes, submersion time was taken from when subjects took a breath before submersion to when they rose to the air pocket inside the side-floating helicopter simulator with the mouth clear of the water.

Even when the time a breath was taken was unclear, e.g. when subjects were sat on the same-side of the simulator as the underwater cameras, there was still enough information in the video to allow a good estimation of the submersion time to be made.

Escape and submersion times from each trial were compared using statistical analysis. The escape and submersion times from the fully inverted trial were compared to those from the side-floating trial, using paired sample t-tests to determine any significant differences. Additional testing was carried out on the ratings from the cross-cabin exercises. This was because only 15 out of 30 subjects made a cross-cabin escape, as instructed, from the fully inverted helicopter simulator. As a result, an independent samples t-test was used to compare the submersion times of the subjects who made a ‘successful’ escape from this scenario with the ratings from the subjects who did not.

3.1.4.6 Statistical significance

For all statistical comparisons, a probability of P<0.05 was taken to be significant.

3.2 Results

3.2.1 Background

A total of 30 naïve subjects, aged 18 to 49 years, completed the side-floating and the fully inverted trials. Subjects were naïve in that none had experienced HUET training before. Fifteen took part in the side-floating trial first and the other 15
went through the fully inverted trial first. This was to control for any order effect. Table 4 shows the average height and weight of the subjects, demonstrating a wide range of body morphologies.

Table 4 – Average height and weight of subjects

<table>
<thead>
<tr>
<th></th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>175.6</td>
<td>82.4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>6.9</td>
<td>14.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>187.5</td>
<td>111.2</td>
</tr>
<tr>
<td>Minimum</td>
<td>162.5</td>
<td>57.0</td>
</tr>
</tbody>
</table>

It can be seen from Table 5 that the majority of subjects rated themselves as being moderately fit, moderately good swimmers, moderately confident about helicopter transport and had no previous knowledge of helicopter underwater escape.

Table 5 – Subjects’ background

<table>
<thead>
<tr>
<th>Variable</th>
<th>Responses %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical fitness</td>
<td>Unfit 6.7</td>
</tr>
<tr>
<td>Swimming ability</td>
<td>Non-swimmer 3.3</td>
</tr>
<tr>
<td>Confidence in helicopter transport</td>
<td>None 0.0</td>
</tr>
<tr>
<td>Previous knowledge of HUET</td>
<td>No 93.3</td>
</tr>
</tbody>
</table>

3.2.2 Perceived worry

Before each trial, subjects were asked to rate 10 factors in terms of how worried they were that the factor might affect their escape (perceived efficacy).

Figure 1 shows that the factor causing most concern before the first trial was disorientation, with 43.3% of subjects moderately worried about it. Finding the exit was also reported to be an issue with 30% expressing moderate worry in relation to this factor. Figure 1 indicates that, overall, for all factors, the majority of subjects were either not worried or only a little worried.
3.2.3 Difficulty ratings after the trials

3.2.3.1 Overall difficulty

Table 6 provides information about how difficult subjects found each capsize. It is clear that the fully inverted cross-cabin capsize was found much more difficult than the side-floating equivalent. In the former, 89% found escape moderately or very difficult compared to only 29% in the latter. This difference was significant at the \( P = 0.0001 \) level.

Table 6 – Subjects’ rating of capsize difficulty

<table>
<thead>
<tr>
<th>CAPSIZE</th>
<th>RATING (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No difficulty</td>
</tr>
<tr>
<td>Fully inverted cross-cabin</td>
<td>0</td>
</tr>
<tr>
<td>Side-floating cross-cabin*</td>
<td>23</td>
</tr>
<tr>
<td>Fully inverted same-side</td>
<td>16</td>
</tr>
<tr>
<td>Side-floating same-side</td>
<td>26</td>
</tr>
<tr>
<td>Reverse fully inverted</td>
<td>23</td>
</tr>
<tr>
<td>Reverse side-floating</td>
<td>20</td>
</tr>
</tbody>
</table>

*Side-floating exercise significantly less difficult than fully inverted exercise \( (P=0.0001) \)
In the escape from the same-side exit following the fully inverted capsize, less people had no or little difficulty and more people had moderate difficulty compared to the equivalent side-floating exercise. The difficulty ratings for the reverse capsizes were closely matched.

3.2.3.2 Cross-Cabin Capsizes

Figures 2 and 3 allow comparison to be made between the difficulty of specific factors in the fully inverted cross-cabin capsize and the side-floating cross-cabin capsize.

Of particular note when comparing the cross-cabin capsizes is the fact that 15 subjects (50%) failed to complete this escape correctly when the helicopter simulator was fully inverted. Ten of these subjects were forced to rise to the air pocket inside the helicopter simulator and the other 5 escaped through their nearest exit instead of crossing the cabin. In the side-floating trial, everyone successfully completed the cross-cabin escape.

Bearing this in mind, it is understandable that the most striking differences between Figures 2 and 3 are the difficulty ratings for ‘disorientation’ and for ‘finding the exit’, in that both were found significantly more difficult (P = 0.005 and P = 0.0001 respectively) in the fully inverted cross-cabin escape. In the fully inverted trial, disorientation made cross-cabin escape ‘very difficult’ for 56.7% of the sample with the same percentage reporting that finding the exit was very difficult. In the side-floating cross-cabin escape, the corresponding figures were 20% and 3.3% respectively.

Another factor which was found significantly more difficult in the fully inverted cross-cabin exercise was ‘exiting through the window’ with 26.7% finding it ‘very difficult’ compared to no one finding it ‘very difficult’ in the side-floating cross-cabin escape. This difference was significant (P = 0.0051) and is hardly surprising considering the fact that 50% of subjects failed to even get to the required exit in the fully inverted cross-cabin exercise.

Finally, there was a significant difference (P = 0.041) between the levels of difficulty with swimming in the trials, with subjects rating it as more difficult in the fully inverted cross-cabin escape, in which they had to swim underwater. This was not even a feature of the side-floating equivalent. Linked to this was the fact that breath holding was rated as more difficult in the fully inverted cross-cabin escape, although the difference was not significant.

It was something of a surprise that the ratings of breath holding difficulty were not significantly different for the cross-cabin escapes given that one required substantial breath holding and the other a breath hold of only a few seconds. As a result, this issue was looked at in more detail. Due to the fact that 15 subjects did not complete the escape from the fully inverted helicopter simulator as intended, it was decided that these subjects should be treated as a separate group. This group’s breath hold ratings were compared to the ratings from the other 15 subjects who did successfully complete this escape. It was found that the former rated breath holding as significantly more difficult than the latter at the P = 0.02 level of significance.
Figure 2 - Subjects' rating of difficulty factors in the FULLY INVERTED cross cabin capsize

Figure 3 - Subjects' rating of difficulty factors in the SIDE-FLOATING cross cabin capsize
Further comparisons were made in order to investigate if there was any difference between the sub-group's cross-cabin breath hold ratings depending on whether the trial was fully inverted or side-floating. No significant difference was found between the fully inverted and side-floating cross-cabin breath hold ratings reported by those who were successful in the fully inverted trial. It was hypothesised that those who failed the fully inverted cross-cabin would rate breath hold as being significantly easier in the side-floating cross-cabin escape. In fact, no significant difference was found. The higher level of difficulty in both exercises suggests that these subjects found breath holding to be difficult per se.

It should be noted that in the fully inverted trials, subjects who rose into the safety air gap 'opted out' rather than continue to hold their breath and make an escape.

3.2.3.3 Sit/escape same-side capsizes

Figures 4 and 5 show how much difficulty was caused by the specific factors in the escapes from the fully inverted and side-floating capsizes when subjects were seated on the same-side as the exit window.

Differences between the difficulty ratings are less marked than those for the cross-cabin capsizes. However, a similar trend was found in that 40% of subjects found disorientation to be moderately or very difficult in the fully inverted same-side escape, compared to only 20% in the side-floating equivalent, although this difference was not significant. Subjects did rate holding their breath as being more difficult in the fully inverted same-side escape than in the corresponding side-floating exercise and this was significant (P = 0.043). This trend was also noted in the cross-cabin escapes and can be accounted for by subjects using the air pocket in the side-floating exercises and not needing to hold their breath for long.

3.2.3.4 Reverse Capsizes

Figures 6 and 7 show the levels of difficulty reported from the escapes after the reverse capsizes. Contrary to the findings so far, these figures show that disorientation caused more difficulty in the side-floating exercise. This can be explained by the fact that the roll was 210° in this capsize, the longer turn causing added disorientation. Also, this was the last fully inverted capsize with no added difficulty, which may have influenced this comparison.

Perhaps as a result of the added disorientation, subjects rated locating the exit as being significantly more difficult in the side-floating reverse capsize (P = 0.03), although the fact that they were in the air pocket allowed them time to orientate themselves. Subjects also reported more difficulty releasing their harness in this exercise (P = 0.05), which had also been observed in the feasibility trials and was thought to be because of the uneven load on the buckle with the body also out of the water.
Figure 4: Subjects' rating of difficulty factors in the FULLY INVERTED same side capsize

Figure 5: Subjects' rating of difficulty factors in the SIDE-FLOATING same side capsize
Figure 6 - Subjects' rating of difficulty factors in the FULLY INVERTED reverse capsize

Figure 7 - Subjects' rating of difficulty factors in the SIDE-FLOATING reverse capsize
3.2.3.5 Summary of results

Table 7 provides a summary of the significant differences which were found when statistical comparisons were made between the difficulty ratings for the corresponding fully inverted and side-floating capsizes.

Table 7 – Significant differences between difficulty ratings

<table>
<thead>
<tr>
<th>Capsizes</th>
<th>Significant Differences</th>
<th>'P' Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-cabin</td>
<td>Fully inverted rated as overall more difficult than side-floating</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Locating exit rated as being more difficult in fully inverted</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Disorientation rated as causing more difficulty in fully inverted</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Exiting window rated as being more difficult in fully inverted</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Swimming rated as causing more difficulty in fully inverted</td>
<td>0.04</td>
</tr>
<tr>
<td>Same-side</td>
<td>Holding breath rated as being more difficult in fully inverted</td>
<td>0.04</td>
</tr>
<tr>
<td>Reverse</td>
<td>Locating exit rated as being more difficult in side-floating</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Releasing harness rated as being more difficult in side-floating</td>
<td>0.05</td>
</tr>
</tbody>
</table>

3.2.4 Post trial evaluations

When subjects were asked which trial they preferred in terms of ease of escape, 90% opted for the side-floating escape. This gives an indication of the lower levels of difficulty which subjects experienced during escape from the side-floating helicopter simulator compared to underwater escape.

Before the subjects had been through either trial they were asked how confident they were about helicopter transport. They were then asked how confident they were about helicopter transport after each trial. Table 8 shows that confidence in helicopter transport was almost exclusively moderate or high throughout the whole study period. The confidence level before the trials was compared to confidence after each trial and no significant differences were found. Confidence in helicopter transport after the fully inverted trial was then compared with confidence in helicopter transport after the side-floating trial and again there was no significant difference.
Table 8 – Subjects’ confidence in helicopter transport

<table>
<thead>
<tr>
<th>Level of confidence in helicopter transport</th>
<th>Before study</th>
<th>After fully inverted capsizes</th>
<th>After side-floating capsizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>37%</td>
<td>37%</td>
<td>30%</td>
</tr>
<tr>
<td>Moderate</td>
<td>63%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>Low</td>
<td>0%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>None</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

As well as general confidence, subjects were asked specifically before each trial how confident they were about escaping from the helicopter simulator. Irrespective of which trial was undertaken first, there was no significant difference between the confidence levels before the trials.

After each trial, subjects were asked how satisfied they were with the way they had coped with the helicopter escape. Table 9 shows that subjects were more satisfied with their coping in the side-floating capsizes than they were in the fully inverted capsizes. In the side-floating trial, 96% of people were either satisfied or very satisfied with how they had coped. This compares to only 76% in the fully inverted trial, with 10% being undecided and 13% being dissatisfied with their coping in this trial. Statistical analysis showed that this difference was significant (P = 0.019).

Table 9 – Subjects’ satisfaction with coping in the trials

<table>
<thead>
<tr>
<th>Level of satisfaction with coping</th>
<th>Fully inverted capsizes</th>
<th>Side-floating capsizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very satisfied</td>
<td>23%</td>
<td>33%</td>
</tr>
<tr>
<td>Satisfied</td>
<td>53%</td>
<td>63%</td>
</tr>
<tr>
<td>Undecided</td>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td>Dissatisfied</td>
<td>13%</td>
<td>3%</td>
</tr>
</tbody>
</table>

After each trial, subjects were also asked how much more confident they felt of coping with a real helicopter ditching compared to before the session. Table 10 shows that 46% of subjects felt much more confident of coping with a real ditching after the fully inverted trial compared to only 36% after the side-floating trial. It is speculated that this may reflect a greater feeling of achievement after the underwater escapes. Overall, a higher percentage reported improved confidence and a lower percentage had less confidence following the side-floating trial.
Table 10 – Subjects’ confidence to cope with a real helicopter ditching after each trial

<table>
<thead>
<tr>
<th>Confidence to cope with a real helicopter ditching</th>
<th>After fully inverted capsizes</th>
<th>After side-floating capsizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Much more</td>
<td>46%</td>
<td>36%</td>
</tr>
<tr>
<td>More</td>
<td>23%</td>
<td>43%</td>
</tr>
<tr>
<td>About the same</td>
<td>16%</td>
<td>16%</td>
</tr>
<tr>
<td>Less</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>Much less</td>
<td>3%</td>
<td>0%</td>
</tr>
</tbody>
</table>

3.2.5  **Physiological correlates of stress**

3.2.5.1 Heart rate

Heart rate traces showed a large degree of noise. However, most traces showed peaks in heart rate as the subject swam across the pool, followed by a peak of similar amplitude which could be time matched to the period spent preparing for ditching and escaping from the helicopter simulator. Appendix 6 shows a typical heart rate trace.

Table 11 – Mean heart rates before, during and after the trials

<table>
<thead>
<tr>
<th>Trial</th>
<th>Sampling period</th>
<th>Mean heart rate</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully inverted</td>
<td>Pre-trial / resting</td>
<td>71</td>
<td>10.2</td>
</tr>
<tr>
<td>Side-floating</td>
<td>Pre-trial / resting</td>
<td>73</td>
<td>10.7</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>During partial submersion</td>
<td>120</td>
<td>23.8</td>
</tr>
<tr>
<td>Side-floating</td>
<td>During partial submersion</td>
<td>124</td>
<td>23.0</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>During 1st capsize: sit/escape same-side</td>
<td>120</td>
<td>22.4</td>
</tr>
<tr>
<td>Side-floating</td>
<td>During 1st capsize: cross-cabin escape</td>
<td>122</td>
<td>17.1</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>During 2nd capsize: reverse roll</td>
<td>121</td>
<td>19.3</td>
</tr>
<tr>
<td>Side-floating</td>
<td>During 2nd capsize: sit/escape same-side</td>
<td>122</td>
<td>18.1</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>During 3rd capsize: cross-cabin escape</td>
<td>124</td>
<td>18.9</td>
</tr>
<tr>
<td>Side-floating</td>
<td>During 3rd capsize: reverse roll 210°</td>
<td>122</td>
<td>23.6</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>Post-trial</td>
<td>91</td>
<td>13.7</td>
</tr>
<tr>
<td>Side-floating</td>
<td>Post-trial</td>
<td>87</td>
<td>15.3</td>
</tr>
</tbody>
</table>
Table 11 shows the average heart rates recorded before, during and after each trial. The average heart rate for each escape was calculated. It can be seen that there was very little difference between heart rate in each trial suggesting that the type of escape did not influence the level of heart rate.

Using statistical analysis, pre-trial heart rate was compared between the different age groups and no significant differences were found. Also, the average heart rates during the exercises were compared between trials and no significant differences were found. It can be concluded from this that the type of escape had no influence on the level of heart rate in these trials.

3.2.5.2 Cortisol

The average salivary cortisol values are shown in Table 12. A high degree of variability in cortisol levels was observed. Statistical analysis showed no significant differences either within or between trials. None of the values were significantly different from the average control value.

Table 12 – Mean salivary cortisol values

<table>
<thead>
<tr>
<th>Trial</th>
<th>Sample</th>
<th>Mean cortisol value (nmol/litre)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Pre-trial</td>
<td>15.3</td>
<td>10.17</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>Pre-trial</td>
<td>12.5</td>
<td>18.11</td>
</tr>
<tr>
<td>Fully inverted</td>
<td>Post-exercises</td>
<td>16.0</td>
<td>11.41</td>
</tr>
<tr>
<td>Side-floating</td>
<td>Pre-trial</td>
<td>15.3</td>
<td>26.44</td>
</tr>
<tr>
<td>Side-floating</td>
<td>Post-exercises</td>
<td>16.3</td>
<td>9.03</td>
</tr>
</tbody>
</table>

The average urinary cortisol, expressed as a ratio against creatinine concentration (see Harris, 1995 for rationale), recorded before each trial is shown in Table 13. It can be seen that the average values were similar before both trials. No significant differences were found between urinary cortisol values depending on either the escape procedure to be followed in the trial or which trial was undertaken first. Again, the variability was high for these values as suggested by the standard deviation.

Table 13 – Mean urinary cortisol values

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean cortisol/creatinine (nmol/mmol)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre fully inverted trial</td>
<td>105.78</td>
<td>58.3</td>
</tr>
<tr>
<td>Pre side-floating trial</td>
<td>110.05</td>
<td>60.5</td>
</tr>
</tbody>
</table>
3.2.6 Psychological stress

Table 14 shows the average state/trait anxiety inventory (STAI) scores which were recorded from these trials. It can be seen that anxiety levels were highest before each trial but had returned to around the control level immediately after completion of the exercises. Statistical analysis showed that the pre-trial anxiety ratings were significantly higher than post trial ratings (P = 0.0005 in each case) and were significantly higher than the control ratings (P = 0.0005 in each case). No significant difference was found when the anxiety in the standard trial was compared to anxiety in the side-floating trial.

Table 14 – Mean STAI scores

<table>
<thead>
<tr>
<th>Time period</th>
<th>Mean trait score (standard deviation)</th>
<th>Mean state score (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>33 (6.6)</td>
<td>30 (7.2)</td>
</tr>
<tr>
<td>Pre- fully inverted exercises</td>
<td>-</td>
<td>39 (9.7)</td>
</tr>
<tr>
<td>Post- fully inverted exercises</td>
<td>-</td>
<td>31 (8.2)</td>
</tr>
<tr>
<td>Pre- side-floating exercises</td>
<td>-</td>
<td>41 (10.8)</td>
</tr>
<tr>
<td>Post- side-floating exercises</td>
<td>-</td>
<td>30 (8.6)</td>
</tr>
</tbody>
</table>

3.2.7 Escape and submersion times

Escape and submersion times were recorded for each trial. These were taken from video footage recorded from inside the helicopter simulator and from the pool-side.

Table 15 shows that mean escape times were much longer in the side-floating capsizes. This was due to the fact that subjects were able to use the air pocket inside the helicopter simulator and breath normally before assessing the situation and making their way to the outside. This extra time could be vital in allowing occupants of a capsized helicopter to orientate themselves and carry out the vital actions necessary to make an escape.

The average submersion time for each exercise is shown in Table 16. It should be noted that these calculated means only include times when the escape was achieved using the set down procedure. If subjects used the safety air pocket or wrong exit, or were unable to escape without assistance, then the submersion times from these escapes were not included in the mean. As a result, each average value can be firmly attached to a specific escape scenario. In a few cases, it was not possible to calculate the submersion time because underwater footage was not available.
Table 15 – Mean escape times from the trials

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Mean escape time (seconds)</th>
<th>Standard deviation</th>
<th>No. escapes included in calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial submersion</td>
<td>39.1</td>
<td>3.8</td>
<td>60</td>
</tr>
<tr>
<td>Fully inverted sit/escape same-side</td>
<td>15.0</td>
<td>3.1</td>
<td>29</td>
</tr>
<tr>
<td>Fully inverted reverse</td>
<td>13.7</td>
<td>2.9</td>
<td>30</td>
</tr>
<tr>
<td>Fully inverted cross-cabin</td>
<td>22.0</td>
<td>3.2</td>
<td>15</td>
</tr>
<tr>
<td>Side-floating sit/escape same-side</td>
<td>26.1</td>
<td>6.5</td>
<td>30</td>
</tr>
<tr>
<td>Side-floating reverse</td>
<td>24.6</td>
<td>5.3</td>
<td>30</td>
</tr>
<tr>
<td>Side-floating cross-cabin</td>
<td>27.7</td>
<td>5.1</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 16 – Mean submersion times

<table>
<thead>
<tr>
<th>Escape</th>
<th>Mean submersion time (seconds)</th>
<th>Standard deviation</th>
<th>No. escapes included in calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial submersion</td>
<td>12.1</td>
<td>3.0</td>
<td>53</td>
</tr>
<tr>
<td>Fully inverted sit/escape same-side</td>
<td>13.0</td>
<td>3.1</td>
<td>29</td>
</tr>
<tr>
<td>Fully inverted reverse</td>
<td>11.7</td>
<td>2.9</td>
<td>30</td>
</tr>
<tr>
<td>Fully inverted cross-cabin</td>
<td>20.0</td>
<td>3.2</td>
<td>15</td>
</tr>
<tr>
<td>Side-floating sit/escape same-side</td>
<td>9.4</td>
<td>2.1</td>
<td>26</td>
</tr>
<tr>
<td>Side-floating reverse</td>
<td>10.2</td>
<td>2.2</td>
<td>25</td>
</tr>
<tr>
<td>Side-floating cross-cabin</td>
<td>9.5</td>
<td>3.0</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 16 shows that the mean submersion times for the side-floating exercises were shorter than those for the corresponding fully inverted capsizes. Statistical analysis showed that subjects’ submersion time was significantly less in the side-floating cross-cabin and sit/escape same-side than in the equivalent fully inverted exercises ($P = 0.0001$ in both cases). The most striking difference was between the submersion times for the cross-cabin exercises. Nearly twice as many subjects successfully completed the side-floating cross-cabin escape and on average they had to hold their breath for only half as long. The large air pocket inside the side-floating helicopter simulator allowed shorter submersion times than was possible after the fully inverted capsizes, when a full underwater escape had to be completed on one breath.
3.3 Discussion

3.3.1 Overall preference

The vast majority of subjects (90%) indicated that they found the escapes from the side-floating helicopter simulator easier and that they preferred these to the escapes from the fully inverted helicopter simulator.

This overall preference was reported despite the fact that subjects were given the same briefing for each trial without bias. All 3 subjects who preferred the fully inverted escapes carried out this trial after the side-floating trial, so that an order and training effect could have influenced their decision. They were also among those who successfully completed the fully inverted cross-cabin exercise. It is possible that they preferred escape from the fully inverted capsizes due to a sense of achievement, feeling good after successfully completing all exercises. This may have outweighed any perceptions relating to ease of escape.

The overall preference for the partial 150° capsise was probably strengthened by the fact that subjects were significantly more satisfied with their coping in the side-floating trials. This difference came about despite subjects reporting difficulties in both trials and is perhaps an indication that, although subjects had a few problems in the side-floating helicopter such as with releasing the harness, they did not regard these as having a detrimental effect on their overall performance. The large air pocket and above water exits allowed them to cope better with these difficulties. This is important since building the confidence to cope is an important aim of helicopter underwater escape training (see Haywood, 1993). Problems during an underwater escape are much more likely to have serious consequences.

3.3.2 Comparison of escape difficulty

The reasons for subjects finding escape from the side-floating helicopter simulator easier than when it was fully inverted seem reasonably clear. Time spent underwater was much shorter, and subjects had time to assess the situation and plan their route out once they had reached the air pocket within the helicopter.

Disorientation and difficulty locating the exit were important factors, particularly in the fully inverted cross-cabin exercise. This escape required the most underwater swimming of any exercise. It seems that having the presence of mind to swim in the right direction across the cabin proved too much for many subjects. For those who did, their inherent buoyancy probably made the task harder. Greater disorientation was almost certainly caused by subjects having to look for an exit with which they had no direct contact, in poor visibility. This seemed to have a knock-on effect in that the exit was harder to find and, in the case of those who failed to complete this escape successfully, impossible to use. These findings are consistent with Ryack (1976 and 1986), Bohemier (1996), Brooks (1994), Rice and Greear (1973), and AAIB (1989); and are symptomatic of escape from a fully inverted helicopter.

This is in stark contrast to the situation in which subjects found themselves in the side-floating cross-cabin escape. They were able to come to the air pocket before proceeding and, as a result, the subsequent actions were found to be easier. It was demonstrated that a cross-cabin escape is much easier from a side-floating
helicopter than from a fully inverted one. This is an important finding since such
an escape may be necessary after a real capsize if the exit next to an individual is
obstructed in any way. In the real situation, individuals sitting in central seats will
also have a better chance of escape as they will not necessarily have to wait for
those in outer seats to escape before they can themselves egress. Wherever
seated, individuals must simply reach the air gap and take a breath, before
assessing the best route out.

The only factor causing some concern in the side-floating helicopter was the
release from the harness. Subjects were suspended from their seats when
seated on the upper side of the helicopter, placing an uneven load on the harness
and buckle. Whilst there was a tendency for the subjects to report greater
difficulty in releasing the harness during side-floating capsizes, this only just
reached significance in reverse capsize. The results suggest that the subjects did
not themselves perceive harness release as a problem. This issue requires
further work to investigate the best harness system for side-floating helicopters
and ensure that escape will not be impaired by such potential problems. (N.B. It
was observed from video footage that when seated on the upper side, subjects
were able to get their head clear of the water without releasing the harness.)

Disorientation and finding the exit were slightly worse after the 210° roll,
presumably due to the greater distance turned, but the consequences would be
mitigated by the presence of the air gap and the shorter breath-hold time in the
side-floating helicopter.

3.3.3 Breath holding and escape times

In general, breath holding was found to be less difficult in escapes from the side-
floating helicopter simulator compared to when it was fully inverted. The cross-
cabin exercises were looked at closely to assess breath-holding difficulty. It was
hypothesised that those who failed the fully inverted cross-cabin escape would
find breath holding easier in the side-floating equivalent. This was not the case
but, instead, it was found that those who found breath-holding a problem did so in
all circumstances. It can be concluded that those individuals who find breath
holding difficult will experience greater benefit, and will have a greater chance of
escape, from a side-floating helicopter with an air pocket, than from a fully
inverted aircraft.

Further evidence for this comes from the fact that subjects spent less time with
their head under the water in the side-floating exercises, despite the fact that they
took longer to escape from the cabin. The time to escape was not related to
difficulty in the side-floating situation. The extra time may be crucial in a real
helicopter ditching, for example, in allowing an individual time to push out a
window. This compares to the fully capsized helicopter where the window must
be pushed out underwater whilst attempting to hold the breath.

The primary advantage of the side-floating helicopter is thus the air gap.
Occupants need only remain underwater long enough to release their harness and
surface within the helicopter cabin. In the current study the highest mean
submersion time in any of the three side-floating exercises was 10.2 seconds. In
a real incident, even in very cold water, this should be enough time for occupants
to rise to the air pocket. They would then have time to orientate themselves
before removing a door or window and making an escape, hopefully from an exit above the water surface.

The time available to escape in a real capsize will be greatly constrained by cold shock, which is a major factor affecting an individual's chances of survival if a helicopter should capsize in the North Sea, where water temperatures may be as low as 4°C in the winter. In water temperatures of 10°C, breath hold time can be as low as 10 seconds in some subjects (Tipton et al, 1995). When exercising underwater, average breath-hold time has been shown to be as little as 17 seconds (Tipton et al, 1995). For the majority of occupants to escape from a capsized helicopter, it is therefore desirable for them to be able to take a breath of air in a time of not much more than 10 seconds. Without breathing aids this may be very difficult since, in a real accident, an occupant may require more time than this to remove an exit. The side-floating configuration thus provides a means of limiting the consequences of cold shock.

3.3.4 Stress

No meaningful differences in the physical indicators of stress were found within or between the trials. Heart rates were significantly higher during the escape exercises compared to pre- and post-trial, but this rate was no higher than when subjects were swimming across the pool. No significant differences were found in either the salivary or urinary cortisol measurements. All but one of the average salivary cortisol values found in this study were slightly lower than a reference value of 14.3 ± 9.1 nmol/L taken from a study on 662 healthy adults (Kirschbaum and Hellhammer, 1989), although not markedly so.

A difference in psychological stress was found within the trials but not between trials. Pre-trial anxiety scores were significantly higher than corresponding post trial scores. The mean pre-trial scores of 39 and 41 were very similar to previous averages observed by Harris et al (1996) of 38.5 and 42.26 among groups of a similar size before HUET training. Indeed, the subjects in this study seem to have a relatively low level of anxiety which is suggested by a mean control score of 30 compared to a mean value of 35 which Spielberger et al (1983) recorded from over 1300 American working males.

It might have been expected that there would be less measurable stress in the side-floating trial, but stress is largely associated with perceived difficulty and problems prior to an event. As pre-conceptions were likely to be the same before each trial it is perhaps not surprising that similar pre-trial levels of stress were observed. Post trial evaluations clearly showed differences in perceived levels of difficulty in the trials, even though this did not influence the measured levels of stress.

3.3.5 Confidence

It is fair to say that the confidence levels which were elicited in this study were not greatly affected by either of the trials. Subjects' confidence about escaping was, on average, moderate to high before each trial irrespective of the order in which they were undertaken. Their confidence in helicopter transport was at similar levels and had not significantly deviated from this after either trial.
Confidence to cope with a real helicopter ditching showed a greater overall improvement following the side-floating capsizes compared to the fully inverted capsizes, suggesting a greater perception of benefit and chance of successful escape if a helicopter comes to rest on its side.

Responses following the fully inverted capsizes were more extreme, with more subjects who were 'much more' confident, but also more subjects who were 'less' or 'much less' confident. This can be attributed to people's performance in the fully inverted, underwater cross-cabin capsizes. If people were successful in this escape this probably gave them a boost of confidence, whereas if they failed the opposite would happen. Overall, the side-floating scenario was better for the confidence of a greater number of people.

Although using naïve subjects helped to more accurately assess the merits of escape from a side-floating helicopter, it should be recognised that the a certain amount of self-selection will have taken place. This is demonstrated by the fact that the majority of subjects rated themselves as being moderately fit, good swimmers and confident about helicopter transport. In addition, when subjects were asked to rate their level of worry about what might affect their escape in the trials, the majority were either not worried or only a little worried about the 10 potential difficulties. These results suggest that the subjects in this study were fairly confident and self-assured people. This may not be representative of the offshore population.

3.3.6 Problems of escape from a side-floating helicopter

Whilst the benefits of escape from a side-floating helicopter were clear, the 150° flotation angle did cause some concerns.

Some problems were observed when subjects tried to release the harness buckle under an uneven load, requiring the application of more force to open it. This was observed when subjects were suspended mostly out of the water on the upper side of the helicopter simulator after capsize. In two cases, subjects were completely unable to release the harness without the assistance of the Training Officer. This problem is not specific to the side-floating situation, with similar problems occasionally being encountered during standard training in the inverted helicopter simulator. Given the uneven loading on the harness, and the higher incidence of problems, it is suggested that further investigation is needed in this area. It is expected that the harness system could be modified relatively easily to remove this problem.

A second concern related to the risk of injury from passengers in upper seats falling down into the air gap with some force. Occupants on the opposite side of the cabin were mostly underwater, and had to surface up into the air gap. Risk analysis suggested a high risk of injury to those surfacing from the lower side of a helicopter from individuals on the upper side falling on top of them. While this is a potential problem for trials and training, it is not seen as a life threatening problem in the real situation. It must be considered that in a real capsize there is probably a similar risk even if the helicopter comes to rest fully inverted. At any capsize angle, it is likely that some occupants may have released their harness before the capsize which would put them in danger of colliding with others. There is also likely to be as much flailing of limbs in the aftermath of a capsize irrespective of the final resting angle of the helicopter. This being the case, the benefits of the
air gap in a side-floating helicopter are felt to be greater than the disadvantage of people falling onto each other.

3.3.7 Wave action

The procedure which was developed for escape from a window above the water surface took into account the possible action of waves acting against the helicopter (given that capsize is more likely in high sea states). Further work is needed to determine the possible effects of wave action on a capsized helicopter, and any specific issues relating to a side-floating position.

It is likely that individuals will have a greater chance of locating, opening and using exits above the water, as it is well documented that these actions are much more difficult if exits are underwater (see Brooks, 1994).

3.3.8 Life-raft deployment

Life-raft deployment has not been included within the remit of this study. Further work would be needed to determine the advantages or disadvantages of deployment from a side-floating helicopter.

4 CONCLUSIONS

4.1 Overall preference

It can be concluded that the vast majority of subjects in this study found it easier to escape from a side-floating helicopter simulator than from a fully inverted one without finding it any more stressful. In the side-floating trial, more subjects were satisfied with how they coped and more were instilled with greater confidence in their ability to deal with a real helicopter ditching. These findings suggest there could be significant benefit in training people to escape from helicopters which were designed to float on their side after capsize.

4.2 Ease of escape

The results of this study indicate why subjects found the side-floating trial easier than the fully inverted one. The provision of an air-pocket and exits above the water were important factors in making escape easier. The air-pocket in particular helped to mitigate the consequences of disorientation and meant that subjects did not need to hold their breath for so long. This latter point is important considering that, in a real helicopter accident, occupants may have to overcome the effects of cold shock which has been shown to reduce breath hold time to as little as 10 seconds. The additional air pocket reduced the required breath-hold time by up to 50% compared to that required for escape from a fully inverted helicopter simulator. This difference may be even greater in a real capsize incident, where additional barriers to underwater escape may be present. This one factor could save a significant number of lives if side-floating buoyancy systems were introduced.
4.3 **Above-water exits**

The task of locating an exit should be easier in a side-floating helicopter due to the likelihood that exits will be above the water on one side of the aircraft. This means that occupants will be less hampered in their attempts to reach and jettison an exit by poor visibility and their inherent buoyancy. Even if subjects are slowed by initial disorientation or are struggling to open an escape route, the presence of an air pocket will provide them with extra time in which to make their escape.

Problems with liferaft deployment have previously been described. Given the different orientation following capsize, consideration needs to be given to the deployment of liferafts by individuals escaping from a side-floating helicopter.

4.4 **Harness release**

There were only two problems with escape from the side-floating helicopter simulator which caused some concern. The most serious problem identified was the potential for an occupant on the upper side to release their harness and fall with force onto someone rising to the air pocket from the lower side. This would not be seen as a major hazard in a real helicopter accident. Injuries are possible in any capsize, particularly if the harness has already been released prior to the capsize. The higher risk of injury during training does, however, require some attention.

The release of the harness caused some difficulty, possibly due to the uneven load on the buckle. Further investigation relating to harness release is needed.

4.5 **Overall benefits**

None of the problems with escape from a side-floating helicopter which were identified in this study are thought to be life-threatening. They do not outweigh the advantages that such a scenario has over escape from a fully inverted aircraft. On the contrary, the evidence suggests that the occupant of a side-floating helicopter has a much better chance of escape and survival than someone inside a fully inverted aircraft.

5 **RECOMMENDATIONS**

5.1 Flotation systems on helicopters should be improved by the incorporation of means to achieve a side-floating attitude in order to improve the chances of survival of the occupants in the event of a ditching and capsize.

5.2 The flotation system should be designed so that the cabin floats with the top of the inverted exits at water level, thereby ensuring ease of escape.

5.3 The carriage and release of liferafts from a side-floating helicopter needs further assessment.

5.4 More work is required in order to make firm conclusions about the effects of an uneven load on a 4-point harness buckle.
5.5 The provision of a hand-hold next to emergency exits would assist in the location of the exit and provide a leverage or reaction point for anyone trying to operate a push-out window.

5.6 Consideration should be given to the appropriate training programme for helicopter passengers who may find themselves fully inverted or on their side in the event of an aircraft capsizing.

6 REFERENCES


RYACK BL, WALTERS GB and CHAPLIN SM (1976) Some relationships between helicopter crash survival rates and survival training. *Groton CT: Naval Submarine Medical Research Laboratory Report No. 77-1.*


Appendix 1 Review of helicopter accidents

1 REPORT ON THE ACCIDENT TO SIKORSKY S.61N HELICOPTER G-BBHN IN THE NORTH SEA, NORTH EAST OF ABERDEEN, ON 1 OCTOBER 1977 (AIB, 1978)

The accident occurred when the helicopter made an emergency landing in very rough seas, due to a technical problem. It capsized almost immediately after touchdown. All three occupants were rescued after 53 minutes immersion, uninjured but suffering from the effects of exposure.

Following the capsize the co-pilot experienced difficulty moving the stowed life-raft towards the cargo door as, with the aircraft inverted, the cabin floorboards had become detached and the baggage compartment doors were hanging down. With the water level rising he instead concentrated on opening the cargo door which he was unable to do at first due to the water pressure on the outside. The commander, who had meanwhile left the flight deck through the starboard sliding window, proceeded to the side of the upturned hull and assisted the co-pilot to prize the door open wide enough so that the two occupants could escape. Since there was no way of restraining the cargo door once it was open, it kept sliding shut under the action of the waves and the pitching hull. The co-pilot and passenger were neck deep in water with little breathing space overhead before they were able to leave the cabin.

2 REPORT ON THE ACCIDENT TO BELL 212 G-BIJF IN THE NORTH SEA, SOUTH EAST OF THE DUNLIN ALPHA PLATFORM, ON 12 AUGUST 1981 (AIB, 1982)

The accident occurred during a daytime flight between the Brent Field and the Dunlin platform. The commander had decided to return to the Brent Field after encountering an area of reduced visibility. During the turn, control of the helicopter was lost resulting in descent, collision with the sea and then rapid capsize. The single fatality and 13 survivors were retrieved by another helicopter and a rig support vessel after some 44 minutes.

Normal access to the passenger cabin was via very large sliding doors on each side of the cabin which, when open, provided access to almost the whole length of the cabin space. These doors are vulnerable to jamming in an accident and so emergency exits were provided in the form of four large windows, two in each door. The windows, by virtue of their size and ease of removal in emergency, were significantly superior to emergency exits commonly found in helicopters. Twelve of the thirteen passengers were able to use the exits effectively to achieve a relatively swift escape to the sea. The remaining passenger had considerable difficulty in freeing himself from his safety belt. This passenger never managed to unfasten the belt but extended it enough so that he could wriggle free. Clearly this effort took its toll and the man was unable to help himself on egress from the helicopter. Eventually fatigue prevented the other passengers from supporting the man who drifted away from the upturned wreck of the helicopter and drowned. Subsequent examination of the safety buckle in question showed it to be in working order.
REPORT ON THE ACCIDENT TO BOEING VERTOL (BV) 234 LR G-BISO, IN THE EAST SHETLAND BASIN OF THE NORTH SEA, ON 2 MAY 1984 (AIB, 1987)

The aircraft was engaged on a flight from the Magnus Field to Aberdeen carrying a full load of 44 passengers, one cabin attendant and two flight deck crew. Two separate flying control system malfunctions produced intermittent loss of collective control. Following a successful landing on water, the crew proceeded to water taxi towards the nearest rig. When the aircraft was found to be taking on water and sinking, an evacuation of the passengers commenced, followed by the crew. All crew and passengers were rescued, without injury.

The report concluded that, for this type of helicopter, there was no great difficulty in achieving a successful escape of a full passenger load through the designated exits, following a controlled ditching in which the aircraft remains upright on the water.

BULLETIN ON THE ACCIDENT TO BOLKOW BO 105D G-AZOM, 5½ NM DUE EAST OF SKEGNESS, LINCOLNSHIRE, ON 24 JULY 1984 (AIB, 1985)

The purpose of the flight was to ferry two charter passengers from Lincolnshire to Norfolk. When the aircraft was about 5nm off the coast of Skegness the commander heard a dull bang which caused him to descend and turn towards Skegness. During the descent he felt further vibrations and so decided to alight on the sea. As power was applied to arrest the rate of descent, all yaw control was lost and the helicopter performed two or three 360° turns before hitting the water.

As a result of rotating into the surface of the sea, one of the four floats detached and the aircraft immediately rolled onto its right side. The aircraft was now lying on its right side with the detached flotation bag beneath the commander’s door, holding it closed. However, one of the passengers had acquainted himself with the jettison mechanism of his door and acted swiftly to make this the most convenient egress from the aircraft. The evacuation was accomplished in less than 30 seconds. Very shortly after that the aircraft capsized.

REPORT ON THE ACCIDENT TO BELL 214 ST G-BKFN, IN THE NORTH SEA 14 MILES NORTH EAST OF FRASERBURGH, SCOTLAND, ON 15 MAY 1986 (AAIB, 1987)

The accident occurred during a flight from Sumburgh to Aberdeen. A technical failure caused a partial loss of collective control which forced the helicopter to ditch. The crew and passengers were able to evacuate safely and were picked up by a fishing vessel.

The commander was forced to operate his emergency exit manually since the automatic jettison mechanism had seized, although this did not hinder his escape. Similarly the life-raft deployment had to be undertaken manually since the crew actuation handle was ineffective due to a technical failure of the aircraft.
Two human factors problems were experienced. Firstly, the secondary escape windows proved resistant when attempts were made to dislodge them, forcing the passengers to proceed to the primary escape windows to make their escape. Secondly, one of the passengers entered the sea inadvertently as a result of slipping off the flotation bag, and subsequently drifted towards the still turning tail rotor. The AAIB report suggests that the addition of a non-slip surface to the float bag material could have prevented the exposure of the passenger to this hazard.

REPORT ON THE ACCIDENT TO AEROSPATIALE AS 332L SUPER PUMA G-BKZH, 35 NM EAST-NORTH-EAST OF UNST, SHETLAND ISLES, ON 20 MAY 1987 (AAIB, 1988)

Although the above accident did not involve a helicopter having to land on water, it was included in this review since the aircraft involved was a Super Puma and underwater escape issues were considered.

The aircraft was in transit between Sumburgh and the East Shetland Basin when it suddenly began to vibrate severely. The crew managed to keep the aircraft under control and assessed the source of the vibration to be the tail rotor. They decided that the aircraft was controllable at reduced power and elected to go to Unst to make a 'run on' landing. This was accomplished successfully and the passengers and crew disembarked without any injuries.

The wind and sea-state appear to have been within the tested parameters for flotation, but the sea state was outside that demonstrated by scale models for a water landing. The crew believed that it was probable that the helicopter would capsize during a ditching with consequent severe egress problems for the passengers. Furthermore they were aware that the Super Puma cabin doors could not be jettisoned when the aircraft was inverted. Although the normal mode of opening the doors was theoretically available when the aircraft was inverted, experience from other ditching accidents had shown that the ensuing disorientation of occupants who find themselves inverted and submerged, escalates the difficulty of performing even the most simple of tasks. The AAIB report recommended that the lack of a facility to jettison the cabin doors on this type of aircraft in an inverted position should be reviewed.

REPORT ON THE ACCIDENT TO SIKORSKY S-61N G-BEID, 29NM NORTH EAST OF SUMBURGH, SHETLAND ISLES, ON 13 JULY 1988 (AAIB, 1990A)

Whilst operating a passenger flight from a North Sea rig to Sumburgh, a mechanical failure caused fire in both of the aircraft's engines. A controlled ditching was carried out onto an almost calm sea. By this time the cabin had filled with smoke. All 21 occupants evacuated successfully into life-rafts and were winched into a search and rescue helicopter. Much of the helicopter was consumed by fire which eventually broke up and sank.

The escape of several passengers appeared to have been slowed because neither of the crew initiated the automatic unlatching control for the rear life-hatch. As a result, the passengers were required to unlatch the life-hatch manually which they had difficulty with, probably due to the cabin being full of noxious thick smoke. The passengers had time to complete the operation and evacuate before being
incapacitated. Had the passengers had less time to act it is probable that the factors which slowed escape may have reduced their chances of survival.

The AAIB report recommended that crew and passengers be provided with accessible means of respiratory and eye protection from the effects of smoke arising from an on-board fire. Also, that S-61N checklists include an instruction to arm the life-hatch unlatching circuit in a ditching or forced landing situation. Appropriate action was taken on life-hatch systems. The CAA agreed to review the case for smoke hoods once products which satisfy the Authority's specification have been developed.

8


The accident occurred during a search and rescue (SAR) mission centred off the coast of Scotland. The SAR crew were called out from Stornoway to conduct a SAR flight for the two occupants of a small fishing boat, which had capsized somewhere in the area of Handa Island. Towards the end of the search while performing a hover manoeuvre, a crew member noticed that the aircraft was travelling backwards very fast. The commander was unable to arrest the situation, the aircraft struck the sea and immediately rolled over. All four crew members were able to escape and board the life-raft and were later rescued by a second SAR helicopter.

The commander, co-pilot and winch operator all managed to escape to the sea after the helicopter ditched, although the winch operator was considerably hampered by the inrush of water through the open starboard cargo door. The winch-man, who had been sitting halfway down the fuselage, was washed by a succession of waves coming from the open forward exits towards the rear of the aircraft. He was eventually trapped in a small air pocket in the extreme tail section of the inverted aircraft. His attempts to reach one of the jettison mechanisms for the rear port emergency exit were frustrated by his own natural buoyancy and the small amount of air trapped in his immersion suit. After being trapped for some 15 minutes, and on the point of losing his will to survive, the winch-man was eventually rescued by the commander who opened the rear port door from the outside upon realising the winch-man was trapped.

The report states that it is recorded that most uncontrolled ditchings of helicopters, in other than ideal conditions, have resulted in a capsize. It is therefore concluded that emergency exit jettison mechanisms, whether on doors or hatches, should be as accessible when an aircraft is inverted as they are when it is upright.

9

REPORT ON THE ACCIDENT TO SIKORSKY S61N G-BDES, IN THE NORTH SEA, 90 NM NORTH EAST OF ABERDEEN, ON 10 NOVEMBER 1988 (AAIB, 1990B)

The aircraft was tasked on a non-scheduled service from Aberdeen to three oil installations in the North Sea. On the return flight the crew and passengers became aware of an unusual buzzing noise followed by increasing vibration. The
commander attempted to reach a suitably equipped platform to land but was forced to execute an immediate ditching. The aircraft capsized almost immediately. The crew and passengers managed to evacuate the aircraft and were rescued without serious injury.

After capsize, neither pilot was able to locate the jettison handle for their emergency exit from an inverted position under water. One pilot proceeded aft to the cargo door which he was not able to open. On the point of drowning the pilot managed to escape by punching out a passenger window. The second pilot had slid open his side window through which he escaped after failing to find the jettison handle for his emergency exit. The edges of the opening were not smooth and presented several projections which could snag clothing or safety equipment during egress.

All eleven passengers escaped, some encountering minor difficulty. One used the left hand escape exit and the others used push out windows. Three passengers reported some difficulty in releasing their lap strap buckle. One passenger reported that he could not grip the fabric tag attached to the window rip-out beading until he had removed a survival glove. One passenger sustained a broken bone in his hand while punching out a window.

REPORT ON THE ACCIDENT TO SIKORSKY S61N G-BEWL, AT BRENT SPAR, EAST SHETLAND BASIN, ON 25 JULY 1990 (AAIB, 1991)

The accident occurred whilst the helicopter was manoeuvring to land on the Brent Spar semi-submersible offshore storage and tanker loading unit. After the helicopter had approached to a hovering position above the helideck, witnesses realised it was positioned dangerously close to a part of the installation’s crane structure. The tips of the tail rotor blades struck part of the crane frame after which the helicopter crashed onto the helideck and almost immediately fell over the side of the deck and into the sea. Seven survivors were rescued from the sea having escaped from the rapidly sinking helicopter. Six occupants including the crew perished.

Evidence of the surviving passengers indicated that, following the impact with the sea, the passenger cabin rapidly filled with water and the survivors escaped through the nearest window to their seat. Most of the cabin windows were either broken or dislodged cleanly by the distortion of the airframe or the force of the water. This clearly aided egress for those who were not incapacitated by the impact.

The collapse of passenger seats coupled with impact forces with the sea, contributed to injury and incapacitation, may have been a direct cause of death, and would certainly have hampered egress. The AAIB report recommended that seat requirements should be reviewed and newly manufactured aircraft should have an effective upper torso restraint installed. The CAA response (CAA, 1991) was to agree with this recommendation in principal and state that such a requirement was in a draft Joint Operational Requirement (European) which was to come into effect soon after September 1992.
The accident occurred at night, in severe weather conditions, during a shuttle of personnel from an oil production platform to a nearby accommodation 'flotel'. Having left the platform helideck and turning towards the flotel the commander reduced power and raised the nose of the helicopter such that the airspeed reduced to zero and a rate of descent built up. Once the pilot was aware of the descent it was too late for him to avert a collision with the sea. The helicopter rolled onto it's right side before capsizing and sinking within a minute or two. All but five of the 17 occupants managed to escape from the helicopter before it sank. Of the twelve survivors in the sea, only six were recovered alive; the others perished in the hostile sea environment.

The commander escaped from the aircraft via the right flight deck door window and emerged close to the co-pilot whose method of egress could not be established. Water ingress into the cabin was rapid and although the survivors seated to the rear reported that they had time to take a deep breath, those at the front did not. This was probably a limiting factor for four of the five who did not exit the helicopter although not physically impeded or incapacitated. The predicted breath holding time in the conditions prevailing was stated to be less than 20 seconds. In addition, once the fuselage inverted, it was thought that those still in it would have had to overcome the extra buoyancy provided by air in their survival suits to be able to reach an exit. One of the passengers who did not manage to exit the helicopter appeared to have been impeded in his attempt to escape by the cord from his acoustic headset which had wrapped around his neck without disconnecting.

It was possible to establish that 6 of the 10 passengers who escaped to the sea had done so with little difficulty via an emergency exit window. Five of these individuals survived the accident. It was not possible to determine the escape routes of the other four passengers.

The AAIB report suggested that the cabin doors of a Super Puma should be able to jettison in an emergency, at any aircraft attitude, in order to aid egress. Also, that the whole question of survival must be assessed in the light of a complete system such that safety deficiencies should not be viewed independently. For example, predicted survival times based on the performance of a survival suit must take into account the ability of an individual to escape from an inverted helicopter cabin which may depend upon such factors as the effectiveness of emergency lighting and the operability of emergency exits.

The helicopter was conducting a charter flight from Aberdeen to the Brae oil field. The helicopter was struck by lightning which resulted in severe vibration and caused loss of tail rotor control, necessitating an immediate ditching in heavy seas. The ditching was executed successfully and the helicopter remained upright enabling the passengers and crew to board a helirraft from which they were subsequently rescued without injury. Despite 6 to 7 metre waves and a 30
knot southerly wind, the helicopter remained afloat for some three hours and thirty minutes.

After ditching, the crew released their cockpit doors and the commander operated the flight deck jettison handle for the right cabin door. The passengers had prepared for evacuation by pushing out most of the windows and releasing and deploying the life rafts. Passengers on the left side of the aircraft were having difficulty since the heliraft was blowing up against the open door on this side, making boarding very difficult. The decision was therefore made for everyone to board the heliraft on the right side of the helicopter.

A feature which had the potential to affect egress in this accident concerned the ejection of the cabin doors. The fact that the aircraft was rolling in the sea seemed to have contributed to the doors not being able to eject cleanly. This is thought to be because when such doors are jettisoned in rough sea conditions with the aircraft rolling through a large angle, the inherent buoyancy of the doors can prevent them from falling vertically, thus preventing the upper rollers from disengaging freely from the locating rails. In this event the upper locating arms will fail and their fractured ends become a potential hazard if the door floats in the region of the heliraft.

In this accident it seemed likely that a sharp end from the starboard door punctured the lower buoyancy chamber of the heliraft which was used. It was recommended that the CAA survey jettisonable doors to determine if they are initially buoyant on jettison and, if so, to inspect the doors for dangerous projections. This was duly undertaken by the Authority in consultation with the relevant manufacturers to determine relevant action.

As well as damaging safety equipment, it seems that this shortcoming of door ejection may hamper egress or cause physical harm in a worst case scenario. This problem with the door jettison of a Super Puma had been noted in other air accident reports (AAIB 9/88 and AAIB 2/93). The AAIB report in this case recommended that the manufacturers of this type of aircraft should review the failure modes of the cabin door upper guide roller mounting arms which can occur during door jettison in rough sea conditions, and take action to prevent such mounting arm failures.
Appendix 2 Witness report

Date of interview: 18.2.99
Interviewer: Dr Susan Coleshaw

Statement

The accident took place in 1964, during daylight hours, in calm conditions, in the Indian Ocean.

I was employed by the Royal Navy acting as a winch-man performing search and rescue duties. The helicopter being flown was a single engine Westland Whirlwind Mk 7. We were standing close in by an aircraft carrier while fixed-wing aircraft were taking off and landing, providing safety cover.

The engine failed, at a height of about 120 feet. On contact with the water, the emergency procedure followed by the pilot was to push the stick hard over to the left, to ditch the helicopter onto its port side. This was achieved, the helicopter hitting the water with the starboard side up. The open main exit door was located on the starboard side.

At the time of the incident I had been sitting in the open exit, with my feet on the step outside the aircraft. I found myself looking up at the sky, while hanging onto the rail at the top of the exit. As the helicopter sank, the water came up to support me. I took my feet back down into the cabin and was then able to swim out as the helicopter sank. I would estimate that it took 10 to 20 seconds from the time of hitting the water to the helicopter sinking.

There were three crew on board, including myself. The pilot was able to successfully escape through the starboard cabin window exit. The third crew member also escaped using the same procedure as myself.

The accident was filmed by personnel on the aircraft carrier (possibly held in MoD film archives). The footage showed that when the helicopter hit the water, the blades on striking the water, went around twice before stopping and in the process appeared to flex and curl upwards without breaking.
Appendix 3  Cabin configuration of Super Puma

Super Puma window dimensions and distances from seat centres to port windows measured at Bristows 23/11/98. Shaded seats marked in orange indicate seats in Dunker, with dunker dimensions and distances in brackets.

Window 680 x 510mm (500 x 445mm)
750mm (1150)
1700mm (1710)
990mm (580)

Window 500 x 440mm

Window 500 x 445mm

Window 590 x 340mm (500 x 445mm)
420mm (580)
830mm (1160)
1310mm (1810)
Appendix 4  View inside helicopter simulator at 150°
Appendix 5 Questionnaires

HELICOPTER ESCAPE RESEARCH

SUBJECT QUESTIONNAIRE

Subject Number ________________________________

Trial Reference ________________________________

Date ________________________________

Instructions For Completing The Questionnaire
You will be given two separate parts of this questionnaire. Part One will be given to you before you take part in the helicopter escape. It will start with some background questions before asking about your feelings directly before these trials. Part Two is to be completed after you return from the pool session and will ask you how you felt during and after the ditchings. You should answer ALL the questions by ticking the appropriate box and writing comments in the spaces provided. Please record both positive and negative comments in as much detail as possible since this feedback is very important to our results.

PART ONE
Background Details

Question 1
How would you rate your physical fitness?

Very fit ☐ Moderately fit ☐ Marginally fit ☐ Unfit ☐

Question 2
How would you rate your swimming ability?

Very good ☐ Moderately good ☐ Basic ☐ Non-swimmer ☐

Question 3
Do you have any previous knowledge of helicopter underwater escape?

YES ☐ NO ☐

If YES please give details

________________________________________________________________________________________

________________________________________________________________________________________

________________________________________________________________________________________

65
Question 4
How much confidence do you have in helicopter transport?

- High confidence
- Moderate confidence
- Low confidence
- No confidence

Feelings Before Helicopter Escape

Question 5
How much confidence do you have in your ability to escape after the capsizes in this trial?

- High confidence
- Moderate confidence
- Low confidence
- No confidence

Question 6
Using the following table, please indicate how worried you are about how the factors in the first column of the table might affect your escape, by placing a tick in the appropriate box.

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<thead>
<tr>
<th>Factor</th>
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Any other comments:

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PART TWO
Feelings During and After Helicopter Escape

Subject number _______________ Trial reference _______________

Question 7
How difficult did you find the first capsize, which was the 180° roll with your seat coming to rest on the lower side (underwater), followed by escape from an upper window?

Very difficult □ Moderately difficult □ A little difficult □ No difficulty □

Question 8
For the first capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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**Question 9**
How difficult did you find the second capsize, which was the 180° roll with your seat coming to rest on the upper side (mostly out of water), followed by escape from an upper window?

Very difficult ☐  Moderately difficult ☐  A little difficult ☐  No difficulty ☐

**Question 10**
For the second capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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Any other comments:
Question 11
How difficult did you find the third capsize, which was the 180° roll with your seat coming to rest on the upper side (mostly out of water), followed by escape from an upper window?

Very difficult □  Moderately difficult □  A little difficult □  No difficulty □

Question 12
For the third capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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Any other comments:

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**Question 13**
How satisfied are you with the way you coped with the helicopter underwater escape training in this session?

- Very satisfied ☐
- Satisfied ☐
- Undecided ☐
- Dissatisfied ☐

**Question 14**
How much confidence do you now have in helicopter transport?

- High confidence ☐
- Moderate confidence ☐
- Low confidence ☐
- No confidence ☐

**Question 15**
How much more confident do you now feel of coping with a real helicopter ditching than you did prior to this session?

- Much more ☐
- More ☐
- About the same ☐
- Less ☐
- Much less ☐

You have now completed the questionnaire

**THANK YOU FOR YOUR HELP**
## HELICOPTER ESCAPE RESEARCH

### SUBJECT QUESTIONNAIRE

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PART ONE
Feelings Before Helicopter Escape

Question 1
How much confidence do you have in your ability to escape after the capsizes in this trial?

High confidence □  Moderate confidence □  Low confidence □  No confidence □

Question 2
Using the following table, please indicate how worried you are about how the factors in the first column of the table might affect your escape, by placing a tick in the appropriate box.

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PART TWO
Feelings During and After Helicopter Escape

Subject number ________________ Trial reference ________________

Question 3
How difficult did you find the first capsize, which was the 150° roll with your seat coming to rest on the lower side (underwater), followed by escape from an upper window?

Very difficult □  Moderately difficult □  A little difficult □  No difficulty □

Question 4
For the first capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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Question 5
How difficult did you find the second capsize, which was the 150° roll with your seat coming to rest on the upper side (mostly out of water), followed by escape from an upper window?

Very difficult [ ] Moderately difficult [ ] A little difficult [ ] No difficulty [ ]

Question 6
For the second capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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Any other comments:

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Question 7
How difficult did you find the third capsize, which was the 210° roll with your seat coming to rest on the upper side (mostly out of water), followed by escape from an upper window?

Very difficult ☐ Moderately difficult ☐ A little difficult ☐ No difficulty ☐

Question 8
For the third capsize, could you please rate the factors in the first column of the table below in terms of how difficult they made the escape, by placing a tick in the appropriate box.

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<td>Holding breath</td>
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<tr>
<td>Disorientation</td>
<td>☐</td>
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</tr>
<tr>
<td>Releasing harness</td>
<td>☐</td>
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<td>Getting clear of seat</td>
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<td>Locating exit</td>
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</tr>
</tbody>
</table>

Any other comments:

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________
Question 9
How satisfied are you with the way you coped with the helicopter underwater escape training in this session?

Very satisfied ☐ Satisfied ☐ Undecided ☐ Dissatisfied ☐

Question 10
How much confidence do you now have in helicopter transport?

High confidence ☐ Moderate confidence ☐ Low confidence ☐ No confidence

Question 11
How much more confident do you now feel of coping with a real helicopter ditching than you did prior to this session?

Much more ☐ More ☐ About the same ☐ Less ☐ Much less ☐

Question 12
Having now completed two exercises, one involving full capsize (180°) and the other involving partial capsize (150° / 210°), which did you prefer in terms of ease of escape?

Full capsize ☐ Partial capsize ☐

You have now completed the questionnaire
THANK YOU FOR YOUR HELP
Appendix 6  Example of heart rate trace

Subject 14 heart rate in partial submersion and 3 side-floating capsizes
CAA PAPER 2001/2

Crashworthiness of Helicopter Emergency Flotation Systems

Study I (Main Study)

Study II (Supplementary Study)

www.caa.co.uk
CAA PAPER 2001/2

Crashworthiness of Helicopter Emergency Flotation Systems

Study I (Main Study)

Prepared by W S Atkins Consultants Ltd
Author: P J Murrell

Study II (Supplementary Study)

Prepared by BMT Fluid Mechanics Ltd
Authors: R G Standing
    R Eichaker

August 2001
General Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority (CAA). The work was instigated at WS Atkins Consultants Limited (WSA) and BMT Fluid Mechanics Limited (BMT), primarily in response to the conclusions and recommendations of earlier research performed for CAA by GKN Westland Helicopters Limited. This earlier work was commissioned by CAA in response to recommendations made in the HARP Report (Report of the Helicopter Airworthiness Review Panel - CAP 491), and was published as CAA Paper 96005 in July 1996. In addition, impetus was added to the project by the recommendation (Recommendation 14.2 (g)) in the RHOSS Report (Review of Helicopter Offshore Safety and Survivability - CAP 641) that “Particular account should be taken [in the CAA’s ongoing research programme on helicopter crashworthiness and ditching stability] of the need to improve provision for flotation after a severe impact, including the possibility of installing extra flotation devices specifically to cater for a crash”.

This paper contains unabridged versions of the following WSA and BMT final project reports, each covering their respective parts of the research:-


This study included: a review of accident data and public domain literature relating to water impact; the development and validation of finite element modelling (FEM) techniques to predict airframe accelerations and forces during water impact; the modelling of three helicopter water impact scenarios (based on actual accidents) using the proprietary FEM code LS-DYNA3D; a review of helicopter emergency flotation equipment design; a top-level cost-benefit analysis of a number of proposed modifications; a review of the requirements and advisory material relating to water impact, ditching and occupant egress.

II. BMT Fluid Mechanics Ltd. Document No.44134r55 Release 5

This study comprised an assessment of the range and variability of impact loads experienced by typical emergency flotation systems during water impact, using a Monte Carlo simulation procedure based on simplified empirical and theoretical formulae. The purpose of this study was to complement the finite element analysis performed by WSA.

The principal conclusions of these studies included:-

- The most effective means of significantly improving the crashworthiness of helicopter emergency flotation systems is through the addition of flotation unit redundancy (preferably through the addition of flotation units at the top of the airframe to provide a side-floating attitude).

- The consequences of a significant proportion of helicopter water impacts could be mitigated through the introduction of automatic arming and deployment of emergency flotation systems.

- The finite element analysis techniques used show significant limitations when attempting to accurately model impacts between complex deformable structures and fluids.

- The nature of drag and planing forces in the water impact loading process are not fully understood, and their magnitudes are likely to be significant in mainly horizontal impacts.
The results of the research reported in this paper are being progressed through the JAA/FAA requirement development and harmonisation procedures. They have been presented to and considered by the JAA/FAA Joint Harmonisation Working Group on helicopter water impact and ditching, and the JAA Helicopter Offshore Safety and Survivability (HOSS) Working Group. Recommendations for changes to the requirements and advisory material have been made by both of these groups to the JAA.

Safety Regulation Group

03 January 2001
Study I  (Main Study)

Prepared by W S Atkins Consultants Ltd
Summary

This document reports on an investigation of the crashworthiness of helicopter emergency flotation systems (EFS), commissioned and funded by the Safety Regulation Group of the UK Civil Aviation Authority (CAA).

The work follows on from GKN Westland Helicopters Limited (GKN WHL) studies into civil and military water impacts. The work was given greater importance following the Review of Offshore Safety and Survival, commissioned by the CAA, which recommended that the provision for flotation after a severe but survivable impact be improved.

This report details the work performed by WS Atkins comprising a complete review of EFS design and associated requirements (JARs), with a particular emphasis on crashworthiness issues.

A review of accident data and public domain literature relating to water impact was undertaken. The aims of this task were to determine the nature and extent of any relevant work that had been conducted elsewhere, identify accidents where a failure of the EFS system contributed to the consequences and to obtain water impact data from actual accidents and research activities.

Finite element modelling techniques were then developed with a view to predicting accelerations and forces on the airframe during a water impact. Using this approach, siting of the EFS to reduce damage on impact could be investigated. The technique was validated against a variety of full and scale model test programmes. The correlation between analysis and test was found to be variable, and highlighted water mesh density and model complexity as the main controlling factors. Questions also arose regarding the validity of some of the test data used for validation.

Three full scale helicopter water impact scenarios were explicitly modelled using LS-DYNA3D to determine the response of a typical airframe during water entry. These scenarios were based on actual accidents which were outside the Federal Aviation Authority’s proposed 95% survivability ditching envelope, but for which there were a significant number of survivors.

From the literature reviews, causes for failure of EFS deployment other than impact damage were identified. A number of modifications to the EFS were proposed and a cost-benefit analysis carried out. Advice was sought from helicopter manufacturers, EFS suppliers and regulatory bodies to ensure their implementation would be practical.

Finally, regulatory requirements for water impact, ditching and occupant egress were reviewed. A series of recommendations, based on the conclusions from all the stages of the project, are made to improve the crash performance of EFS and the associated regulatory requirements and guidance material.
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
</tr>
<tr>
<td>2</td>
<td>Description of Emergency Flotation Systems</td>
</tr>
<tr>
<td>3</td>
<td>Literature review</td>
</tr>
<tr>
<td></td>
<td>3.1 Introduction</td>
</tr>
<tr>
<td></td>
<td>3.2 Methodology</td>
</tr>
<tr>
<td></td>
<td>3.3 Results of Literature Review</td>
</tr>
<tr>
<td></td>
<td>3.4 Results of Accident Review</td>
</tr>
<tr>
<td></td>
<td>3.4.1 Air Accident Investigation Branch (AAIB)</td>
</tr>
<tr>
<td></td>
<td>3.4.2 Royal Navy Flight Safety and Accident Investigation Centre (RNFSARC)</td>
</tr>
<tr>
<td></td>
<td>3.4.3 CAA Flight Safety Data Department</td>
</tr>
<tr>
<td></td>
<td>3.4.4 Aircraft Insurance Companies</td>
</tr>
<tr>
<td></td>
<td>3.4.5 Federal Aviation Administration (FAA)</td>
</tr>
<tr>
<td>3.5</td>
<td>Summary of UK Civil Water Impacts</td>
</tr>
<tr>
<td></td>
<td>3.5.1 G-BJIF, Bell 212, 12/8/81, North Sea (Dunlin Alpha) [12]</td>
</tr>
<tr>
<td></td>
<td>3.5.2 G-ASWI, Wessex 60, 13/8/81, North Sea [AAIB]</td>
</tr>
<tr>
<td></td>
<td>3.5.3 G-BDIL, Bell 212, 14/09/82, North Sea (Murchison Platform) [13]</td>
</tr>
<tr>
<td></td>
<td>3.5.4 G-BEON, Sikorsky S61N, 16/7/83, St Marys (Isles of Scilly) [14]</td>
</tr>
<tr>
<td></td>
<td>3.5.5 G-BJIR, Bell 212, 20/11/84, North Sea [AAIB]</td>
</tr>
<tr>
<td></td>
<td>3.5.6 G-BEWL, Sikorsky S61N, 25/07/90, North Sea (Brent Spar) [15]</td>
</tr>
<tr>
<td></td>
<td>3.5.7 G-TIGH AS 332L Super Puma, 14/03/92 North Sea (Cormorant ‘A’ Platform) [16]</td>
</tr>
<tr>
<td></td>
<td>3.5.8 Non Fatal Accidents</td>
</tr>
<tr>
<td>3.6</td>
<td>Conclusions</td>
</tr>
<tr>
<td>4</td>
<td>COMPUTER modelling</td>
</tr>
<tr>
<td></td>
<td>4.1 Introduction</td>
</tr>
<tr>
<td></td>
<td>4.2 Modelling Methods</td>
</tr>
<tr>
<td></td>
<td>4.3 Validation of Helicopter Model</td>
</tr>
<tr>
<td></td>
<td>4.4 Validation of Water Model for Vertical Impacts – Capsule Model</td>
</tr>
<tr>
<td></td>
<td>4.5 Validation of Water Model for Horizontal Impacts – Orbiter Model</td>
</tr>
<tr>
<td></td>
<td>4.6 Validation of Water Model for Horizontal Impacts– Seaplane Hull Model</td>
</tr>
<tr>
<td></td>
<td>4.7 Validation Conclusions</td>
</tr>
<tr>
<td></td>
<td>4.8 Helicopter Water Impact Scenarios</td>
</tr>
<tr>
<td></td>
<td>4.8.1 Brent Spar (Lagrangian Water)</td>
</tr>
<tr>
<td></td>
<td>4.8.2 Cormorant Alpha (Lagrangian Water)</td>
</tr>
<tr>
<td></td>
<td>4.8.3 Isles of Scilly (Lagrangian Water)</td>
</tr>
<tr>
<td></td>
<td>4.8.4 Eulerian Modelling</td>
</tr>
<tr>
<td></td>
<td>4.8.5 Comparison of Panel Loads Against Empirical Predictions</td>
</tr>
<tr>
<td>4.9</td>
<td>Modelling Conclusions</td>
</tr>
</tbody>
</table>

| 5       | Emergency Flotation DESIGN Review | 26 |
| 5.1     | Introduction | 26 |
| 5.2     | Emergency Flotation Problems | 26 |
|         | 5.2.1 Floats Not Armed | 27 |
|         | 5.2.2 Floats Armed But Not Activated | 27 |
|         | 5.2.3 Floats Activated But Not Deployed | 28 |

Study I: v
5.2.4 Uneven Float Deployment 28
5.2.5 Incomplete Inflation Due to Adverse Ambient Conditions 29
5.2.6 Float Damage Upon Impact 30
5.2.7 Floats Deployed But Helicopter Immediately Overturns 31

5.3 Summary of Design Recommendations to Improve Emergency Flotation System Crashworthiness 32

6 Cost Benefit Analysis 33
6.1 Overview 33
6.2 Causes of EFS Failure 34
  6.2.1 Float Deployment 34
  6.2.2 Accident Data 34
6.3 EFS Design Modifications 35
6.4 Assessment of Benefits 36
  6.4.1 Effect on Outcome 36
  6.4.2 Effect on Fatalities 37
6.5 Determination of Implementation Costs 39
6.6 Cost-Benefit 39
6.7 Discussion of Results 40

7 REVIEW OF REGULATORY REQUIREMENTS 41
7.1 JAR 29.801: Ditching 41
7.2 JAR 29.563: Structural Ditching Provisions 43
7.3 JAR 29.561: Emergency Landing Conditions 44
7.4 JAR 29.562: Emergency Landing Dynamic Conditions 44
7.5 JAR 29.807: Passenger Emergency Exits 44
7.6 Recommendations For Regulation Changes 44

8 CONCLUSIONS 45

9 RECOMMENDATIONS 47

Acknowledgements 48

References 49

Appendix A: Royal Navy Accident Records 87
Appendix B: Space Capsule and Orbiter Modelling Data 91
Appendix C: Joint Airworthiness Requirements and Advisory Material 93
Appendix D: Cost Benefit Study – NTSB Accident Summaries 111
Appendix E: Cost Benefit Study – UK Accident Summaries 131
Appendix F: Cost Benefit Study – Worked Example 135
# List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1:</td>
<td>WG30 Finite Element Model</td>
<td>51</td>
</tr>
<tr>
<td>Figure 2:</td>
<td>Cut Away of WG30 Model after Ground Impact, Together With Lynx Test Comparison</td>
<td>52</td>
</tr>
<tr>
<td>Figure 3:</td>
<td>Acceleration Time History Pulse Recorded at Cabin Floor</td>
<td>53</td>
</tr>
<tr>
<td>Figure 4:</td>
<td>Acceleration Time History Pulse Recorded at Main Rotor Gearbox</td>
<td>54</td>
</tr>
<tr>
<td>Figure 5:</td>
<td>Arrangement of the Space Capsule Impact Scenario</td>
<td>55</td>
</tr>
<tr>
<td>Figure 6:</td>
<td>Acceleration of Space Capsule from Test and Analysis</td>
<td>56</td>
</tr>
<tr>
<td>Figure 7:</td>
<td>Vertical Displacement of Space Capsule from Test and Analysis</td>
<td>57</td>
</tr>
<tr>
<td>Figure 8:</td>
<td>Finite Element Mesh of Orbiter Space Shuttle</td>
<td>58</td>
</tr>
<tr>
<td>Figure 9:</td>
<td>Lateral Acceleration of Orbiter using Lagrangian Mesh</td>
<td>59</td>
</tr>
<tr>
<td>Figure 10:</td>
<td>Set-up for the two Hull Scenarios Showing Differences in Trim Angle and Flight Path</td>
<td>60</td>
</tr>
<tr>
<td>Figure 11:</td>
<td>Vertical Displacement of Hull for Case 1</td>
<td>61</td>
</tr>
<tr>
<td>Figure 12:</td>
<td>Vertical Acceleration of Hull for Case 1</td>
<td>62</td>
</tr>
<tr>
<td>Figure 13:</td>
<td>Vertical Velocity of Hull for Case 1</td>
<td>63</td>
</tr>
<tr>
<td>Figure 14:</td>
<td>Vertical Displacement of Hull for Case 2</td>
<td>64</td>
</tr>
<tr>
<td>Figure 15:</td>
<td>Vertical Acceleration of Hull for Case 2</td>
<td>65</td>
</tr>
<tr>
<td>Figure 16:</td>
<td>Vertical Velocity of Hull for Case 2</td>
<td>66</td>
</tr>
<tr>
<td>Figure 17:</td>
<td>Brent Spar – Global Acceleration at Full Speed</td>
<td>67</td>
</tr>
<tr>
<td>Figure 18:</td>
<td>Brent Spar – Full Speed: Maximum Plastic Strain Throughout Time Period</td>
<td>68</td>
</tr>
<tr>
<td>Figure 19:</td>
<td>Brent Spar – Half Speed: Maximum Plastic Strain Throughout Time Period</td>
<td>69</td>
</tr>
<tr>
<td>Figure 20:</td>
<td>Comparison of Nodal Velocity for Rigid and Non-Rigid Analysis</td>
<td>70</td>
</tr>
<tr>
<td>Figure 21:</td>
<td>Nodal Acceleration Before and After Filtering</td>
<td>71</td>
</tr>
<tr>
<td>Figure 22:</td>
<td>Location of Nodes for Monitoring Acceleration</td>
<td>72</td>
</tr>
<tr>
<td>Figure 23:</td>
<td>Filtered Vertical Acceleration for Gearbox, Floor and Side Panel</td>
<td>73</td>
</tr>
<tr>
<td>Figure 24:</td>
<td>Cormorant Alpha – Global Acceleration at Full Speed</td>
<td>74</td>
</tr>
</tbody>
</table>
INTRODUCTION

The Safety Regulation Group of the Civil Aviation Authority is currently investigating the crashworthiness of helicopter emergency flotation systems (EFS). The work follows on from GKN Westland Helicopters Limited (GKN WHL) studies into civil and military water impacts [1,2]. The work was given greater importance following the Review of Offshore Safety and Survival [3], commissioned by the Civil Aviation Authority (CAA), which recommended that the provision for flotation after a severe but survivable impact be improved.

CAA commissioned WS Atkins (Contract 084/SRG/R&AD) to undertake a crashworthiness review of EFS design, operation and legislation. The work was divided into the five key tasks summarised below:

- **Task 1 – Literature Review:** The aim of this task was to determine the nature and extent of any relevant work that had been conducted elsewhere, identify accidents where a failure of the EFS system contributed to the consequences and to obtain water impact data from actual accidents and research activities.

- **Task 2 – Computer Modelling:** The aim of this task was to understand and to predict the loadings generated in a typical helicopter airframe during a water impact using finite element (FE) modelling techniques. The techniques were validated against a variety of full scale and model test programmes. The method was then applied to three specific accident scenarios for which there were a significant number of survivors, but which were outside the Federal Aviation Authority’s proposed 95% survivability ditching envelope.

In addition to the WS Atkins modelling work, supporting work was undertaken by BMT Fluid Mechanics Ltd [4]. BMT’s work examined the highly variable nature of water impacts. Their method used an empirical statistical approach to determine the range of possible loadings on single airframe panels and sponsons, over a large variety of impact orientations, speeds and sea states.

- **Task 3 – Review of EFS Design:** A review of typical EFS designs was undertaken and proposals developed to improve overall system functionality, reliability and operation following a water impact.

- **Task 4 – Cost and Benefits Analysis:** The proposals developed under Task 3 were assessed against estimated cost of implementation and potential benefit in terms of reductions of the probability of EFS failure to determine their relative merit.

- **Task 5 – Review of Regulatory Requirements:** Finally, the airworthiness and operational requirements relating to water impact, ditching and occupant egress were reviewed, and recommendations for improvements proposed.

This report describes the work carried out by WS Atkins whilst undertaking these tasks, concluding with a series of recommendations for improving the crashworthiness of emergency flotation systems.
2 DESCRIPTION OF EMERGENCY FLOTATION SYSTEMS

In order to provide additional buoyancy upon ditching, helicopters which operate over water are fitted with emergency flotation devices. They are designed to maintain the emergency exits above water level long enough for the occupants to escape and board the life rafts.

The system comprises two or more inflatable bags mounted either onto the helicopter lower fuselage or to the landing skids. During normal operation the floats are stowed and packed within a protective cover until activation. Different helicopters have different numbers, sizes and locations of flotation units, depending on the inherent buoyancy and stability of the fuselage. Typical mounting locations are outrigger sponsons (S61N), pods (AS332L rear), fuselage (AS332L nose) and skids (Bell 206).

The floats are inflated from canisters of pressurised gas. The mechanism for inflating the devices relies on two stages. The first stage is arming the inflation system. This is necessary to prevent inadvertent inflation while in flight. Some systems have additional safeguards that prevent inflation outside certain flight conditions. The second stage is deployment, which is triggered either by manual operation or by immersion switches and/or inversion switches.

3 LITERATURE REVIEW

3.1 Introduction

The purpose of this stage of the work was to develop an understanding of the water impact response of helicopters from inspection of historical records and published research. The objectives of this stage were:

1 To identify potential improvements to the EFS.

2 To provide an indication of the potential benefit resulting from improvements to the EFS.

3 To provide validation data for Task 2 of the project which involved computer simulation of helicopter water impacts.

The aim of the review was therefore to examine accidents that were considered survivable, but where failure of the EFS for whatever reason increased the likelihood of occupants drowning. In addition, a literature search of relevant research papers and reports was also carried out.

3.2 Methodology

The main purpose of the study was to establish the data associated with accidents where fatalities occurred due to failure of the EFS. Accidents considered non-savable were disregarded, as the impact in these cases often resulted in gross failure of the fuselage.
The review utilised the following sources:

- Relevant information from the literature search.
- Review of information held in the CAA library.
- Review of Air Accident Investigation Reports.
- Communication with the CAA Safety Data Department
- Communication and meetings with the UK Air Accident Investigation Branch (AAIB).
- Communication with Royal Navy Flight Safety and Investigation Centre.
- Review of information held at Royal Navy Flight Safety and Investigation Centre.
- Communication with helicopter insurers.
- Communication with US Federal Aviation Authority (FAA).

The results from the different sources are described in Section 3.4.

The main information sought from each source was as follows:

- Whether the flotation systems functioned correctly.
- Whether the accident was deemed survivable, i.e. the fuselage remained relatively intact.
- The consequence of EFS failure in terms of casualties.
- Aircraft loading and impact parameters.
- Structural damage.
- Sea state at the time of the accident.

In addition to the above requirements, the study concentrated on medium to large helicopter types such as the Sikorsky S61-N and AS332L Super Puma, although relevant data on other helicopter types is also included.

3.3 Results of Literature Review

An on-line search was carried out on three different databases. A general engineering database, an aviation database and a US government publication database. For all searches the combination of keywords used were:

(\textit{helicopter or rotorcraft}) and (\textit{flotation or floatation or ditching or impact or crash})

This generated a title search of some 300 articles.
The most noteworthy result of the search is that little new information was discovered. A similar exercise had been carried out by GKN Westland Helicopters Ltd (GKN WHL) in 1993 [1] and partly in 1995 [2], to provide information for general structural response to helicopter impacts. The current review served to confirm the results of these studies. In addition it was already known that the US FAA were also engaged in sponsoring work relating to helicopter EFS [5,6,7].

The review also highlighted some research work being carried out in the National Aerospace Laboratory in The Netherlands [8,9]. The work considers design of compliant composite panels for use in a helicopter floor to withstand water impact. This work is of interest to this study, particularly in the latter stages considering mitigation, but is not of direct relevance.

The work being carried out in the US was researched further during an American Helicopter Society (AHS) Conference in Phoenix during September 1998. General discussions were held on the current status of US research into helicopter crashworthiness including helicopter airbags, energy absorbing seats and composite energy absorbing design. Of particular interest were papers from Sikorsky [10] using MSC/DYTRAN to model helicopter water impact and a paper on the developments of hybrid approaches [11]. The general conclusion was that the work being carried out in the US was at a similar stage to research in the UK. The conference agreed that there was a lack of good validation data; the US DoD announced that they were in the process of funding some full scale drop tests of helicopters onto water which would hopefully fulfil this need.

3.4 Results of Accident Review

As mentioned in Section 3.3, a number of sources were contacted to establish data relating to ditched or impacted helicopters where failure of the EFS had increased the chances of fatalities due to drowning. The quality and quantity of data held by these sources is discussed below.

3.4.1 Air Accident Investigation Branch (AAIB)

The AAIB investigates UK civil and also military aircraft accidents. The main aim of each investigation is to establish the cause of the accident and to recommend proposals to address any operational or design shortcomings highlighted by the investigation.

The findings of significant accidents are published in AAIB reports. Since the primary issue of the investigation is to establish cause of the accident, the areas of interest to this study are not generally addressed in any detail. This approach is changing though, and more recent accident reports present additional data. Some of the additional information is as a consequence of helicopters now carrying flight data recorders. These provide information regarding the helicopter orientation and velocity at the point of impact that previously had often to be based on judgement.

In addition to the reports, the AAIB was approached to establish what additional data might be held. Unfortunately the information required by this study is often not gathered or is not kept beyond the investigators’ personal copies. Some further information is available for the most recent accidents, but this diminishes rapidly for events that occurred more than 5 or 6 years ago.
Discussions were held with several of the investigating engineers on 9th January 1997 at Farnborough. The main source of additional data gathered related to video footage of the wreckage of G-TIGH (accident near the Cormorant Alpha platform) lying on the sea bed and during recovery. The footage shows the relatively intact fuselage and EPS system. Damage to the nose section is visible but it is difficult to establish if damage occurred during the initial impact with the sea or subsequently with the sea bed. This is a factor in most accidents where the airframe sank. Often, further damage is caused during recovery of the airframe.

3.4.2 Royal Navy Flight Safety and Accident Investigation Centre (RNFSAIC)

The RNFSAIC performs a similar role to the AAIB for Royal Navy (RN) accidents. They investigate accidents and produce a report to establish the cause. The RN operate the Sea King, from which the civilian Sikorsky S61-N was derived. The search was therefore restricted to this helicopter type, although consideration was also given accidents involving the Wessex helicopter which is of a similar size to the Sea King.

A review of the available accident reports from 1980 was carried out at the RNFSAIC. Of the 10 accidents reviewed only one matched the requirements but the fuselage sank in very deep water and was not recovered. The survivors were also unsure as to the precise condition of the helicopter after the accident. Some of the accidents, where the airframe broke up on impact, were considered not survivable. A list of the corresponding accidents and associated descriptions is given in Appendix A for completeness.

The amount of historical data available was generally better than for the AAIB records. The main reporting on structural damage recorded major damage such as fuselage break-up or loss of sponsons. It was concluded however that, apart from data for the assessment of benefit (Task 4), the only useful data related to the retention, or otherwise, of the Sea King forward sponsons for modelling validation purposes.

3.4.3 CAA Flight Safety Data Department

The CAA maintain a database of all UK civil aircraft accidents. The database also contains some military accidents as well as some non-UK accidents. The database contains only basic information similar to the International Civil Aircraft Organisation (ICAO) database, with additional CAA comments.

The database is, however, useful in ensuring that no obvious accident records are missed, and in identifying overseas accidents of interest to the study. For those countries which publish air accident reports it was considered by the CAA Safety Data Department that the level of information would be comparable to the UK reports and would therefore be of limited value. It was not considered feasible to pursue non-US overseas accident data.

3.4.4 Aircraft Insurance Companies

The helicopter insurers also keep records relating to helicopter accidents and associated damage. One of the major companies, Air Claims, were contacted to establish the quantity and quality of records they kept. In addition to records similar to the ICAO database, they also have limited information relating to the extent of damage for accidents where they were the acting loss adjusters. This information
relates more to the cost of repairs, and does not distinguish between damage caused at different stages of the accident or subsequent salvage. Where the helicopter is not considered economically viable to repair, the reports are more limited as the loss equates to the cost of the complete helicopter. This is often the case for those helicopters where flotation systems failed and the helicopter sank.

It was considered that it was not worthwhile pursuing data from this source at this stage.

3.4.5 Federal Aviation Administration (FAA)

The FAA have sponsored work reviewing helicopter ditching and water related impacts [5,6]. As a result of these studies, occupant drowning was identified as the most significant post impact hazard and resulted in additional research work [7], which concentrated on the performance of EFS and possible areas of improvement. A brief summary of the data held within these reports relevant to this study is given below.

The data used in the reports relates to 67 accidents that occurred in the US between 1982 and 1989. The report considers all types of helicopter, therefore some small and some very large helicopter accidents are included in the results. The sample sizes for the individual helicopter types included, however, do not allow meaningful comparisons to be made. The report identifies 26 fatalities that occurred in survivable or partially survivable accidents. These were composed of 19 fatalities due to drowning, 1 due to exposure and 6 through impact related injuries. In considering these figures it should be noted that a significant proportion of US over water flights take place over the Gulf of Mexico, where sea conditions are considerably less harsh than the North Sea.

The problems with the EFS were categorised by failure type and the number of occurrences of each. Of a sample size of 35 float-equipped helicopters, the problems and associated frequencies of occurrence can be summarised as follows:

- no problems (11);
- damaged by impact (7), (3 of which deployed unevenly);
- did not deploy after activation (3);
- uneven deployment (2);
- other problems (2);
- floats armed but not activated (2);
- floats not armed (8).

The majority of the impact damage to floats occurred with systems where the float was inflated prior to impact with the water. For the three EFS that failed to deploy, one suffered electrical damage caused by the impact, and no reason was given for the failure of the remaining two.

Unfortunately, no direct correlation can be made between the number of fatalities.
The research also highlights the fact that occupants survived impacts where the helicopters’ vertical and horizontal velocities far exceed the FAA’s proposed 95% survivability envelope. However, occupants often encountered post-impact difficulties and drowned.

3.5 **Summary of UK Civil Water Impacts**

A summary and discussion of the UK civil helicopter fatal water impacts since 1980 is given below. The list is confined to medium to large helicopter types that are of relevance to this study. A description of each fatal accident is provided in this section. In addition, Section 3.5.8 gives a brief description of relevant non-fatal impacts.

3.5.1 **G-BJIF, Bell 212, 12/8/81, North Sea (Dunlin Alpha) [12]**

- **Conditions**: Helicopter hit the water with an unknown rate of descent (>1.5m/s). Helicopter inverted almost immediately. Helicopter remained upturned but floating and was used as support for survivors.

- **Damage**: No significant damage to the cabin space. Lower fuselage skins stoved and fuselage frames, keel members and cabin floor suffered extensive damage.

- **Flotation System**: EFS automatically deployed but damage sustained during impact had caused the right feeder pipe to rupture.

- **Casualties**: 1 fatality due to exposure out of 14 occupants.

3.5.2 **G-ASWI, Wessex 60, 13/8/81, North Sea [AAIB]**

- **Conditions**: Helicopter crashed into sea following loss of power to main rotor gearbox. Helicopter crashed from 1500ft.

- **Casualties**: All 13 occupants were killed. This was considered a non-survivable impact.

3.5.3 **G-BDIL, Bell 212, 14/09/82, North Sea (Murchison Platform) [13]**

- **Conditions**: Impact with water with significant forward speed, considered non survivable accident.

- **Damage**: Damage typical of high speed forward impact.

- **Flotation System**: No mention of EFS in AAIB report.

- **Casualties**: All six occupants died.

3.5.4 **G-BEON, Sikorsky S61N, 16/7/83, St Marys (Isles of Scilly) [14]**

- **Conditions**: Aircraft flew into water in straight horizontal flight on approach to landing.

- **Damage**: Both sponsons broke off. Water entered the cabin forcibly, and water pressure burst two freight bay hatches in floor. Water also destroyed the aircraft.
hull for most of its length below floor level. Helicopter then rolled over and sank.

- **Impact Conditions**: Aircraft slightly nose down and banked slightly to port. Forward airspeed 80 to 100 knots (41 – 51m/s), low rate of descent. Large number of seat failures (post accident testing suggest that this occurs at longitudinal accelerations >12g). Sea State calm.

- **Flotation System**: The flotation systems were attached to the sponsons and were therefore unavailable for deployment.

- **Casualties**: 6 survivors, 20 fatalities. No incapacitating injuries, all fatalities caused by drowning.

### 3.5.5  
**G-BJIR, Bell 212, 20/11/84, North Sea [AAIB]**

- **Conditions**: Control of helicopter lost following decay of rotor RPM. Helicopter then fell into sea. Considered non-survivable accident.

- **Casualties**: Both crew died in the accident.

### 3.5.6  
**G-BEWL, Sikorsky S61N, 25/07/90, North Sea (Brent Spar) [15]**

- **Conditions**: Helicopter tail rotor struck handrail on Brent Spar. Helicopter struck helideck, causing damage to left-hand sponson and fuselage, and causing left hand emergency escape hatch to enter cabin. Helicopter then fell off platform almost vertically into the water where it sank almost immediately.

- **Damage**: Damage to left hand sponson consistent with large lateral force (not vertical) on deck impact. Right hand sponson detached in rearward direction and nose of sponson damaged indicating impact with the water. Fuselage suffered failure from close to cockpit bulkhead to just aft of cargo door (station 120 to station 170). Tail boom failed and folded to left. Damage to seats indicated that impact with water was mainly vertical but had some longitudinal and lateral components. Impact less severe in rear of cabin.

- **Impact Conditions**: Helicopter fell through 95 feet, therefore impact velocity was 75 feet/s (50 mph, 22m/s), pitch 5° to 10° below horizon and roll 10° to right of horizontal. Estimated deceleration 20-25g at cabin floor. Sea State calm.

- **Flotation System**: Intact and attached to damaged sponsons, however it was not deployed.

- **Casualties**: 7 survivors, 6 fatalities. Two suffered severe injuries as a result of the impact. The remainder suffered less severe injuries but were unable to escape and drowned.

### 3.5.7  
**G-TIGH AS 332L, Super Puma, 14/03/92 North Sea (Cormorant ‘A’ Platform) [16]**

- **Conditions**: Aircraft struck the water when flying between two platforms. The aircraft entered an uncontrolled descent which pilot attempted to recover. After impact with water aircraft rolled over to an inverted position and then sank within a minute or two of impact.
• **Damage:** Damage to aircraft suggests initial impact occurred into a wave on the right side of the nose area. Report indicates crushing damage to fuselage.

• **Impact Conditions:** Pitch 4.1° nose up, roll 0.3° left. Rate of descent 25 feet/second (7.6 m/s) and derived ground speed of 43 Kt. Severe wind and snow, Sea State high (significant wave height 7 – 8 metres, max. 11 – 13 metres, period 8 – 10 seconds).

• **Flotation System:** Two bags mounted in collar around nose, and one each at structural frames at the sponsons. System was armed and post accident testing revealed the system was working but required firing by pilots. No water immersion switches.

• **Casualties:** 6 survivors, 11 fatalities. All injuries were slight and should not have affected the ability of an individual to escape from the helicopter. Five of the fatalities were trapped inside the cabin.

3.5.8 **Non Fatal Accidents**

G-ASNL, Sikorsky S61N, 11/03/83, North Sea [AAIB]

Controlled ditching. EFS successfully deployed. No fatalities but helicopter sank during attempted recovery.

G-BDIJ, Sikorsky S61N, 17/10/88, Handa Island [17]

Helicopter inadvertently flown into sea. Starboard side of boat hull damaged due to impact with water at approximately 5° nose down pitch, banked 15° to right and slipping to the right. Helicopter moving forward at no more than 5 Kt. and descending in excess of 1000 fpm (5.1 m/s) at point of impact. Ruptures in skin in areas below cockpit, boat hull badly creased. Starboard sponson torn away. Helicopter subsequently sank. Calm sea. Crew escaped, no fatalities. No mention of flotation system in AAIB report.

G-BDES, Sikorsky S61N, 10/11/88, North Sea [AAIB]

Helicopter ditched but overturned in strong winds. All passengers and crew escaped. Helicopter remained afloat but inverted for 24 hours before eventually sinking.

G-TIGK, AS332L Super Puma, 19/01/95 [AAIB]

Helicopter underwent successful auto-rotational ditching following lightning strike. EFS deployed and all occupants evacuated safely into a liferaft.

3.6 **Conclusions**

A survey of UK Civil and Royal Navy helicopter water impacts has been conducted with regard to performance of emergency flotation systems. In addition, a worldwide literature search has been carried out to identify existing research into helicopter emergency flotation systems.
The conclusions of the data review are:

- Little 'new' data to that already known at the start of the review is available.
- The accident data is almost exclusively limited to the information published in the accident reports, especially for accidents more than 8 years ago.
- Where levels of damage are supplied, they are often too general for detailed comparison with computer modelling techniques.
- Sponson mounted emergency flotation systems, such as the S61N, are particularly vulnerable to impact damage.
- Pod mounted emergency flotation systems are less prone to damage.
- Significant fatalities were observed in accidents where the EFS had failed to arm and/or deploy.

4 COMPUTER MODELLING

4.1 Introduction

The review of crash data and EFS performance, reported in Section 3, indicated that the location of the floats may have an effect on whether or not they are damaged on impact.

It was proposed that the impact of a helicopter with water would be modelled using finite element techniques (FE), so that the loads and accelerations on different panels of the aircraft could be investigated. In this way, the best location for minimal damage could be established for both location of floats and pipe routing. It was also anticipated that the method could be used to determine the panel force levels during actual survivable impacts with a view to defining a maximum panel force design limit.

A non-linear FE model of a WG30 helicopter was developed from data supplied by GKN WHL. This aircraft was considered to represent a typical design of medium weight helicopter. Water models using two separate modelling techniques were also developed.

The finite element software LS-DYNA 3D was chosen to model a variety of impacts between the helicopter and water models. LS-DYNA 3D is widely used to assess the plastic response of structures under extreme loads and has a variety of fluid modelling methods.

In order to gain confidence in the modelling results, it was necessary to validate both the responses of the WG30 and water models.

For the airframe used in the assessment, no water or ground drop test results were available. A survey of available test data highlighted that, for most helicopters where ground drop test data was available, the landing gear was usually deployed. The load paths for impacts with the gear deployed are very different from water impacts. For ground impact conditions, the initial contact normally occurs on the landing gear.
(when deployed) which absorbs some of the impact energy. The load is then transferred to the airframe at discrete points where the undercarriage is attached. When an impact occurs with water, the load is transferred over the entire fuselage area in contact with the water. The only useful validation data available was that of a drop test of a similar airframe (GKN WHL Lynx) onto a flat concrete surface, with the landing gear retracted [18]. This was therefore used for the validation of the airframe model.

The water modelling methodology was validated by analysing re-entry space capsule impacts for which test data existed [19]. This was to validate the suitability of the water modelling method for vertical drop type scenarios. For impacts with longitudinal as well as vertical motion, the water modelling method was validated against Sea Plane Hull and Space Shuttle test data [20,21].

To summarise, due to the lack of helicopter water impact data, it was proposed that four simulated impacts would be validated. These were:

- Helicopter model validation against a level drop test of a similar helicopter with landing gear retracted.
- Water model validation against the NASA Gemini space capsule drop tests for impacts with main component of velocity vertical.
- Water model validation against space shuttle orbiter data for impacts with large longitudinal velocities.
- Water model validation against Sea Plane Hull and Space Shuttle data for impacts with vertical and longitudinal velocities.

Once the validation procedure was completed, three specific helicopter water impact scenarios were analysed. These were the accidents that occurred at the Brent Spar, the Cormorant Alpha and the Scilly Isles [15,16,14]. These scenarios represented water impacts that were known to have a significant number of survivors, but which were considerably outside the FAA’s proposed 95% survivability curve. Panel loadings and structural accelerations were compared against damage described in the accident reports. Both full speed and half speed impact conditions were considered to try to understand trends in the response of the structure.

In addition to the WS Atkins modelling work, supporting work [4] was undertaken by BMT Fluid Mechanics Ltd (BMT). Their method used an empirical statistical approach to determine the range of possible loadings on single airframe panels and sponsons in isolation. The aim of BMT’s work was to consider the likely loadings over a very large number of possible impact scenarios and parameter variation using a Monte Carlo simulation approach. The work was intended to complement the specific accident modelling being performed by WS Atkins. Panel force results predicted by the two methods for the Brent Spar and Cormorant Alpha incidents were made for comparison purposes.

4.2 Modelling Methods

LS-DYNA3D contains two processing techniques, Lagrangian and Eulerian, which can be coupled together. In both techniques, the equations of motion are integrated in time using central differences. The method requires very small time steps for a stable
solution. Thus, it is particularly suitable to assessing the crash behaviour of aircraft structures. These analyses are complex in that they involve both non-linear dynamic material response and large structural deformations. It is widely used in the automotive and rail industries to develop crashworthy designs.

The main advantage of this explicit method is that the governing equations are coupled allowing an ‘element by element’ solution, requiring no global stiffness matrix assembly or inversion. The method is generally recognised to be very robust for highly non-linear problems.

The LS-DYNA3D code contains many material models and, importantly for crash analysis, contact in the structure is efficiently handled by introducing temporary ‘penalty forces’ as additional external forces to resist penetration and control sliding.

**Structural Modelling (Lagrangian)**

The Lagrangian method is the most common finite-element processing technique for engineering applications.

Grid points are located on the body being analysed. Elements of material with constant (invariant) mass connect the grid points, forming a mesh. As the body deforms, the grid points move with the body and the elements (mesh) distort. The LS-DYNA3D Lagrangian processor uses explicit formulation and allows large deflection with material and geometric non-linearities. The helicopter, space capsule, orbiter and seaplane hull models were all constructed using Lagrangian elements.

**Fluid Modelling (Lagrangian)**

Fluids may be modelled in a similar way to structures using Lagrangian elements. The fluid is defined using an elastic material with zero shear modulus, which effectively allows neighbouring elements to slide relative to each other. Only the bulk modulus and density have to be defined to capture the shock wave through the fluid.

**Fluid Modelling (Eulerian)**

The Eulerian method may also be used for analysing fluids. The grid points remain fixed in space, defining fixed volumes, or elements. As the fluid moves through these Euler elements or mesh, the mass, momentum, and energy of the fluid is transported from one element to another. The LS-DYNA3D Eulerian processor is essentially an explicit in-viscid computational fluid dynamics code.

### 4.3 Validation of Helicopter Model

The airframe used in the analysis was based on the GKN WHL WG30 helicopter. This aircraft is a medium weight helicopter (4500 kg), constructed from riveted aluminium ribs, stringers and panels.

**Airframe Model**

The FE model of the WG30 was constructed by adapting an existing model used by GKN WHL to undertake vibration assessments. The model incorporated all the important structural components, including the main ring frames and outer fuselage
panels. The mesh density in the model was increased in the lower fuselage and roof sections, where large deformations were expected. The detail in these sections extended to the explicit modelling of the stringers, ribs and panel stiffeners.

The final helicopter model is shown in Figure 1. It utilises some 6,000 elements, mainly four noded shell elements for the main structure, plus a few beam elements to represent the tail rotor assembly. An elastic-plastic material was used to model the majority of helicopter fuselage. The following assumptions were applied in the model construction to ensure that reasonable development and analysis time-scales could be achieved.

- Failure was not included in the material model since, by assessing the levels of plastic strain in the model, it is possible to predict the extent of failure, if any, in the material.

- The rivets connecting the fuselage components were not modelled explicitly; instead a continuous mesh was used.

- The modelling detail extends to the individual stringers in the lower regions of the fuselage, however beam elements were used in the upper structure to provide stiff connections in the engine, gearbox and rotor head.

- Point masses were added to the model to represent the large mechanical items such as the engines, gearboxes and fuel.

It was considered that the simplifications listed above were not important given the types of results required and the levels of deformation observed in the accidents.

**Validation Method**

The airframe model was validated using data from a drop test of the Lynx helicopter onto a flat concrete surface with the landing gear retracted [18]. The Lynx and WG30, although not identical, are very similar in terms of weight, size and main structural components. The WG30 design uses many of the same components and design features as the Lynx, as it was the next helicopter that GKN WHL designed of this size. Both helicopters have their two engines, main rotor gearbox (MRGB) and rotor assembly mounted across two forged aluminium ring frames, located either side of the passenger compartment doorway. The airframes date from the same era and use the same fabrication techniques and materials.

The test results for the Lynx were therefore considered sufficiently representative for validation of predicted deformations of the main fuselage structure and levels of deceleration experienced in important areas.

The test configuration was simply represented in the analysis by modelling the ground as a rigid surface. The model was given the same vertical impact velocity as the test airframe of 8.2m/s, with no discernible pitch or roll.

The data recorded in the test were acceleration and relative displacements within the cabin. In addition, several high-speed cameras were used to record the event from different directions. Despite the differences in the designs of the tested and analysed helicopters, their behaviour was remarkably similar.
Results

Figure 2 shows a cut-away view of the WG30 helicopter model after impact with the ground. Structural deformation can be seen in the cockpit floor and rear bulkhead with buckling of the main ring frames. It can also be seen that the cabin roof has dropped, due to the mass of the engine, gearbox and rotor head in this region. This ties in well with observations of the Lynx drop test (see lower plate in Figure 2), showing similar levels of deformations in the key areas.

The acceleration time histories recorded at the cabin floor during the test and analysis are shown in Figure 3. Both curves exhibit a short peak, followed by a period of low acceleration as the cabin floor oscillates. The test result showed a double peak, whereas the analysis showed only a single peak. The double peak in the test is likely to be a result of the fuselage initially striking the ground remotely from the accelerometer location. The peak values of acceleration for both curves are around 110-120 g.

The accelerations recorded at the MRGB for the test and analysis helicopters are shown in Figure 4. The test helicopter exhibited a peak acceleration of nearly 80 g whilst the analysis peak was only around 25 g. The variation was considered to be caused by the stiffer structural design of the test airframe compared to that employed in the analysis and the simplified connections between the MRGB and main structure assumed in the FE model.

Conclusion

Given the structural differences between model and test sample, these results were considered encouraging in the context of predicting generic deformation modes and local accelerations.

4.4 Validation of Water Model for Vertical Impacts – Capsule Model

The water model was validated against a drop test performed by NASA on the Gemini space capsule [19]. The test report investigates the water landing characteristics of a conical shaped re-entry capsule having a segment of a sphere as its base.

Capsule Model

The geometry of the space capsule was relatively straightforward and a rigid surface FE model of the capsule was created. The physical data on the capsule can be found in Table 1 of Appendix B. The correct mass and inertia properties were explicitly attached to the capsule in the FE model. The capsule was modelled with water represented by both Eulerian and Lagrangian meshes.

Impact Conditions

The arrangement of the Space Capsule impact scenario is shown in Figure 5. It consists of a body of water 6x6x4m with an average element length of 300mm.

The NASA test report recorded both acceleration and displacement time histories for the capsule. The report, however, did not detail the instrumentation used in the test
or the level of filtering employed. Therefore, some judgement was used in interpreting the LS-DYNA3D results and an SAE 180Hz filter was applied to the analysis data.

**Comparison of Acceleration Results**

The comparison of accelerations for the test capsule and the two FE analyses is shown in Figure 6. These are for an impact velocity of 9m/s in the vertical direction, with no inclination of the capsule.

The accelerations predicted in the analyses were in good agreement with the test results for both the Eulerian and Lagrangian water models. Both analyses reproduced the correct shape of test curve, but with more noise being exhibited by the Eulerian model. The peak acceleration recorded in the test was 41m/s², compared to the FE prediction of 42m/s² for the Lagrangian model and 44 m/s² for the Eulerian model.

For the Lagrangian model, the peak acceleration was delayed by approximately 0.01 seconds. This was not considered to be significant and within the tolerances of the analysis and test instrumentation.

**Comparison of Displacement Results**

A comparison of the test and analysis displacements of the capsule are shown in Figure 7. As with the accelerations, the curves generally show good agreement.

The Lagrangian model under predicts the displacements, especially towards the end of the analysis, where the results start to diverge. The results show that the Lagrangian mesh formulation used to model the water is ‘too hard’ towards the latter stages of the analysis. This is due to its inability to model fluidity effects, which require significant displacement of the water.

The Eulerian model shows very good agreement with the test data. Initially the impact is slightly “harder” than the test results leading to an underestimate of displacement. However, at the end of the analysis, the displacement is overestimated compared to the test results. This was considered to be due to the omission of buoyancy, which will tend to reduce the displacement into the water.

**Conclusion**

Both the Eulerian and Lagrangian water models gave good predictions for the initial peak deceleration for vertical water impacts.

The Eulerian model was better at predicting displacements over the duration of the analysis due to its ability to model more accurately fluid flow effects. Towards the end of the analysis, the Eulerian mesh predicted too large a displacement due to the omission of buoyancy forces within the model.

**4.5 Validation of Water Model for Horizontal Impacts – Orbiter Model**

The Orbiter validation model is shown in Figure 8. The test arrangement [21] was based on a 1/20th scale model of a ‘rigid’ space shuttle. The test arrangement was very different to the capsule, as the shuttle had a large forward velocity and it skimmed across the water surface.
Orbiter Model

In a similar manner to the capsule model, the Orbiter model was constructed from rigid shells that represented the outer surface only. Appropriate mass and inertia properties were applied to the rigid body geometry. The physical data on the orbiter is summarised in Table 2 of Appendix B.

Impact Conditions

The impact conditions for the model was a forward velocity of 78m/s, 2.3m/s vertical velocity and 12o nose-up. The large forward velocity required a large water model, 200x54x5m in size.

As with the capsule modelling, the Orbiter test report documented accelerations and displacements of the test model. Again, both Lagrangian and Eulerian water models were considered. One of the issues with the fly in incident was that the event had a long duration relative to the vertical drop. The Orbiter also bounced along the surface and therefore spent a significant amount of time travelling through air. The long event duration resulted in long simulation run times.

Results

The results for the Lagrangian water mesh are shown in Figure 9. Initially, the rear section of the Orbiter hit the water (at 0.02s), and then bounced upwards. Whilst in the air and still travelling at a large longitudinal velocity, the nose rotated downwards before descending and striking the water for a second time (0.8s onwards).

The initial deceleration, where the rear of the Orbiter struck the water, for both the test and analysis occurred at the same time (0.02 s). A peak of 0.5g was predicted by the analysis compared to 0.25g in the test. However, in the analysis the deceleration pulse was sharper and of shorter duration.

The nose of the Orbiter contacted the water again in both cases at approximately 0.8s, indicating the correct flight time between the impacts was predicted. However, the maximum deceleration for the analysis was much larger, 13g compared to 5.5g for the test. Similarly, the analysis deceleration pulse was extremely sharp compared to the sustained deceleration observed in the test. This was due to the nose of the Orbiter not digging into the water in the analysis. The Lagrangian water model could not accommodate significant fluid displacements and planing effects, hence, the Orbiter was not sufficiently retarded and skimmed across the water's surface in the analysis.

The model was re-run with an Eulerian water formulation. Due to the large size of the water model, it was only possible to use a coarsely refined mesh. Even with a coarse mesh the run times were excessively long. After several weeks of solving, no useful data had been produced. The size of the problem was simply too big to be solved effectively with the current level of computing power. (Silicon Graphics Origin 2000 with four parallel microprocessors)
Conclusions

The Lagrangian water model was found not to be capable of modelling impacts with large components of horizontal velocity. The orbiter did not plough into the water due to the inability of the Lagrangian mesh to capture large fluid flow effects.

For the Eulerian model, no usable results were obtained due to the high speed of the Orbiter, long analysis times and the low density of the water mesh.

4.6 Validation of Water Model for Horizontal Impacts– Seaplane Hull Model

The Orbiter work had shown the Lagrangian water model to be unsuitable for impacts with large longitudinal velocities, and the model was too large and complex to solve with the Eulerian water model. Therefore, in order to assess the suitability of the Eulerian model, a smaller problem with a slower impact speed was required. Work performed on seaplane hulls landing on water was therefore chosen to validate the Eulerian water for planing impacts.

The experimental data on seaplane hull impacts was obtained from a literature review carried out by BMT [20]. The experiments were performed at the NASA Langley Laboratory and the data contained results from tests on seaplane hulls for impacts with both longitudinal and vertical velocities.

The data supplied with the BMT report included the following information:

- Geometrical drawings of the seaplane hulls.
- Graphs of vertical displacement, velocity and acceleration versus time.
- Data on trim angle and flight path angle.

Methodology

Two hull impact scenarios were modelled using the Eulerian water modelling method. Figure 10 shows the finite element mesh for the two cases studied. This figure also shows the differences in flight path angle and trim angle. The configurations are summarised in Table 1 below. They represent extremes of hull-water approach used in the tests. Case 1 had a small trim angle with a steep flight path, whilst Case 2 had a large trim angle and a shallow flight path.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant Velocity at contact with water</td>
<td>13.8 m/s</td>
<td>29.4 m/s</td>
</tr>
<tr>
<td>Trim angle</td>
<td>3°</td>
<td>12°</td>
</tr>
<tr>
<td>Flight path angle</td>
<td>6.22°</td>
<td>1.13°</td>
</tr>
</tbody>
</table>

Table 1 : Seaplane Hull Impact Conditions.

The hull was modelled from drawings supplied in the report, again using rigid shell elements.
Case 1 was modelled for 0.09 seconds with four different setups:

- Zero gravity, normal mesh
- Zero gravity and refined mesh
- Gravity on hull only, normal mesh
- Gravity on water only, normal mesh

Case 2 was modelled for 0.09 seconds with two different setups:

- Gravity on hull, normal mesh
- Zero gravity, normal mesh

The results were compared for velocity, displacement and acceleration in the vertical direction against those from the test.

Results

The results for Case 1 are shown in Figures 11 to 13. The basic analysis results (zero gravity), show that the displacements and velocities were lower than the test results. The accelerations (Figure 12) exhibited a large initial peak that was not shown in the test data.

Increasing the mesh density increased the accuracy of the results, but they were still significantly different to the test data. The large initial acceleration pulse still remained.

Applying gravity to the hull only slightly reduced the vertical accelerations, resulting in larger vertical velocities and displacements. Applying gravity only to the water had little effect on the results.

The results for Case 2 are shown in Figures 14 to 16. The results show that good agreement was made between test and analysis when zero gravity was applied. Applying gravity to the hull increased the levels of acceleration, velocity and displacement.

Discussion

The results of the analyses for the two cases were considerably different. This may be due to the characteristics of the impact being different. Case 2 was travelling about twice the speed of Case 1. Also Case 1 was closer to a vertical drop situation, whereas in Case 2 the back of the hull hits the water rather than the underside of the hull.

Characterising different types of impact for complicated aircraft structures could prove difficult. In these situations, mesh refinement would have to be carried out until convergence of the solution had been obtained. However, for large models this is likely to result in mesh densities that are beyond the scope of today’s computing power.
Other questions arise of the validity of the test data. The tests were carried out in the late 1940s and early 1950s. The test apparatus, described in the BMT report [20], included a ‘buoyancy engine’ as part of the dropping mechanism. This buoyancy engine was to “represent aerodynamic lift, and thereby control the vertical velocity of the model after contact with the water”. However, no detailed description is given of the degree of aerodynamic lift given, nor of the accuracy and repeatability of the lift. All that can be determined is that the lift is somewhere between free fall and zero gravity – the bounds of the analysis. According to the BMT report, there also seems to be some question as to the accuracy of the device used to measure the velocity and displacement. It is apparent that the sample rate of the test data may not have been fast enough to capture the initial high accelerations encountered by the seaplane hull.

Given these factors, there is doubt over the suitability of the data for validation of the analysis methodology.

4.7 Validation Conclusions

Given the differences between the model and the airframe under test, good validation was achieved for the response of the WG30 airframe model.

Both the Lagrangian and Eulerian water models were found to be suitable for vertical impacts. However, the Lagrangian approach only gave correlation over the initial impact duration. Longer duration events, or impacts with large horizontal velocity components require the accurate representation of fluid flow effects, which cannot be accurately modelled using the Lagrangian approach.

It was concluded from the seaplane hull and Orbiter work that the Eulerian approach was more suitable for planning impacts. However, it appears likely that for most cases, fine mesh densities would be required to give good answers. This would be difficult to achieve given the limitations of current computer hardware.

4.8 Helicopter Water Impact Scenarios

Three actual accident scenarios were modelled using both Eulerian and Lagrangian meshes to represent the water. The three cases are summarised in Table 2 below:

<table>
<thead>
<tr>
<th>Craft Velocity m/s</th>
<th>Pitch</th>
<th>Roll</th>
<th>Sea Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>Brent Spar</td>
<td>0</td>
<td>0</td>
<td>-22</td>
</tr>
<tr>
<td>Cormorant Alpha</td>
<td>22</td>
<td>0</td>
<td>-7.6</td>
</tr>
<tr>
<td>Isles of Scilly</td>
<td>41</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Helicopter Impact Conditions.
Each scenario represents a helicopter/sea accident which resulted in a full accident investigation by the AAIB, [14, 15, 16]. Both full (actual) and half speed impact conditions were analysed to determine trends in the response of the airframe.

The Brent Spar scenario essentially represents a vertical drop; the Isles of Scilly an impact with longitudinal motion only; and Cormorant Alpha an impact with both longitudinal and vertical motion.

It should be noted that the helicopters involved in the actual accidents were considerably stronger that the WG30 model used in the FE analysis:

- A Sikorsky S61N was involved in the Brent Spar and Isle of Scilly accidents. This helicopter has four main structural ring frames as opposed to just two on the WG30. It also has its engines and gearbox mounted on separate frames rather than having all the massive items supported in one place.

- A Super Puma was involved in the Cormorant Alpha accident which also has a more robust ring frame arrangement and more generous distribution of massive items.

Both these helicopters were therefore designed to survive much higher impact loadings than the WG30. It was anticipated that some of the scenarios, although survivable for stronger airframes, may result in gross structural failure of the WG30 model.

**Post Processing**

The results for the impact scenarios were post processed using a combination of four different methods:

1. **Global Acceleration**: The overall response of the airframe can be examined by looking at the global acceleration of the model over the duration of the impact. The global acceleration is the average of the resultant accelerations of each element in the model. It only has a magnitude, although the direction can be estimated from the model’s general retardation and flight path. The method averages out any local effects in the structure to give the overall response. It is useful for assessing general behaviour and gives a degree of confidence in the overall performance of the model.

2. **Plastic Strain**: The likelihood of failure of parts of the structure can be predicted by looking at plastic strain. For aluminium structures, tensile strains above 0.1% can be considered to result in initiation of structural failure.

3. **Contact Forces**: The hydrodynamic forces on the panels of the airframe can be assessed by examining the contact forces between the airframe and water elements. This method was used to compare results with empirical predictions obtained by BMT [4] for the Brent Spar and Cormorant Alpha scenarios.

4. **Nodal Accelerations**: Local loads in the airframe can be estimated by extracting accelerations of appropriate nodes in the model. They are particularly useful for examining local effects which may be masked in the overall global response. However, they tend to be more “noisy” as data from a single point includes significant high frequency/high amplitude vibrations. The results are therefore
typically filtered to remove the high frequency components. This problem is more pronounced for high speed impacts due to the larger shock waves oscillating through the structure.

4.8.1 Brent Spar (Lagrangian Water)

Global Response

The global accelerations for the full and half speed impacts are shown in Figure 17. For the full speed case, a peak acceleration of 23 g is observed before dropping off to around 12 g. The accident report for this accident estimated, from the damage that the cabin floor had experienced, the peak deceleration was between 20 and 25 g. The acceleration levels for the half speed case are approximately half.

Airframe Failure

The areas of possible failure in the structure were investigated by looking at the maximum plastic strain in each element throughout the whole time period. These results are shown in Figures 18 and 19 for the full and half speed impact conditions respectively.

For the full speed case (Figure 18), large parts of the airframe have strains well above 0.1%. This indicates that the main structural ring frames and tail boom are likely to fail. This is due to the high inertia and mass of the engines, rotor and MRGB causing the cabin roof to collapse downwards.

In the actual accident, the fuselage cockpit bulkhead aft of the cargo door and tail boom failed. Less severe damage occurred in the rear of the cabin than at the front. Clearly, the WG30 would have sustained far greater level of structural damage. The full speed Brent Spar conditions are considered to be unsurvivable for a WG30 airframe.

For the half speed case (Figure 19), less damage is sustained. However, areas above 0.1% strain exist in the main structural ring frames and the tail. A considerable amount of damage is therefore expected to occur in these areas at the half impact speed.

Panel Forces

The panel force results and comparison with BMTs empirical predictions are discussed in Section 4.8.5 below.

Local Loadings

The results for the nodal accelerations were less promising. The Brent Spar impact conditions proved to provide a very hard landing for the WG30, resulting in large structural deformation of the cabin roof. The level of damage was exacerbated by the lack of fluidity in the Lagrangian water formulation. The nodal accelerations and deformations of parts of the helicopter were very high. The hardness of the landing and the flexible nature of the airframe model combined to give nodal results that were very noisy due to excessive vibration of the mesh nodes on impact. This was demonstrated by changing all of the airframe materials to rigid.
Figure 20 compares the vertical velocities of a node in the floor for both the rigid and non-rigid airframe models. It can be seen that the rigid model does not vibrate and therefore does not show the large peaks in velocity and therefore acceleration. Heavy filtering would be necessary to extract appropriate accelerations from the deformable model. However, excessive filtering was shown to excessively distort the results.

Figure 21 shows the vertical acceleration of a node in the aircraft floor before and after filtering with SAE 60 Hz and 180 Hz filters. It can be seen that the 60 Hz filtered acceleration reaches approximately 800 g. However, this peak value can be changed by the level of filtering. The overall acceleration levels can therefore not clearly be determined due to the noise levels.

Figure 22 shows the locations of the three nodes that were used to monitor acceleration. Figure 23 shows the filtered signals (SAE 60 Hz) for these nodes on the floor, side panel and gearbox. The initial impact occurs close to the floor panel and the acceleration reaches 2000 g. The side panel acceleration peaks approximately 0.005 seconds later at about 800 g. The gearbox acceleration (17 g, 0.07 seconds after initial contact) is comparably low as it is farther away from the impact site and has a large inertia. Figure 23 shows the timing of the peak values relative to each other but, as described in the paragraph above, it does not give reliable quantitative acceleration values due to excessive nodal vibrations and the heavy filtering.

4.8.2 Cormorant Alpha (Lagrangian Water)

The results for the Cormorant Alpha scenario should be treated as being indicative only. The impact has a significant horizontal velocity component. The validation work had shown that the Lagrangian water model was not suited to “fly-in” scenarios, due to its inability in modelling large fluid flow effects. The initial peak loads are considered to be representative, but the analysis becomes less representative and less conservative once the water has had time to flow a significant distance.

Global Response

The global accelerations for the full and half speed Cormorant Alpha scenarios are shown in Figure 24. For the full speed case, a peak acceleration of approximately 3 g is predicted, then dropping off to around 1.2 g. The acceleration levels for the half speed case are approximately half.

Airframe Failure

Maximum plastic strains for the full and half speed impacts are shown in Figures 25 and 26.

For the full speed case (Figure 25), strains above 0.1% occur around the tail boom, engine/rotor/MRGB connections to the main ring frames and locally around the point of impact on the nose. Therefore, limited failure in these regions would be expected.

In the actual accident, crushing damage was observed to the forward and right of the fuselage, the tail boom folded and the right hand side cabin door failed. This level of damage is consistent with that predicted by the WG30 model.

For the half speed case (Figure 26), strains over 0.1% were predicted around the tail boom.
Panel Forces and Local Loadings

The panel force results and comparison with BMT’s empirical predictions are discussed in Section 4.8.5 below.

In a similar manner to the Brent Spar results, noise prevented useful data being extracted from the nodal accelerations.

4.8.3 Isles of Scilly (Lagrangian Water)

The Isles of Scilly scenario is a “fly-in” accident. Therefore, the results should be treated as being indicative only due to the inability of the Lagrangian water model to predict large fluid flow effects. The initial peak loads are considered to be representative, but the analysis becomes less representative and less conservative once the water has had time to flow.

Global Response

The global accelerations for the full and half speed scenarios are shown in Figure 27. For the full speed case, a peak acceleration of 9 g is predicted, then dropping off to around 2 g. The acceleration levels for the half speed case are approximately a third of the full speed results.

The accident report for this accident estimated the peak deceleration to be greater than 12 g. This was based on failure of the seat connections to the cabin floor.

Airframe Failure

Maximum plastic strains for the full and half speed impacts are shown in Figures 28 and 29.

For the full speed case (Figure 28), strains above 0.1% occur in the panels around the nose wheel retraction holes, the edges of the floor and in the middle of the main ring frame. Failure was also predicted around the tail boom. Failure of the floor panels and subsequent water ingress is not included in the model. Once a floor panel had failed it would be likely that the influx of water would cause significant damage to the remaining floor panels.

In the actual accident the sponsons detached and all the hull below the cabin floor was destroyed.

For the half speed case (Figure 29), minimal areas of failure were predicted.

Panel Forces and Local Loadings

No empirical predictions were made by BMT for this scenario, therefore no data was extracted from the FE model for comparison.

In a similar manner to the Brent Spar results, noise prevented useful data being extracted from the nodal accelerations.

4.8.4 Eulerian Modelling

The three impact scenarios were repeated with the Eulerian water mesh. The results for the full speed impacts are shown in Figures 30 to 33.
Global Response

The global acceleration responses (Figure 30) for the Brent Spar and Cormorant Alpha scenarios were much higher than with the Lagrangian water model. Large and sustained levels of acceleration were observed in both cases.

The Scilly Isles result exhibited a short duration peak, followed by a sustained period of small negative acceleration.

These spurious accelerations were considered to be a result of problems with the software code. The solver appears to have difficulty in coupling the deformation in the airframe structures with the mass transfer through the Eulerian water mesh.

Structural Failure

The results for the plastic strains (Figures 31 to 33) were also not realistic. For the Brent Spar and Cormorant Alpha scenarios, all the damage was located in the upper part of the airframe. There was relatively little damage predicted at the primary impact locations around the nose.

Conversely for the Scilly Isles scenarios, only two very localised failures are predicted on the nose of the airframe.

Conclusion

It was concluded that the Eulerian water model was not suitable for complex deformable models. The airframe model consisted of deformable materials, lumped masses and beam elements, whereas the validation models had only contained rigid shell elements. A considerable amount of development work would be necessary to fully understand the limitations of the Eulerian water methodology which was beyond the scope of this study.

4.8.5 Comparison of Panel Loads Against Empirical Predictions

Table 3 summarises the panel contact force results for the Lagrangian Brent Spar and Cormorant Alpha scenarios. Two panels near to the impact point on the nose of the airframe were considered. The location of the side and base panels are shown in red in Figure 34.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>FE Modelling</th>
<th>Empirical Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Panel Load</td>
<td>Side Panel Load</td>
</tr>
<tr>
<td>Brent Spar</td>
<td>Full Speed</td>
<td>481 kN</td>
</tr>
<tr>
<td></td>
<td>Half Speed</td>
<td>219 kN</td>
</tr>
<tr>
<td>Cormorant Alpha</td>
<td>Full Speed</td>
<td>70 kN</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

Table 3: Comparison of Panel Forces
Supporting work was undertaken by BMT Fluid Mechanics Ltd [4]. Their method used an empirical statistical approach to determine the range of possible loadings on single airframe panels and sponsons over a large variety of impact orientations. The results from the BMT study for the two specific impact scenarios and appropriate panels are included in Table 3 for comparison.

For the full speed Brent Spar impact a peak load of 481 kN was predicted for the base panel by the FE modelling. This agreed extremely well with the empirical prediction of 594 kN. A similar level of correlation was observed for the half speed cases.

The correlation for the side panel was less satisfactory. The empirical results were much higher than those predicted by the FE model. This was due to two factors:

- The empirical approached assumed the side panel to be the primary impact point. In reality, the side panel was not the first point of contact. The FE model was geometrically accurate with the base of the airframe contacting the water first. Therefore, the FE results would be expected to be lower as the side panel did not take the full impact force.

- The lack of “fluidity” in the Lagrangian mesh would contribute to under-predicting the side panel force, as less water would be in contact with the sides of the airframe. However, over the small timescale of the initial impact this effect would be small.

For the Cormorant Alpha scenario, the FE base panel results were lower than the empirical approach. This was attributed to the fact the base panel was not the primary impact point in the actual accident.

For the side panel, no FE data was obtained, as the panel did not contact the water during the initial impact. The empirical results were considered to overestimate the actual load seen by the panel. It should be noted that the both the empirical and FE methods are less reliable for planing type impacts due to poor understanding of drag and planing effects.

Although both approaches were not fully validated, they did predict loadings of similar magnitudes. Given the large differences in the two approaches and uncertainties in the analyses, the results were considered encouraging.

4.9 Modelling Conclusions

From the FE validation work, it was concluded that:

1. The only relevant validation data for the WG30 airframe was of a Lynx impact onto the ground with the undercarriage retracted. The WG30 and Lynx airframes were considered similar in terms of mass distribution and main structural members. The response of WG30 model exhibited good correlation with the test data. Local acceleration levels at the MRGB were a factor of five less than those observed in the cabin floor.

2. The Lagrangian and Eulerian water models were validated against a variety of test data. Rigid bodies were used to model both vertical and horizontal impacts.
• The Lagrangian water model was only suitable for determining initial accelerations during vertical impacts. It was not suited to fly-in impacts or impacts that occurred over a significant period of time as it cannot model large fluid displacements.

• The Eulerian water model was more suited to both vertical and fly-in impacts. However, very refined meshes were required to achieve converged results for the validation cases. The number of elements required for high speed impacts or complex models, such as the WG30 model, proved to be prohibitively large, resulting in very long analysis times. There were some doubts as to the validity of the test data used for the seaplane hull validation work. Further work would be required to gain sufficient confidence in the accuracy of the Eulerian method.

From the Brent Spar, Cormorant Alpha and Scilly Isles scenarios, it was concluded that:

1 The Eulerian water model produced no useful data for impacts with deformable structures. The WG30 model included complex geometry, elastic-plastic materials, shell and beam elements and lumped masses. The Eulerian modelling technique is considered insufficiently mature to accurately model complex water/deformable structure impacts.

2 The Lagrangian water model was only suitable for determining initial acceleration levels for vertical impacts such as the Brent Spar scenario. Global responses and strain levels were generally consistent with damage detailed in the accident reports. However, results for local accelerations were too noisy to extract any useful information. Large nodal vibrations occurred on impact and resulted in large local accelerations of very small duration. This resulted in the need for heavy filtering, which removed useful information from the data. Reasonable correlation with empirical methods was achieved using panel force data for the Brent Spar and Cormorant Alpha scenarios.

5 EMERGENCY FLOTATION DESIGN REVIEW

5.1 Introduction

The purpose of this task was to review current EFS design in light of the findings of Sections 3 and 4, and to propose modifications to improve EFS crashworthiness.

5.2 Emergency Flotation Problems

The problems associated with emergency flotation systems are well understood and discussed in the Survey and Analysis of Helicopter Flotation Systems [7] commissioned by the FAA. This section summarises these problems and then adds to the discussion. The main problems that are associated with float deployment are listed below. Each of these problems is then addressed in the following sections.

• Floats are not armed.

• Floats are armed but not activated.
• Floats are activated but do not deploy.
• Uneven float deployment.
• Incomplete inflation due to adverse ambient conditions.
• Floats damaged upon impact.
• Floats deployed but helicopter over turns.

Four of the incidents reported in the FAA report were ditchings where the EFS had failed to deploy. The information relating to the ditching cases (approximately 6%) could not be clearly distinguished from the main data but, since a ditching is effectively a “gentle” impact, system failures that occur under these less onerous conditions are of interest to this study.

5.2.1 Floats Not Armed

To prevent inadvertent float deployment in flight, current flotation systems typically require a two-step process for inflation. First, the inflation circuit must be armed and second, the inflation is activated either automatically (e.g. water immersion switches) or by a trigger operated by the pilot. The fact that many helicopters equipped with emergency flotation systems impact the water with the floats unarm ed is a cause of concern. FAA guidelines recommend that the inflation system be safeguarded against inadvertent activation by using a separate float arming circuit. Unfortunately, the pilot is often preoccupied with controlling and landing the helicopter during an emergency situation and thus may fail to arm the inflation system before contacting the water. Therefore, another method for preventing inadvertent float deployment would be desirable.

One solution is to provide an override function that senses the condition that makes float deployment unsafe. For example, if the airspeed must be below a certain value for safe deployment, then the airspeed indicator would be used to send a bypass signal to the arming circuit. The float arming circuit would effectively be automatic in that the floats could be activated at any time during a flight provided the helicopter is within the safe deployment envelope (based on sensor input). A backup manual arming system is also recommended.

5.2.2 Floats Armed But Not Activated

Flotation systems fitted with activation circuits that must be triggered by the pilot suffer from the same problems as manually operated arming circuits. The pilot often does not have time, does not remember, or is physically unable to activate the floats. In addition, pilot activated floats suffer from timing problems. Activating the floats too early will make them more vulnerable to damage during the impact. Activating the floats too late will mean that, by the time the floats are fully inflated, water ingress may be too far advanced. The floats may then not be able to maintain the stability of the floating helicopter for the desired time period. Therefore, floats activated by automatic means (e.g. water immersion switches) are more desirable. However, again, a backup manual activation switch is recommended.
5.2.3  *Floats Activated But Not Deployed*

One reason for all floats failing to deploy after activation is electrical wiring faults. FAA guidelines recommend a mechanical backup system for electrically activated systems, but also allow backup electrical systems provided they are shown to be independent and of high reliability. In either case, thought should be given to protecting wiring by avoiding routes through areas which are most likely to be damaged. For example, wires should not be run next to the lower fuselage skin, which is likely to tear during impacts involving significant horizontal velocities. Use should be made of flexible armoured cable racing.

Inflation devices (bottles) store compressed gas at high pressures and are used to inflate the bags rapidly. The bottles are typically ‘fired’ by a pyrotechnic charge that punctures a diaphragm in the bottle, causing the gas to release. Use of multiple bottles or redundant firing mechanisms is desirable in the event that a bottle does not fire. The firing mechanism and the controlling electronics should be tested and certified to the shock acceleration levels likely to be seen in the area in which they are located during a partially survivable water impact. Electronics and firing mechanisms should be upgraded if necessary or, alternatively, bottles could be located higher up the fuselage where acceleration levels are likely to be much lower.

5.2.4  *Uneven Float Deployment*

The three main causes of uneven deployment, are as follows:

- Inflation bottles failing to fire.
- Bags failing to fully inflate.
- Failure of the flow line connecting the bags to the inflation bottles.

**Bottle Failure**

FAA guidelines recommend use of either a single inflation bottle or use of a multiple bottle system, interconnected to help prevent uneven deployment. Single bottle systems however, suffer from the problem that the entire system fails if the bottle does not fire (see above). Therefore, multiple-interconnected bottles are recommended. Thought should be given to bottle positioning. Placing bottles too near to airframe members which could deform and puncture the bottles should be avoided.

**Bag Failure**

Where an inflation system is interconnected, the gas will follow the path of least resistance. If a float bag is severely damaged (torn), then more flow will be diverted to that float causing less inflation for the intact float chambers. Float inflation systems, however, operate under high pressure and high flow velocities are developed in the distribution lines. Therefore, most of the flow resistance is in the flow distribution lines and not in the resistance associated with inflating the bag. The amount of gas actually lost due to a ripped chamber is thus small. Therefore, it is important to design the flow distribution lines with equal resistance and/or use flow distributing valves to ensure equal float deployment in all eventualities.
Bags should be divided into multiple cells to limit the buoyancy volume lost due to small tears in inflation bags. When considering uneven deployment, it is important to assess the implications of uneven inflation times and not just uneven final inflation volumes.

**Flow Line Failure**

Flow lines severing during impact present more of a problem. If the break is near to the high pressure gas supply, then the path to the break will be of significantly less resistance and will result in a problematic loss of gas volume. Thus, care should be taken to route flow lines away from areas most likely to be damaged in a water impact. Full use should be made of flexible high pressure wire coated hoses. Rigid flow lines should be avoided as the deforming airframe could easily lead to pipe rupture.

For the three impact scenarios considered in Section 4, the maximum strains experienced in the model are shown in Figures, 22, 23, 25, 26, 28 and 29. The highly strained regions indicate parts of the aircraft that would deform significantly or experience gross structural failure. These areas are not suitable for the routing of any pipe work, as deformation of the structure would lead to breakage and rupture of pipe lines. These are primarily the main ring frames of the airframe, which support massive items in the roof, the floor skin and the tail boom connection to the fuselage.

Mounting bottles near to bags will reduce the length of flow line required, thus reducing the risk of pipe rupture. However, the likelihood of damaging the bottles would be increased, as they would be located in more vulnerable areas of the airframe. This arrangement also makes cross feeding between bottles more difficult. Careful consideration should be given to the trade off between redundancy with interconnected bottles, the higher risk associated with longer pipe runs and vulnerability of equipment.

**5.2.5 Incomplete Inflation Due to Adverse Ambient Conditions**

The types of gases used to inflate the flotation systems are typically nitrogen or helium. The gases are compressed to approximately 3000 psi and expanded to approximately 2.25 psi in the inflated floats. The pressure of the compressed gas within the bottle must be adjusted before flight to take account of variations in ambient temperature. However, ambient conditions may change during flight which can mean that the pressure supplied to the floats drops by plus or minus 1.5 psi [7] resulting in incomplete inflation.

The American Navy H-46 system is designed to work without a pyrotechnic charge [7]. In this case, a solid propellant is burned to warm pressurised/liquefied carbon dioxide contained within a Kevlar reinforced aluminium pressure vessel. The pressure within the vessel is raised until a burst valve releases the gas into the float bags. This inflation method automatically adjusts the amount of solid propellant burned depending upon the ambient conditions. This ensures that the gas supplied to the floats has a uniform and constant temperature and pressure regardless of the prevailing ambient conditions.
5.2.6  Float Damage Upon Impact

Emergency floats are stored in a packed position in some form of protective cover until activated. The floats tend to be positioned to produce a slight nose-up attitude in water to prevent the cockpit and cabin from being submersed under water. In general, the floats are configured either as a skid-mounted or fuselage-mounted system, depending on the landing gear configuration.

Skid Mounted Floats

Skid mounted float systems tend to have very simple storage methods. Each float is folded and stored in a protective cover, typically made of a waterproof material such as nylon, and mounted on top of the landing gear skid. The float bag covers for these systems are fitted with snaps that pop open upon float deployment.

The main problem with skid mounted flotation systems is that the skids are attached to the underside of the fuselage and are therefore vulnerable in an impact. In an impact the skids would initially take the full force and may break away from the airframe. In this event the floats would become separated from the fuselage.

Fuselage Mounted Floats

Heavier helicopters that do not use skid landing gear require more sophisticated and thus heavier fuselage-mounted systems.

Nose floats may be stored inside fuselage skin flaps. These storage compartments are hinged on one side and remain attached to the fuselage upon deployment of the floats. The main landing gear floats are usually stored inside the main landing gear doors, requiring the doors to blow out to the fully open position upon deployment of the floats.

Fuselage-mounted floats that are activated before impact are often damaged by high water entry forces. Flotation systems which do not deploy until after impact are not subjected to these forces, resulting in fewer cases of float system damage caused by the impact.

Location of Flotation Equipment

The results presented in Section 4 indicate that the degree of damage experienced by the EFS would depend on their location on the fuselage. Panel forces reported in Section 4.8.5 (Table 3) show that side panels typically experience a much lower force than base panels. Additionally, the airframe validation work had shown that for a vertical drop, accelerations at the rotor gearbox were a factor of five less than those experienced by the cabin floor.

Positioning the EFS such that it is not located at likely impact locations or on parts of the structure which are likely to fail, would result in an increased chance of post impact survivability. The nose, tail boom and underside of the aircraft are particularly vulnerable during water impacts.
Attachment and Structural Design Loads

The loads experienced by the floats, their attachments and the surrounding airframe can be extremely high during water impacts. The integrity of the floats and surrounding structure is therefore an important consideration.

Work performed by BMT [4], suggests that the current design loads are more than adequate for ditching scenarios. However for severe impacts, doubling the design loads for airframe panels would have little effect on improving survivability. Primary impact loads are too large to allow the development of practical design solutions given the material and weight constraints of an airframe. Greater benefit would be obtained through the provision of redundant flotation.

Parts of the airframe that are claimed to provide passive buoyancy (i.e. sealed spaces such as fuel tanks) should be shown to remain intact and attached to the passenger cabin during a severe but survivable impact. In all the scenarios analysed in Section 4.8 the tail boom consistently failed. Some aircraft manufacturers claim voids in the tail boom as passive flotation. In an impact the tail boom is very likely to fail and any buoyancy it provides would, thus, be of no benefit.

Float Redundancy

Currently, redundant flotation is only provided by sub-compartments within a bag. During a severe but survivable impact the complete bag is likely be lost, thus negating both the redundant and normal flotation capacity.

If redundancy was provided at bag level, then the likelihood of significant loss of flotation capacity would be greatly reduced. Work performed by BMT [4], predicts that the provision of redundant bags would significantly improve the chances of the EFS continuing to perform its function following an impact.

The redundant flotation should be located in areas less likely to experience high loads during a severe impact, such as the upper part of the airframe.

5.2.7 Floats Deployed But Helicopter Immediately Overturns

Immediate overturning of helicopters upon impact is the most common cause of occupant drowning in an otherwise survivable accident. Helicopters have a natural tendency to invert in water because of their relatively high centre of gravity. Combining this inherent instability with wave action, high winds, and impacting the water at a significant velocity or improper attitude, greatly increases the chance of overturning. Once a helicopter has capsized the cabin quickly fills with water and the helicopter will totally invert. There is little time for the occupants to escape.

Currently, emergency flotation devices are designed to keep the helicopter upright to facilitate egress in the event of a controlled ditching. The requirement is to keep at least one exit on either side of the airframe above the water line. This necessitates the location of flotation equipment near to the underside of the airframe. However, this area is typically most prone to damage in an impact and also results in just two stable flotation attitudes.
In an accident, lives would be saved if a second aim became to keep the cabin partially dry in the event of significant damage to the primary flotation system. This would require the location of additional flotation equipment in areas of the airframe around the sides or top of the cabin. This additional flotation could be designed to allow the helicopter to float on its side [22], whilst still achieving an acceptable egress route for the occupants.

This would prevent total inversion following capsize, retaining an air pocket within the cabin and maintaining a number of escape routes above the water surface. Additionally it would provide redundant flotation located in a less vulnerable area of the airframe.

5.3 Summary of Design Recommendations to Improve Emergency Flotation System Crashworthiness

- EPS should have automatic arming.
- A manual independent backup arming system is recommended, where automatic arming systems are used.
- Floats should be activated automatically by immersion switches.
- A manual, independent, backup activation system is recommended where automatic activation systems are used.
- Distribution lines should be designed with equal resistance and/or flow distributing valves should be used to ensure equal float deployment, even with a bag ruptured.
- Flexible hoses should be used for flow distribution lines.
- Bags should be divided into multiple cells to limit the effect of small bag ruptures.
- Inflation systems that limit the effect of varying ambient conditions should be considered.
- Systems which require inflation should be deployed after impact.
- Floats should be designed for balanced deployment (timing as well as volume), even with system damage.
- Where possible, floats should be located away from likely primary impact sites, such as the nose, sponsons and floor of the airframe.
- Distribution hoses and wiring should not be routed through areas of the airframe likely to undergo severe deformation or failure during an impact. Short pipework, or individual gas bottles located near each bag would reduce the risk of flow line failure due to structural deformation. However, careful consideration should be given to the trade off between redundancy with interconnected bags and the higher risk associated with longer pipe runs.
- Redundant flotation should be provided at bag level, as well as compartments within a bag.
• To take account of severe but survivable impacts, redundant flotation bags should be located in the upper part of the airframe to minimise the risk of damage. These could also be arranged to allow the helicopter to float on its side retaining an air pocket in the cabin and maintaining a number of escape routes above the water surface, rather than capsizing into a fully inverted position.

• Finally, any claimed passive buoyancy (e.g. fuel tanks or tail boom voids) for ditching should only be allowed if it can be demonstrated that the appropriate part of the airframe remains attached to the passenger compartment during and after an impact.

6 COST BENEFIT ANALYSIS

This section develops a methodology for determining the benefits of modifications to the EFS in the context of their implementation costs and potential for saving life.

6.1 Overview

The raw data for the cost benefit study was obtained from a search of helicopter water impacts contained in the NTSB database and from UK accident reports. The search provided information as to how actual EFS had failed for a range of helicopter types and accident scenarios. Only accidents where both the EFS failed and where fatalities were sustained were considered.

From the data an EFS failure deployment tree was constructed. The tree quantified how various EFS failure modes contributed to whether the helicopter maintained an air pocket in the cabin with an over-water escape route, inverted or sank.

A variety of modifications were proposed for various stages of the EFS deployment process aimed at improving the likelihood of successful operation. These modifications were based on the findings of Section 5 of this report.

The benefit for each modification, in terms of affecting the probabilities of sinking and inversion, was assessed using the failure event tree. This change in functional effectiveness was translated into an occupant survival number. Modifications which improved the chances of maintaining an air pocket in the cabin with an over water escape route were assumed to provide the greatest benefit in terms of occupant survivability. Modifications that reduced the chances of sinking, but increased the probability of inversion, were assumed to be less effective.

The estimated costs of each modification were obtained from an EFS manufacturer and a helicopter manufacturer.

Finally, a cost benefit study was undertaken for the current UK offshore helicopter support fleet to determine whether implementation of the modifications would be cost effective in terms of potential lives saved over the remaining service life of the fleet. A worked example of a cost benefit calculation is given in Appendix F.
6.2 Causes of EFS Failure

6.2.1 Float Deployment

The successful deployment of the EFS can be described as a sequence of events, each of which has to be carried out successfully if the EFS is to deploy correctly. If any event is not successfully carried out, the EFS will not inflate correctly. Figure 35 shows the sequential path of events. The desired aim is to keep the helicopter afloat, with an air pocket in the passenger cabin and an over-water escape route, long enough to enable all the occupants to board the liferafts.

The first stage in the deployment sequence is to arm the system. If the system is not switched on then it cannot operate. The system then needs to be activated. If either of these stages do not occur the helicopter will sink. For the purposes of this study, the stages of arming and activation have been grouped together as the pilot is assumed to be a common failure mode.

Once the system is activated, the compressed air needs to be discharged from the bottles and to reach the floats. If the gas is not discharged then the helicopter will sink. If the floats, pipe work between the floats or the storage bottles have been damaged then all, some, or none of the floats may inflate. If none of the floats inflate then the helicopter will sink, if some inflate then the asymmetric inflation is likely to cause the helicopter to invert and possibly sink.

Finally, if all the floats correctly inflate the helicopter can still invert and/or sink due to external factors such as bad weather or impact attitude/velocity.

6.2.2 Accident Data

An on-line search of the NTSB accident database, between 1982 and 1999, identified 20 accidents where the EFS had failed and where fatalities were sustained (Appendix D).

A search of UK accidents, between 1980 and 1999, identified four accidents (Brent Spar, Cormorant Alpha, Dunlin Alpha and Scilly Isles) which fulfilled the criteria (Appendix E).

For each of the 24 relevant accidents the failure mode of the EFS was determined. Appendices D and E provide details of each accident and the assumptions made as to the likely EFS failure mode. Table 4 summarises the results of the EFS failure modes.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Failure Event</th>
<th>Number of Cases</th>
<th>Outcome</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sink</td>
<td>Invert</td>
</tr>
<tr>
<td>1</td>
<td>EFS not armed or not activated</td>
<td>12</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Gas did not discharge from bottles</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>All gas did not reach all floats</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Damaged floats</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Helicopter affected by external factors</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td><strong>Totals</strong></td>
<td><strong>24</strong></td>
<td><strong>16</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

Table 4 : Summary of Relevant Accidents
In half of the cases considered the EFS failed to activate, resulting in 12 sinkings. In all the cases where the EFS activated, the air discharged successfully from the storage bottles. However, in two cases the gas did not reach the floats and the helicopters inverted. Six cases sustained varying levels of float damage leading to four sinkings and two inversions. In the remaining four cases, where the EFS deployed successfully, the helicopters inverted due to external factors.

No cases resulted in an air pocket in the cabin and an over-water escape route. This is not surprising as the study is specifically concerned with EFS failures that resulted in fatalities.

Using the above data, a probability tree was constructed (Figure 36) in order to analyse the EFS deployment process. The upper branches indicate the probability of success for each stage, given the previous event has been performed successfully. The lower branches indicate the probabilities of failure at each stage.

The overall probability for each of the three outcomes was determined by multiplying together the probabilities along each branch and adding those which lead to the outcome of interest.

6.3 EFS Design Modifications

A list of possible modifications to the EFS was drawn up, based on the findings of Section 5 of this report. The modifications comprised:

- **Arm System**: Float activation system is armed at all times, except during flight conditions in which activation of floats would be hazardous. It was considered that the best way to achieve this was to manually arm the system on takeoff with any subsequent disarming being automatic. This modification would improve the probability of successfully completing the first stage of the deployment process (Modification A, Figure 36).

- **Activate System**: Floats activated automatically by immersion switches. Hence, the floats are deployed after impact with the water. A manual independent backup activation system would be provided. This modification would improve the probability of successfully completing the first stage of the deployment process (Modification B, Figure 36).

- **Bottle Redundancy**: Systems that have either more than one bottle or a redundant activation system within a single bottle, and in which the firing electronics are designed to survive the impact shock. This modification would improve the probability of successfully completing the second stage of the deployment process (Modification C, Figure 36).

- **Ambient Conditions**: Inflation system that minimises the effect of varying ambient conditions on the quantity of gas leaving bottles. This modification would improve the probability of ensuring that the correct quantity of gas reaches the floats and hence successfully completing the third stage of the deployment process (Modification D, Figure 36).

- **Flexible Hoses**: Flexible hoses used for flow distribution lines to minimise damage caused by impact. This modification would improve the probability of
successfully completing the third stage of the deployment process (Modification E, Figure 36).

- **Even Flow**: Flow distribution lines designed with equal resistance, and/or use of flow valves to achieve even bag deployment in the event of small ruptures. Floats are designed for balanced deployment (timing as well as volume), even with bottle damage. Bags divided into multiple cells to limit effect of small ruptures. These modifications would improve the probability of successfully completing the third stage of the deployment process (Modification F, Figure 36).

- **Float Attachment/Protection**: Increased float attachment design loads and protection from impact. These modifications would reduce the chances of the existing floats being damaged during an impact. They would improve the probability of successfully completing the fourth stage of the deployment process (Modification G on Figure 36).

- **Float Location**: Re-location of existing floats to regions of the airframe less susceptible to impact damage. This modification would improve the probability of successfully completing the fourth stage of the deployment process (Modification H, Figure 36).

- **Float Redundancy**: Systems that incorporate complete flotation unit redundancy, additional to the existing floats required for ditching. Redundant floats can be added anywhere on the airframe, apart from at the top (see below). This modification includes the advantages of both float location and float redundancy as it necessitates the location of additional flotation away from the underside of the airframe which experiences the highest impact loads. This modification would improve the probability of successfully completing the fourth stage of the deployment process (Modification I, Figure 36).

- **Side Floating**: This is a specific case of redundancy as floats are located at the top of the airframe. This additional flotation allows the helicopter to float on its side, preventing total inversion while retaining an air pocket in the cabin and maintaining an over-water escape route to the surface. This modification includes the advantages of both float location and float redundancy as it necessitates the location of additional flotation at the top of the airframe which sees lower impact loads. It will also reduce the likelihood of inversion in high sea states or adverse impact conditions. This modification would therefore improve the probability of successfully completing the fourth and final stages of the deployment process (Modification J, Figure 36).

6.4 **Assessment of Benefits**

6.4.1 **Effect on Outcome**

The benefit for each modification alone, in terms of reducing the probabilities of sinking and inversion, was assessed using the failure event tree (Figure 36).

Implementation of each modification was assumed to result in the successful completion of the appropriate stage of deployment (i.e. the probability of failure was reduced to zero). In this way, the effect of each modification on the probabilities of the three outcomes could be quantified. Table 5 shows the results of this exercise.
<table>
<thead>
<tr>
<th>Modification</th>
<th>Probability of Above Water Escape Route</th>
<th>Craft Inverted</th>
<th>Craft Sinks</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Modifications</td>
<td>0.0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>A+B – Arming and Activation</td>
<td>0.0</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>C – Bottle Redundancy</td>
<td>0.0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>D – Ambient Conditions</td>
<td>0.0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>E – Flexible Hoses</td>
<td>0.0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>F – Even Flow</td>
<td>0.0</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>G – Float Attachment/Protection</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>H – Float Location</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>I – Float Redundancy</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>J – Side Floating</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 5: Probabilities of An Above Water Escape Route, Craft Inverting or Sinking for each Modification.

Automatic arming and activation produced the greatest benefits in terms of reducing the probability of the helicopter sinking. Increased float attachment and protection, float re-location and additional redundancy all produced lesser benefits in this regard. Side floating not only reduced the probabilities of sinking and of inversion, but also increased the probability of maintaining an over water escape route. The remaining modifications produced no benefit.

6.4.2 Effect on Fatalities

In order to interpret these changes in functional effectiveness in terms of their potential for saving life, it was necessary to consider what effect they would have if they were installed on an actual fleet of helicopters. The UK helicopter offshore support fleet was chosen for this exercise because of the relatively high quantity of data available.

As at 15th December 1999, there were 79 helicopters in the UK offshore support fleet [23]. The fleet consists of a variety of different helicopter types with varying degrees of remaining service life. There have been four serious accidents (Brent Spar, Cormorant Alpha, Dunlin Alpha and Scilly Isles) over the last 20 years (the period of the data search), that resulted in fatalities and where the EFS had failed to operate correctly.

A total of 38 occupants were killed in the four UK accidents. 12 of these fatalities were known to have been due to impact injuries or due to exposure following escape from the helicopter. These 12 cases were therefore discounted, as successful operation of the EFS would not have prevented these deaths. The remaining 26 fatalities were assumed to have been caused by EFS failure, which had resulted in drowning due to insufficient time being available to escape. This yields an average fatality rate of 1.3 per annum. (The assumed causes of death for the four UK accidents are summarised in Appendix E).
The change in functional effectiveness derived for each individual modification from the EPS deployment tree was translated into an occupant survival number (see Appendix F). The modifications were assumed to improve the probability of survival for all of the 26 fatalities caused by EFS failure in proportion to their estimated benefits (see Table 5), adjusted as described below. The small sample size of only four accidents precluded a case by case benefit analysis.

Modifications which improved the chances of maintaining an air pocket in the cabin with an over water escape route were assumed to provide the greatest benefit in terms of occupant survival. These modifications would increase the time available for escape, and facilitate escape through the provision of over-water escape routes. It was assumed that these modifications would be 90% effective in reducing the number of fatalities.

Modifications that reduced the chances of sinking, but did not reduce the probability of inversion, were assumed to be less effective as egress would be more hazardous. These modifications were assumed to be 50% effective in reducing fatality levels.

Given the above assumptions a proportion of “occupant” benefit for each modification could be derived. Table 6 summarises the number of lives saved for each modification.

<table>
<thead>
<tr>
<th>Modification</th>
<th>Number of Lives Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+B – Arm and Activate System</td>
<td>4.3</td>
</tr>
<tr>
<td>C – Bottle Redundancy</td>
<td>0</td>
</tr>
<tr>
<td>D – Ambient Conditions</td>
<td>0</td>
</tr>
<tr>
<td>E – Flexible Hoses</td>
<td>0</td>
</tr>
<tr>
<td>F – Even Flow</td>
<td>0</td>
</tr>
<tr>
<td>G – Float Attachment/Protection</td>
<td>2.2</td>
</tr>
<tr>
<td>H – Float Location</td>
<td>2.2</td>
</tr>
<tr>
<td>I – Float Redundancy</td>
<td>2.2</td>
</tr>
<tr>
<td>J – Side Floating</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Table 6: Lives Saved for each Modification

Side floating provided the greatest benefit as this prevents total inversion. It also incorporates the benefits of redundancy and locating floats in less vulnerable areas, as it would necessitate the location of flotation equipment at the top of the airframe. Arming and activating the system provided a similarly high level of benefit. Float Attachment/Protection, Float Location and Float Redundancy all gave a lower level of benefit. The remaining modifications did not provide a benefit.
6.5 Determination of Implementation Costs

The cost of each modification was determined by consultation with helicopter manufacturer GKN WHL, and EFS manufacturer FPT Industries. They provided estimates of the relative cost of implementing each modification for retro-fit onto existing designs.

The costs were provided as a proportion of the cost of the whole flotation system by the manufacturers. The exception to this was the costs for float location. WS Atkins estimated this at 50%. This modification entails the removal of existing floats and moving them to less vulnerable areas and represents a major change to the EFS and possibly the airframe.

The cost of an EFS for a JAR29 helicopter was estimated to be in the region of £200,000 by CAA following discussions with a major North Sea helicopter operator. This figure was used to convert the relative costs into absolute figures. Table 7 details the proportionate cost of each modification and the cost of implementing each modification on the current UK Offshore Support Fleet of 79 helicopters.

<table>
<thead>
<tr>
<th>Modification</th>
<th>Proportion EFS Cost (JAR29)</th>
<th>Cost of Implementation on UK Offshore Fleet (79 Aircraft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A + B – Arm and Activate System</td>
<td>0.07</td>
<td>£1,106,000</td>
</tr>
<tr>
<td>C – Bottle Redundancy (2 Extra Bottles)</td>
<td>0.10</td>
<td>£1,580,000</td>
</tr>
<tr>
<td>D – Ambient Conditions</td>
<td>0.07</td>
<td>£1,106,000</td>
</tr>
<tr>
<td>E – Flexible Hoses</td>
<td>0.05</td>
<td>£790,000</td>
</tr>
<tr>
<td>F – Even Flow</td>
<td>0.01</td>
<td>£158,000</td>
</tr>
<tr>
<td>G – Float Attachment/Protection</td>
<td>0.15</td>
<td>£2,370,000</td>
</tr>
<tr>
<td>H – Float Location</td>
<td>0.50</td>
<td>£7,900,000</td>
</tr>
<tr>
<td>I – Float Redundancy</td>
<td>0.15</td>
<td>£2,370,000</td>
</tr>
<tr>
<td>J – Side Floating</td>
<td>0.3</td>
<td>£4,740,000</td>
</tr>
</tbody>
</table>

Table 7: Costs For Each Modification.

6.6 Cost-Benefit

The cost-benefit of each modification to the EFS was quantified in terms of cost per life saved. The cost of retro-fitting the modifications on the UK offshore support fleet was divided by the number of lives the modification would save over the remainder of the fleet's service life. Values of £2,000,000 per life and an average 20 year remaining service life were assumed in the calculation. The cost per life saved figures for each modification are summarised in Table 8.
<table>
<thead>
<tr>
<th>Modification</th>
<th>Cost/Life Saved</th>
<th>Cost Effective?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A + B – Arm and Activate System</td>
<td>£255,000</td>
<td>Yes</td>
</tr>
<tr>
<td>C – Bottle Redundancy (2 Extra Bottles)</td>
<td>No Benefit</td>
<td>No</td>
</tr>
<tr>
<td>D – Ambient Conditions</td>
<td>No Benefit</td>
<td>No</td>
</tr>
<tr>
<td>E – Flexible Hoses</td>
<td>No Benefit</td>
<td>No</td>
</tr>
<tr>
<td>F – Even Flow</td>
<td>No Benefit</td>
<td>No</td>
</tr>
<tr>
<td>G – Float Attachment/Protection</td>
<td>£1,094,000</td>
<td>Yes</td>
</tr>
<tr>
<td>H – Float Location</td>
<td>£3,646,000</td>
<td>No</td>
</tr>
<tr>
<td>I – Float Redundancy</td>
<td>£1,094,000</td>
<td>Yes</td>
</tr>
<tr>
<td>J – Side Floating</td>
<td>£938,000</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8: Cost per Life Saved for Each Modification.

6.7 Discussion of Results

Arming and activating the system, float attachment, redundancy and side floating all provided cost effective options in terms of their potential for saving life.

Float location was not cost effective due to the large cost associated with moving floats on the airframe. This modification would also cause problems with the existing ditching requirements, which specify that at least one exit on each side of the cabin should be maintained above water level.

Although the other modifications did not provide any benefit, it should be noted that the small sample size resulted in only very few failures being attributed to these stages of the deployment process. Therefore, it is not surprising that they produced no benefit as the modifications cannot improve on the existing successful outcomes. It should also be noted that bottle redundancy, flexible hoses and even flow are considered to be standard features on modern EFS designs.

The costs for each modification were based on retro-fitting them to existing helicopters. It is anticipated that costs for new build would be lower as the benefit of the full service life would be accrued and that they would be easier and therefore less expensive to implement on a helicopter which is being built, rather than making retrospective changes to existing designs.

The costs accounted for in the study were installation and material costs only. They did not include indirect costs such as design costs, helicopter down time, labour, costs and increases in operating costs due to added weight or drag. In order to address these detailed cost issues a type specific study would be required to be undertaken on a particular helicopter.

However, the study clearly shows that there are significant benefits to be made by implementing automatic arming and activation, side floating, redundancy and improved float protection or attachment to helicopters in the UK offshore fleet.

A key assumption in the study was that each modification would be 100% reliable in terms of its operation. This assumption was necessary due to the small sample size
and the lack of information on system reliability during an impact. Although this is slightly non-conservative, the cost-benefit for the four key modifications are well below £2,000,000 per life. Therefore, even if the modifications were assumed to be just 50% reliable they would still be cost effective in terms of their potential for saving life.

7

REVIEW OF REGULATORY REQUIREMENTS

The regulatory body for rotorcraft in the UK is the Civil Aviation Authority (CAA). The CAA has adopted the Joint Aviation Authority (JAA) requirements (JARs) for certification of rotorcraft.

The JAA requirements for rotorcraft ditching are effectively tied to the American Federal Aviation Authority (FAA) requirements (FARs). These regulatory bodies are responsible for maintaining and enforcing airworthiness and operational requirements to ensure an acceptable level of safety is achieved for helicopter design, manufacture and operation. As the FARs are largely identical to the JARs for water ditching, only the JAR requirements are discussed in detail in this section.

The following JARs relate to water ditching, flotation, emergency landing conditions and evacuation issues:

- JAR 29.801: Ditching
- JAR 29.561: Emergency Landing Conditions
- JAR 29.562: Emergency Landing Dynamic Conditions
- JAR 29.807: Passenger Emergency Exits

For certain JARs, where advisory material has not been explicitly provided, the FAA’s Advisory Circulars (AC) have been adopted to clarify the intent of the requirements. It should be noted that these documents are intended to give an acceptable means, but not the only means of achieving compliance with the requirements. FAA AC 29-2B relates to the sections listed above.

The JAR text and relevant sections of AC 29-2B are given in Appendix C. A brief discussion of each of the above sections is given below, followed by a series of recommendations for improvements. The main JARs directly related to crashworthiness are the emergency landing conditions. However, the other JARs have been reviewed as they impinge indirectly on crashworthiness and survivability issues.

7.1 JAR 29.801: Ditching

This clause specifies the general ditching requirements. Its main concern is protecting the occupants and ensuring that there is an adequate escape route. Ditching is defined as:
“An emergency landing on water, deliberately executed, with the intent of abandoning the rotorcraft as soon as possible. The rotorcraft is assumed to be intact prior to water entry with all controls and essential systems, except engines, functioning properly”

Ditching is therefore assumed to be a controlled water entry, rather than at an uncontrolled/inappropriate attitude and velocity which would occur in an impact. The JAR only gives broad guidance using phrases like “minimise the probability of injury” and “probable behaviour”, and provides little specific guidance. The basic requirement is for the helicopter to remain afloat in a mainly upright position, long enough to allow the occupants to exit the helicopter and board the liferafts, under the most likely sea conditions for the intended area of operation.

Ditching certification is not required unless requested by the applicant. Certification is demonstrated either by scale model tests, or by comparison with helicopters of similar design.

The AC gives considerably more detail than the JAR, and discusses four main certification areas for ditching:

1. **Water Entry:** Model tests or direct comparison with craft of similar design with proven ditching characteristics should be used to determine the optimum behaviour of the helicopter in a water ditching. During ditching the helicopter is assumed to be auto-rotating and rotor lift of up to two thirds of the maximum design weight is assumed to act through the centre of gravity. The following parameters are used to establish the worst case ditching loads:

   - Probable variation from the optimum pitch angle.
   - Forward speeds up to the knee in the helicopter’s height velocity diagram, reduced by the wind speed associated with each applicable sea state.
   - Vertical descent velocity of 5 ft/s (1.52 m/s).
   - Yaw attitudes up to 15 degrees.
   - Wave heights up to and including Sea State 4 are given as examples for North Sea operation.

   The structural integrity of the floats and their attachments are then required to be demonstrated under the most onerous ditching condition. The effects of the vertical and drag loads may be considered to act independently. Probable failure of windows, doors, skins and panels should also be considered.

2. **Flotation Systems:** For fixed (normally inflated) flotation systems, consideration should be given to the following loadings on the floats.

   - Air loads throughout the approved flight envelope.
   - Water entry loads.
   - Water loads after entry.
For floats that are normally deflated, flotation bags are only required to be assessed against water loads after water entry. A manual or fully automatic activation system is required, together with a redundant alternative. It should be demonstrated that inflation at any flight condition within the approved operating envelope is not hazardous unless a very reliable safeguard is in place. The AC gives an example of a manual arming circuit as a reliable inflation safeguard. A means should also be available to check the gas cylinder pressures and the status of the EFS prior to take off.

The inflation system should be designed to minimise the probability of floats inflating improperly. The inflation time should be short enough to prevent the helicopter from becoming partially submerged. Additionally, the AC recommends that the floats should be shown to inflate (without puncture) when subjected to static water pressure.

3 Flotation and Trim: Flotation and trim characteristics should be demonstrated to be satisfactory to at least Sea State 4. This is typically achieved using scale models with solid floats. Probable damage to the airframe should be considered when demonstrating compliance against the trim requirements. Adequate flotation and trim characteristics should also be demonstrated at Sea State 2 for a rupture in the most critical flotation bag compartment.

4 Occupant Egress and Survival: The ability of the occupants to deploy and board the liferafts should be demonstrated. This can be achieved either by a full scale helicopter test on calm water or, more typically, by a “representative” ground based test. The flotation bags should not obstruct occupant egress.


The structural ditching provisions define the landing condition for a controlled ditching, and loading requirements for the emergency floats.

The AC recommends that the helicopter support structure, floats and attachments should be substantiated for rational limit and ultimate ditching loads. The ditching event is defined slightly differently to that in clause 29.801. Namely a forward velocity of up to 30 Knots (15.4 m/s) with a minimum vertical velocity of 1.52 m/s, in a Sea State 4 condition. The attitude of the helicopter and the likely variation in yaw and pitch angles should also be considered. The AC recommends that flight tests should be undertaken to confirm the auto-rotation attitude and variability in yaw and pitch angles. For floats that are fixed or deployed prior to impact, the floats and attachments are required to be designed against the buoyancy load developed by a fully immersed float. Consideration should also be given to restoring moments induced by side winds, asymmetrical helicopter loading, inertia, wave action and probable damage sustained under the ditching requirements of 29.801. For floats deployed in flight, the air loads should be “substantiated” and an air speed safety factor of 1.11 applied to the maximum deployment speed. The AC recommends that landing load factors and likely water distribution are determined from water drop tests or validated analysis.

For floats deployed after impact, the same immersion loadings as for fixed floats apply. In addition, they must be capable of resisting a combined vertical and drag load generated by a relative speed of 20 Knots (10.3 m/s) between the helicopter and
water. This requirement is different to the loads specified in 29.801, which states that the vertical and drag loads can be treated independently.

7.3 JAR 29.561: Emergency Landing Conditions

This section relates to emergency landings onto both land and water. It is primarily concerned with protecting the occupants from serious injury during a crash landing. To this end it specifies inertial loads for items within the passenger cabin which would be likely to injure occupants if they became detached from the airframe. Additionally, ultimate inertial load factors are defined for heavy equipment such as rotors, engines and fuel tanks, which although not inside the cabin may intrude into the passenger compartment during the impact. As EFS are typically sited in non-occupied areas and are of relatively low mass, they would not be capable of intruding into the cabin and therefore would not be covered by this section.

7.4 JAR 29.562: Emergency Landing Dynamic Conditions

This requirement is concerned with protecting occupants from excessive shock loadings during an emergency landing. This is achieved by specifying design and loading requirements for the passenger seats and attachments. Acceptable levels of injury to the occupant are also defined. This clause does not, therefore, apply to EFS.

7.5 JAR 29.807: Passenger Emergency Exits

This clause is concerned with the number and size of emergency exits. The criteria are based on the number of passenger seats in the airframe. In all cases at least one exit in each side of the rotorcraft should remain above the waterline. The flotation devices must not obstruct the exits, and a test must be conducted to demonstrate the proper functioning of all exits.

7.6 Recommendations For Regulation Changes

- The main focus of the JARs is on controlled water entry rather than crashworthiness. It is recommended that guidance on good design practices for accident or high energy impacts should be incorporated in the AC.

- Redundant flotation should be specified at bag level as well as individual compartment level. In an impact, where high loads would be experienced, if one compartment has been ruptured the whole bag is likely to have been damaged.

- A requirement for secondary flotation bags away from the underside of the structure should be considered. The floor region experiences the greatest loads in a water impact, as it is typically the primary impact site. Location away from the underside of the helicopter would greatly improve survivability of the flotation bags.

- Consideration should be given to relaxing the requirement to maintain at least one emergency exit on each side of the helicopter above the water line for severe but survivable impacts. Work being undertaken by CAA is investigating the benefits of side floating in terms of occupant egress. Side floating would help mitigate the effects of capsize following an impact. It should be used in conjunction with, rather than an alternative to floating upright.
• Identical sea state conditions should be specified for both redundant and normal flotation configurations to improve flotation times following an impact.

• Shock loadings should be specified for all safety critical equipment. Currently impact loads are only defined for passengers, or items likely to injure occupants or penetrate the cabin. These loads should be limited by human survivability criteria. There would be little advantage in having a system which functions if the occupants have not survived.

• The use of automatic arming and deployment devices should be incorporated into the JAR design requirements. This would dramatically improve the reliability of the system. These measures would negate the need to involve a conscious decision by the pilot to activate or deploy the flotation bags. Following an accident, the pilot will likely be in shock and disorientated. Historical evidence has shown that the pilot may fail to deploy the flotation system following an uncontrolled water entry. The use of manual backup/override systems would improve reliability and redundancy.

• The regulatory material should be improved by removing the duplication and inconsistencies between the ACs on 29.801 and 29.563. The definition of ditching should be made consistent throughout the text.

• The JARs should be better defined. In particular the applicability of the AC guidance should be more explicit.

8 CONCLUSIONS

A comprehensive review of the crashworthiness of helicopter EFS, their design and regulation has been performed.

A survey of EFS performance in UK Civil and Royal Navy helicopter water impacts was undertaken. In addition, a world-wide literature search was carried out to identify existing research into helicopter EFS.

Little ‘new’ data to that already known at the start of the survey was found. The accident data was almost exclusively limited to the information published in the accident reports, especially for accidents more than eight years ago. Where levels of damage were supplied, they were often too general to be of use for detailed assessments.

Historically, sponson mounted EFS, such as on the S61N, were found to be particularly vulnerable to impact damage. Pod mounted EFS were less prone to damage. Significant fatalities were observed in accidents where the EFS had not been armed and/or deployed.

A detailed assessment of the behaviour of a generic helicopter under a variety of water impact scenarios was performed using non-linear FE methods. The scenarios were based on actual accidents which were outside the FAA’s proposed 95% survivability envelope, but which had a significant number of survivors.
The airframe and water body FE models were validated against a variety of drop tests and various scale model tank tests. The only relevant validation data for the airframe was of a Lynx impact onto the ground with the undercarriage retracted. Given the minor differences between the Lynx and modelled airframe, good correlation with the test data was observed.

Two water models were developed using Lagrangian and Eulerian formulations. For validation purposes, rigid bodies were used to model both vertical and fly-in impacts. The Lagrangian water model was found only to be suitable for determining initial accelerations during vertical impacts. It was not suited to fly-in impacts or impacts that occurred over a significant period of time, as it is incapable of modelling large fluid displacements. The Eulerian water model was more suited to both vertical and fly-in impacts. However, very refined meshes were required to achieve a converged result. The number of elements required for high speed impacts or complex models proved to be prohibitively large, resulting in very long analysis times. There were doubts as to the validity of the test data used for some of the water model validation work.

The Eulerian modelling technique is considered not mature enough to accurately model complex water deformable structure impacts. The Lagrangian water model was only suitable for determining initial acceleration levels for vertical impacts such as the Brent Spar scenario. Global responses and strain levels were generally consistent with damage detailed in the accident reports. However, results for local accelerations were too noisy to extract any useful information. Reasonable correlation with empirical results performed by BMT was achieved.

A review of the design and operation of EFS was performed. This was based on limited data produced by the FAA on US water impacts between 1982 and 1989. Several design modifications were proposed to improve the performance of EFS following a severe impact.

A general cost benefit study was performed to assess whether implementation of any of the modifications would be cost effective in terms of their potential for saving life if they were fitted to the current UK offshore fleet. Automatic arming and activation, redundancy, side floating and increased float protection/attachment all provided cost per life saved figures of $1,000,000 or less. All these modifications offer significant cost-effective methods for saving life and should be considered in further detail in a type specific study.

Several of the proposed modifications are now considered as industry standard and are fitted to the majority of new EFS. These include automatic activation, even gas distribution, flexible hoses and bottle redundancy. The fact that some of the modifications are incorporated voluntarily into current designs does not obviate the need to mandate them in future design requirements. Due to the evolution of EFS design, a study of modern helicopter water impacts may uncover a different list of reasons for failure of the EFS and fatalities. However, only limited data is likely to be available.

The regulatory requirements relating to water ditching, flotation, emergency landing conditions and evacuation issues were reviewed, with an emphasis on crashworthiness issues. A series of recommendations for EFS design and regulatory changes were then made. These are summarised in Section 9 of this report.
RECOMMENDATIONS

The crashworthiness of EFS can be improved by incorporating the following design features:

1. Automatic arming.
2. Automatic activation of floats by immersion switches.
3. Provision of a manual, independent, backup activation and arming system where automatic systems are used.
4. Distribution lines designed with equal resistance and/or flow distribution valves used to ensure equal float deployment, even with a bag ruptured.
5. Flexible hoses used for flow distribution lines.
6. Bags divided into multiple cells to limit the effect of small bag ruptures.
7. Inflation systems designed to limit the effect of varying ambient conditions.
8. Systems which require inflation to be deployed after impact.
9. Floats designed for balanced deployment (timing as well as volume), even with system damage.
10. Where possible, floats located away from likely primary impact sites, such as the nose, sponsons and floor of the airframe.
11. Distribution hoses and wiring not routed through areas of the airframe likely to undergo severe deformation or failure during an impact. Short pipework, or individual gas bottles located near each bag used to reduce the risk of flow line failure due to structural deformation. NB: Careful consideration should be given to the trade off between redundancy with interconnected bags and the higher risk associated with longer pipe runs.
12. Redundant flotation provided at bag level, as well as compartments within a bag.
13. Redundant flotation bags should be located in the upper part of the airframe to minimise the risk of damage. These could be arranged to allow the helicopter to float on its side retaining an air pocket in the cabin and maintaining a number of escape routes above the water surface, rather than capsizing into a fully inverted position.
14. Any claimed passive buoyancy (e.g. fuel tanks or tail boom voids) for ditching is only allowed if it can be demonstrated that the appropriate part of the airframe remains attached to the passenger compartment during an impact.

To improve regulatory requirements, the following changes to the Joint Airworthiness Requirements (JARs) and/or Advisory Circulars (ACs) are recommended:
15 The main focus of the JARs is on controlled water entry rather than crashworthiness. It is recommended that guidance on good design practices for accidental or high energy impacts should be incorporated in the AC.

16 Redundant flotation should be specified at bag level as well as at individual compartment level. In an impact, where high loads would be experienced, if one compartment has been ruptured the whole bag is likely to have been damaged.

17 A requirement for secondary flotation bags away from the underside of the structure should be considered. The floor region experiences the greatest loads in a water impact, as it is typically the primary impact site. Location away from the underside of the helicopter would greatly improve survivability of the flotation bags.

18 Consideration should be given to relaxing the requirement to maintain at least one emergency exit on each side of the helicopter above the water line for severe but survivable impacts. Work being undertaken by CAA is investigating the benefits of side floating in terms of occupant egress.

19 Identical sea state conditions should be specified for both redundant and normal flotation configurations to improve flotation times following a severe impact.

20 Shock loadings should be specified for all safety critical equipment. Currently impact loads are only defined for passengers, or items likely to injure occupants or penetrate into the cabin. These loads should be limited by human survivability criteria. There would be little advantage in having a system which functions if the occupants have not survived.

21 The use of automatic arming and deployment devices should be incorporated into the JAR design requirements. This would dramatically improve the reliability of the system. These measures would negate the need to involve a conscious decision by the pilot to activate or deploy the flotation bags. Following an accident, the pilot will likely be in shock and disorientated. Historical evidence has shown that the pilot may forget to deploy the flotation system following an uncontrolled water entry. The use of manual backup/override systems would improve reliability and redundancy.

22 The regulatory material should be improved by removing the duplication and inconsistencies between the ACs on 29.801 and 29.563. The definition of ditching should be made consistent throughout the text.

The JARs should be better defined. In particular the applicability of the AC guidance should be more explicit.

ACKNOWLEDGEMENTS

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23 Email from CAA to WS Atkins Consultants Ltd, 4th April 2000.
Figure 2: Cut Away of WG30 Model after Ground Impact, Together With Lynx Test Comparison
Figure 3: Acceleration Time History Pulse Recorded at Cabin Floor
Figure 4: Acceleration Time History Pulse Recorded at Main Rotor Gearbox
Space Capsule

Water Body

Figure 5: Arrangement of the Space Capsule Impact Scenario
Figure 6: Acceleration of Space Capsule from Test and Analysis
Figure 7: Vertical Displacement of Space Capsule from Test and Analysis
Figure 8: Finite Element Mesh of Orbiter Space Shuttle
Figure 9: Lateral Acceleration of Orbiter using Lagrangian Mesh
Case 1: Steep Flight Path, Level Attitude

Case 2: Shallow Flight Path, Inclined Attitude

Figure 10: Set up of Two Hull Scenarios Showing Differences in Trim Angle and Flight Path
Figure 11: Vertical Displacement of Hull for Case 1
Figure 12: Vertical Acceleration of Hull for Case 1
Figure 13: Vertical Velocity of Hull for Case 1
Figure 14: Vertical Displacement of Hull for Case 2
Figure 15: Vertical Acceleration of Hull for Case 2
Figure 16: Vertical Velocity of Hull for Case 2
Figure 17: Brent Spar – Global Acceleration at Full and Half Speed
Figure 18: Brent Spar – Full Speed: Maximum Plastic Strain Throughout Time Period
Figure 19: Brent Spar – Half Speed: Maximum Plastic Strain Throughout Time Period
Figure 20: Comparison of Nodal Velocity for Rigid and Non-Rigid Analysis
Figure 21: Nodal Acceleration Before and After Filtering
Figure 22: Location of Nodes for Monitoring Acceleration
Figure 23: Filtered Vertical Acceleration for Gearbox, Floor and Side Panels
Figure 24: Cormorant Alpha – Global Acceleration at Full and Half Speed
Figure 25: Cormorant Alpha – Full Speed: Maximum Plastic Strain Throughout Time Period
Figure 26: Cormorant Alpha – Half Speed: Maximum Plastic Strain Throughout Time Period
Figure 27: Isles of Scilly – Global Acceleration at Full Speed
Figure 28: Isles of Scilly – Full Speed: Maximum Plastic Strain Throughout Time Period
Figure 29: Isles of Scilly – Half Speed: Maximum Plastic Strain Throughout Time Period
Figure 30: Global Accelerations For Full Speed Scenarios Eulerian Water Models
Figure 31: Plastic Strain for Full Speed Brent Spar Scenario Eulerian Water Model
Figure 32: Plastic Strain for Full Speed Scilly Isles Scenario  Eulerian Water Model
Figure 33: Plastic Strain for Full Speed Cormorant Alpha Scenario Eulerian Water Model
Figure 34: Location of Side Panels Under Consideration
Figure 35: Sequence of Events in Successful Float Deployment
Figure 36: Probability Tree for Deployment of EFS
Appendix A  Royal Navy Accident Records

The following information was gathered as a result of a visit to Royal Navy Flight Safety and Accident Investigation Centre at RNAS Yeovilton on 18/2/97. After each accident a discussion of the main accident features relevant to this study are given.

1  21/1/81 Sea King XV665 RN Report 2/81 – Gulf of Oman
   • Yaw control failure.
   • 4 occupants, 0 injuries.
   • Nose down, 10knts forward, 0 down speed, auto rotation controlled ditching.
   • Slight damage to 6 sub frames below cockpit floor and panel torn, no window breakage.
   • 1 EFS bag fired, the other did not due to manual switch not fully depressed.

2  18/2/81 Sea King RN Report 3/81 – Falmouth
   • Controlled ditching. Very little information found.
   • 7 occupants, 4 minor injuries.

3  6/3/81 Sea King RN Report 4/81 – Oman
   • Mid air collision between two Sea Kings.
   • 4 occupants in one helicopter, 4 fatalities.
   • No attempt at flotation heavy impact with water, considered non survivable.
   • 4 occupants in other helicopter, 1 fatality, 1 minor injury.
   • Impacted water from 20ft with 30knt ground speed into Sea State 4. Occupants thought it was drifting right.
   • Helicopter inverted and tail broke off.
   • 1 EFS bag fired. No more additional information found.

4  8/11/85 Sea King, RN Report 4/85
   • Controlled descent from 40ft following failure of main rotor gearbox.
   • 4 occupants, no injuries.
   • EFS deployed, no record of damage.
5 **22/10/86 Sea King XD632 RN Report 3/86**

- Helicopter ditched after fuel starvation.
- 3 occupants, 1 minor injury.
- 20knt forward speed, nose up attitude.
- On striking the water the tail broke off and helicopter sank in 2300 fathoms, no recovery attempt made.
- It was thought that one maybe both sponsons were broken off on impact.
- Sea state 2/3, slight with 15knt wind.

6 **24/2/87 Sea King, RN Report 2/87**

- Sudden impact 35knots in acute nose down attitude.
- 3 occupants, 3 fatalities
- Large structural damage to fuselage, right hand sponson torn off disrupting fuselage frames. Fuselage broke up into 3 section. Forward part of lower boat hull remained attached by cables. Aft fuselage section at rear of internal floor separated. Tail cone separated aft of rear undercarriage. Rotor head and gearbox remained attached.
- No attempt at EFS, considered non-survivable due to major structural break-up.

7 **16/10/87 Wessex, RN Report 4/87**

- Uncontrolled descent, leading to 4.5g impact, no forward speed.
- 3 occupants, 1 injury.
- EFS deployed but helicopter inverted after 5 minutes.

8 **13/10/88 Sea King, RN Report 3/88**

- Heavy impact at 87knts forward speed.
- 4 occupants, 2 fatalities, 1 minor injury.
- Helicopter broke up on impact, severe damage.

9 **10/9/91 Sea King ZD631, RN Report 3/91**

- Controlled ditching following failure of MRGB.
- 4 occupants, no fatalities or injuries.
- EFS deployed successfully.
- Rough seas caused helicopter to sink after 20 minutes, rough weather also prevented salvage of helicopter.
10  6/11/93 Sea King ZE419, RN Report 5/93 – Islay

- 27knts backwards impact, 2.2m/s descent, nose up 12°.
- 4 occupants, 1 fatality, 1 serious (breathing gear used in escape)
- Helicopter broke into 3 sections, across the tail and at mid fuselage. 1 sponson severely damaged.
- EFS did not operate due to immediate loss of electric power (EFS on auto deploy system). Investigation held view that if it had fired it would have been ineffective.
- Sea State 3.
Appendix B  Space Capsule And Orbiter Modelling Data

<p>| | |</p>
<table>
<thead>
<tr>
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<tr>
<td>Moments of Inertia Yaw</td>
<td>731 kgm²</td>
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Table 1: Pertinent Physical Properties Of Space Capsule

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Weight</td>
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<tr>
<td>Centre-of-Gravity location (length from rear )</td>
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<tr>
<td>Moments of Inertia Pitch</td>
<td>7.95x10⁶ kgm²</td>
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<tr>
<td>Moments of Inertia Yaw</td>
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</tr>
<tr>
<td>Moments of Inertia Roll</td>
<td>1.09x10⁶ kgm²</td>
</tr>
</tbody>
</table>

Table 2: Pertinent Physical Properties Of Space Shuttle Orbiter
Appendix C Joint Airworthiness Requirements and Advisory Material

1.1 JAR 29.561 General

(a) The rotorcraft, although it may be damaged in emergency landing conditions on land or water, must be designed as prescribed in this section to protect the occupants under those conditions.

(b) The structure must be designed to give each occupant every reasonable chance of escaping serious injury in a crash landing when -

1. Proper use is made of seats, belts, and other safety design provisions;

2. The wheels are retracted (where applicable); and

3. Each occupant and each item of mass inside the cabin that could injure an occupant is restrained when subjected to the following ultimate inertial load factors relative to the surrounding structure:

(i) Upward - 4 g

(ii) Forward -16 g

(iii) Sideward - 8 g

(iv) Downward - 20 g, after the intended displacement of the seat device.

(c) The supporting structure must be designed to restrain under any ultimate inertial load factor up to those specified in this paragraph, any item of mass above and/or behind the crew and passenger compartment that could injure an occupant if it came loose in an emergency landing. Items of mass to be considered include, but are not limited to, rotors, transmission and engines. The items of mass must be restrained for the following ultimate inertial load factors:

1. Upward - 1.5 g

2. Forward - 8 g

3. Sideward - 2 g

4. Downward - 4 g

(d) Any fuselage structure in the area of internal fuel tanks below the passenger floor level must be designed to resist the following ultimate inertia factors and loads, and to protect the fuel tanks from rupture, if rupture is likely when those loads are applied to that area:

1. Upward - 1.5 g

2. Forward - 4.0 g

3. Sideward - 2.0 g

4. Downward - 4.0 g
1.2 Advisory Circular 29-2B: JAR 29.561 General

218. § 29.561 GENERAL.

a. Explanation.

(1) The occupants should be protected as prescribed from serious injury during an emergency/minor crash landing on water or land for the conditions prescribed in the standard. The standard states that each occupant should be given every reasonable chance of escaping serious injury in a minor crash landing.

(2) Section 29.561(b)(3) specifies certain ultimate inertial load factors but allows a lesser downward vertical load factor by virtue of a 5 FPS ultimate rate of descent at maximum design weight.

(3) In addition, the occupants must be protected from items of mass inside the cabin as well as outside the cabin. For example, a cabin fire extinguisher must be restrained for the load factors prescribed in this section. A transmission or engine must be restrained to the load factors in § 29.561(b)(3) if located adjacent to, above, or behind the occupants.

(4) For aircraft equipped with retractable landing gear, the landing gear must be retracted for compliance.

(5) Fuel tank protection.

(i) Underfloor fuel tanks are specifically addressed in § 29.561(d). The fuselage structure must be designed to resist crash impact loads prescribed in § 29.561(b)(3) and to also protect the fuel tank from rupture as prescribed. The landing gear must be retracted if the rotorcraft is equipped with retractable gears.

(ii) Section 29.963(b), a general rule tank design standard, also refers to § 29.561. This standard specifies that each tank and its installation must be designed or protected to retain fuel without leakage under the emergency landing conditions in § 29.561. Paragraph 454 of this AC relates to this standard.

(6) The minor crash conditions contained in § 29.561(b)(3) must also be considered in designing doors and exits (§ 29.783(d) and (g), and § 29.809(e)).

b. Procedures.

(1) The design criteria report or another similar report of the rotorcraft structural limits should contain the (ultimate) minor crash condition load factors.

(2) Section 29.785 (Paragraph 336 of this AC) concerns application of this design standard to seats (berths, litters), belts, and harnesses.

(3) The ultimate design landing and maneuvering load factors may exceed the minor crash condition load factors. The highest load factor derived must be used.

(i) For example, for light weight conditions, the ultimate maneuvering load factor may be 5.25g as specified in § 29.337.

(ii) The ultimate vertical landing load factors derived from §§ 29.471 through 29.521, whichever are appropriate for the design, may exceed the 4.0g down load factor in this section. The rotorcraft landing case design limit contact velocity must be at least 6.5 FPS (see §§ 29.473 and 29.725).

(4) As specified in § 29.561(b)(3)(iv), the downward load factor is 4.0, or a lower design load factor may be used at maximum design weight.

(i) The lower load factor relates to a rotorcraft impacting a flat, hard landing surface at 5 FPS (ultimately) vertical rate of descent. The load factor derived for each unique design is a function of the rotorcraft impact/crushing characteristics.
(ii) The 4.0 g down load factor case is related to either a fixed or retractable gear rotorcraft. This condition is not dependent on impact characteristics of the rotorcraft.

(iii) As noted in Paragraph b(3) above, the design landing load factors may exceed each of the two previous cases and would then become the prominent design (vertical load) parameter for seats, transmissions, fire extinguishers, and so forth.

(5) Items of mass such as fire extinguishers, radio equipment, liferafts, engines, and/or transmissions must be restrained for the appropriate load factors.

(6) Cargo/baggage compartments separated from the passenger compartment must be designed for load factors specified in § 29.787. The conditions in § 29.561 are excepted from that standard.

(7) Each fuel tank and its installation are subject to the loads stated in this standard whether “under floor” or located elsewhere. (See § 29.963(b) also.) Under floor fuel tanks are specifically addressed in § 29.561(d); however, an acceptable means of compliance with CAR 7.261 which is identical to and preceded § 29.561(d) is quoted here for information.

NOTE: Fuselage keels whose design and structural strength are such as to resist crash impacts associated with the emergency landing conditions of § 7.260 (§ 29.561) without extreme distortion which might tend to rupture the fuel tank may be considered to comply with the requirements of this section (7.261).

Puncture resistant “bladder” fuel cells that are adequately designed and also protected from the stated impact loads imposed on the fuselage may also satisfy the standards.

(8) For rotorcraft with retractable landing gear, alternative landing gear positions and the resulting effects on potential fuel release should be evaluated.

218A. § 29.561 (Amendment 29-29 EMERGENCY LANDING CONDITIONS - GENERAL.

a. Explanation. Amendment 29-29 adds or increases the design static load factors of § 29.561 in three different areas:

(1) The design static load factors for the cabin in § 29.561(b)(3) are increased in concert with the dynamic test requirements of new § 29.562.

(2) Design static load factors are added in § 29.561(c) for external items of mass located above and/or behind the crew and passenger compartment.

(3) The static load factors, which were formerly only referenced in § 29.561(d), are now included explicitly in § 29.561(d) for substantiation of internal fuel tanks which are below the passenger floor.

b. Procedures. The procedures of Paragraph 218, § 29.561, continue to apply except the new load factors of § 29.561 should be used. Penetration of any items of mass into the cabin or occupied areas should be prevented.

218B. § 29.561 (Amendment 29-38) EMERGENCY LANDING CONDITIONS-GENERAL.

a. Explanation. Amendment 29-38 adds a new rearward emergency load factor of 1.5g to both §§ 29.561(b)(3)(v) and 29.561(c)(5). The addition of the 1.5g rearward load factor in § 29.561(b)(3)(v) is to provide an aft ultimate load condition for substantiation of the constraints required for retention of both occupants and significant items of mass inside the cabin that could otherwise come loose and cause injuries in an emergency landing. The addition of the 1.5g rearward load factor to § 29.561(c)(5) is to provide an aft ultimate load condition for substantiation of the support structure for retention of significant items of mass above and forward of the occupied volume(s) of the rotorcraft that could otherwise come loose and injure an occupant in an emergency landing. Amendment 29-38 also increases the forward, sideward, and downward emergency load factors of § 29.561(c)(2), (c)(3), and (c)(4), respectively, for retention of items of mass above and behind the occupied volume(s) that could otherwise come loose and injure an occupant in an emergency landing.
b. **Procedures.** The procedures of Paragraphs 218 and 218A continue to apply except the newly specified load factors must be used. A list of the significant items of mass to be considered should be compiled by the applicant and approved by the certifying authority.
2.1 JAR 29.562 Emergency Landing Dynamic Conditions

(a) The rotorcraft, although it may be damaged in a crash landing, must be designed to reasonably protect each occupant when -

(1) The occupant properly uses the seats, safety belts, and shoulder harnesses provided in the design; and

(2) The occupant is exposed to loads equivalent to those resulting from the conditions prescribed in this section.

(b) Each seat type design or other seating device approved for crew or passenger occupancy during take-off and landing must successfully complete dynamic tests or be demonstrated by rational analysis based on dynamic tests of a similar type seat in accordance with the following criteria. The tests must be conducted with an occupant simulated by a 77 kg (170-pound) anthropomorphic test dummy (ATD), sitting in the normal upright position.

(1) A change in downward velocity of not less than 9.1 metres per second (30ft/s) when the seat or other seating device is oriented in its nominal position with respect to the rotorcraft's reference system, the rotorcraft's longitudinal axis is canted upward 60°, with respect to the impact velocity vector, and the rotorcraft's lateral axis is perpendicular to a vertical plane containing the impact velocity vector and the rotorcraft's longitudinal axis. Peak floor deceleration must occur in not more than 0.031 seconds after impact and must reach a minimum of 30g.

(2) A change in forward velocity of not less than 12.8 metres per second (42ft/s) when the seat or other seating device is oriented in its nominal position with respect to the rotorcraft's reference system, the rotorcraft's longitudinal axis is yawed 10°, either right or left of the impact velocity vector (whichever would cause the greatest load on the shoulder harness), the rotorcraft's lateral axis is contained in a horizontal plane containing the impact velocity vector, and the rotorcraft's vertical axis is perpendicular to a horizontal plane containing the impact velocity vector. Peak floor deceleration must occur in not more than 0.071 seconds after impact and must reach a minimum of 18.4g.

(3) Where floor rails or floor or sidewall floor attachment devices are used to attach the seating devices to the airframe structure for the conditions of this section, the rails or devices must be misaligned with respect to each other by at least 10°, vertically (i.e. pitch out of parallel) and by at least a 10°, lateral roll, with the directions optional, to account for possible floor warp.

(c) Compliance with the following must be shown:

(1) The seating device system must remain intact although it may experience separation intended as part of its design.

(2) The attachment between the seating device and the airframe structure must remain intact, although the structure may have exceeded its limit load.

(3) The ATD's shoulder harness strap or straps must remain on or in the immediate vicinity of the ATD's shoulder during the impact.

(4) The safety belt must remain on the ATD's pelvis during the impact.

(5) The ATD’s head either does not contact any portion of the crew or passenger compartment, or if contact is made, the head impact does not exceed a head injury criteria (HIC) of 1000 as determined by this equation.
\[ HIC = \left( t_2 - t_1 \right) \left[ \frac{1}{\left( t_2 - t_1 \right)} \int_{t_1}^{t_2} a(t) \, dt \right]^{2.5} \]

Where – \( a(t) \) is the resultant acceleration at the centre of gravity of the head form expressed as a multiple of \( g \) (the acceleration of gravity) and \( t_2 - t_1 \) is the time duration, in seconds, of major head impact, not to exceed 0.05 seconds.

(6) Loads in individual shoulder harness straps must not exceed 794 kg (1750 pounds). If dual straps are used for retaining the upper torso, the total harness strap loads must not exceed 907 kg (2000 pounds).

(7) The maximum compressive load measured between the pelvis and the lumbar column of the ATD must not exceed 680 kg (1500 pounds).

(d) An alternate approach that achieves an equivalent or greater level of occupant protection, as required by this section, must be substantiated on a rational basis.

2.2 Advisory Circular 29-2B: JAR 29.562 Emergency Landing Dynamic Conditions

219. § 29.562 EMERGENCY LANDING DYNAMIC CONDITIONS.

a. Explanation. Amendment 29-29 adds new requirements for the dynamic testing of all seats in rotorcraft.

b. Procedures. AC 20-137, “Dynamic Evaluation of Seat Restraint Systems and Occupant Restraint for Rotorcraft (Normal and Transport),” provides procedures for complying with § 29.562 using the 170-pound anthropomorphic test dummy specified in § 29.562(b). Those seats not occupied for takeoff and landing, and so placarded and identified in the rotorcraft flight manual (RFM), may be excluded from compliance.

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3.1 JAR 29.563 Structural ditching provisions

If certification with ditching provisions is requested, structural strength for ditching must meet the requirements of this section and JAR 29.801(e).

(a) Forward speed landing conditions. The rotorcraft must initially contact the most critical wave for reasonably probable water conditions at forward velocities from zero up to 30 knots in likely pitch, roll, and yaw attitudes. The rotorcraft limit vertical descent velocity may not be less than 1.52 metres per second (5ft/s) relative to the mean water surface. Rotor lift may be used to act through the centre of gravity throughout the landing impact. This lift may not exceed two-thirds of the design maximum weight. A maximum forward velocity of less than 30 knots may be used in design if it can be demonstrated that the forward velocity selected would not be exceeded in a normal one-engine-out touchdown.

(b) Auxiliary or emergency float conditions

(1) Floats fixed or deployed before initial water contact. In addition to the landing loads in sub-paragraph (a) of this paragraph, each auxiliary or emergency float, or its support and attaching structure in the airframe or fuselage, must be designed for the load developed by a fully immersed float unless it can be shown that full immersion is unlikely. If full immersion is unlikely, the highest likely float buoyancy load must be applied. The highest likely buoyancy load must include consideration of a partially immersed float creating restoring moments to compensate the upsetting moments caused by side wind, unsymmetrical rotorcraft loading, wave water action, rotorcraft inertia, and probable structural damage and leakage considered under JAR 29.801 (d). Maximum roll and pitch angles determined from compliance with JAR 29.801 (d) may be used, if significant, to determine the extent of immersion of each float. If the floats are deployed in flight, appropriate air loads derived from the flight limitations with the floats deployed shall be used in substantiation of the floats and their attachment to the rotorcraft. For this purpose, the design airspeed for limit load is the float deployed airspeed operating limit multiplied by 1.11.

(2) Floats deployed after initial water contact. Each float must be designed for full or partial immersion prescribed in sub-paragraph (b)(1) of this paragraph. In addition, each float must be designed for combined vertical and drag loads using a relative limit speed of 20 knots between the rotorcraft and the water. The vertical load may not be less than the highest likely buoyancy load determined under paragraph (b) (1) of this paragraph.


220. § 29.563 (Amendment 29-12) STRUCTURAL DITCHING PROVISIONS.

   a. **Explanation.** Amendment 29-12 included certification requirements for ditching approvals. The rotorcraft must be able to sustain an emergency landing in water as prescribed by § 29.801(e).

   b. **Procedures.** Refer to Paragraph 337, § 29.801, for procedures.

220A. § 29.563 (Amendment 29-30) STRUCTURAL DITCHING PROVISIONS.

   a. **Explanation.** Amendment 29-30 added specific structural conditions to be considered to support the overall ditching requirements of § 29.801. These conditions are to be applied to rotorcraft for which over-water operations and associated ditching approvals are requested.
(1) The forward speed landing conditions are specified as:

(i) The rotorcraft should contact the most critical wave for reasonable, probable water conditions in the likely pitch, roll, and yaw attitudes.

(ii) The forward velocity relative to wave surface should be in a range of 0 to 30 knots with a vertical descent rate of not less than 5 FPS relative to the mean water surface.

NOTE: A forward velocity of less than 30 knots may be used for multiengine rotorcraft if it can be demonstrated that the forward velocity selected would not be exceeded in a normal one-engine-out touchdown.

(iii) Rotor lift of not more than two-thirds of the design maximum weight may be used to act through the CG throughout the landing impact.

(2) For floats fixed or deployed before water contact, the auxiliary or emergency float conditions are specified in § 29.563(b)(i). Loads for a fully immersed float should be applied (unless it is shown that full immersion is unlikely). If full immersion is unlikely, loads resulting from restoring moments are specified for sideward and unsymmetrical rotorcraft landing.

(3) Floats deployed after water contact are normally considered fully immersed during and after full inflation. An exception would be when the inflation interval is long enough that full immersion of the inflated floats does not occur; e.g., deceleration of the rotorcraft during water impact and natural buoyancy of the hull prevent full immersion loads on the fully inflated floats.

b. Procedures.

(1) The rotorcraft support structure, structure-float attachments, and floats should be substantiated for rational limit and ultimate ditching loads.

(2) The most severe wave heights for which approval is desired are to be considered. A minimum of Sea State 4 condition wave heights should be considered (reference Paragraph 337 (§ 29.801) of this AC for a description of Sea State 4 conditions).

(3) The landing structural design consideration should be based on water impact with a rotor lift of not more than two-thirds of the maximum design weight acting through the center of gravity under the following conditions:

(i) Forward velocities of 0 to 30 knots (or a reduced maximum forward velocity if it can be demonstrated that a lower maximum velocity would not be exceeded in a normal one-engine-out landing).

(ii) The rotorcraft pitch attitude that would reasonably be expected to occur in service. Autorotation flight tests or one-engine-inoperative flight tests, as applicable, should be used to confirm the attitude selected. This information should be included in the Type Inspection Report.

(iii) Likely roll and yaw attitudes.

(iv) Vertical descent velocity of 5 FPS or greater.

(4) Landing load factors and water load distribution may be determined by water drop tests or analysis based on tests.

(5) Auxiliary or emergency float loads should be determined by full immersion or the use of restoring moments required to react upsetting moments caused by sideward, asymmetrical rotorcraft landing, water wave action, rotorcraft inertia, and probable structure damage and punctures considered under § 29.801. Auxiliary or emergency float loads may be determined by tests or analysis based on tests.

(6) Floats deployed after initial water contact are required to be substantiated by tests or analysis for the specified immersion loads (same as for (5) above and for the specified combined vertical and drag loads).
4.1 JAR 29.801 Ditching

(a) If certification with ditching provisions is requested, the rotorcraft must meet the requirements of this paragraph and JAR 29.807 (d), 29.1411 and 29. 1415.

(b) Each practicable design measure, compatible with the general characteristics of the rotorcraft, must be taken to minimise the probability that in an emergency landing on water, the behaviour of the rotorcraft would cause immediate injury to the occupants or would make it impossible for them to escape.

(c) The probable behaviour of the rotorcraft in a water landing must be investigated by model tests or by comparison with rotorcraft of similar configuration for which the ditching characteristics are known. Scoops, flaps, projections, and any other factors likely to affect the hydrodynamic characteristics of the rotorcraft must be considered.

(d) It must be shown that, under reasonably probable water conditions, the flotation time and trim of the rotorcraft will allow the occupants to leave the rotorcraft and enter the life rafts required by JAR 29.1415. If compliance with this provision is shown by buoyancy and trim computations, appropriate allowances must be made for probable structural damage and leakage. If the rotorcraft has fuel tanks (with fuel jettisoning provisions) that can reasonably be expected to withstand a ditching without leakage, the jettisonable volume of fuel may be considered as buoyancy volume.

(e) Unless the effects of the collapse of external doors and windows are accounted for in the investigation of the probable behaviour of the rotorcraft in a water landing (as prescribed in sub-paragraphs (c) and (d) of this paragraph), the external doors and windows must be designed to withstand the probable maximum local pressures.

4.2 Advisory Circular 29-2B: JAR 29.801 Ditching

337. § 29.801 (Amendment 29-12) DITCHING.

a. Explanation.

(1) Ditching certification is accomplished only if requested by the applicant.

(2) Ditching may be defined as an emergency landing on the water, deliberately executed, with the intent of abandoning the rotorcraft as soon as practical. The rotorcraft is assumed to be intact prior to water entry with all controls and essential systems, except engines, functioning properly.

(3) The regulation requires demonstration of the flotation and trim requirements under “reasonably probable water conditions.” The FAA/AUTHORITY has determined that a sea state 4 is representative of reasonably probable water conditions to be encountered. Therefore, demonstration of compliance with the ditching requirements for at least sea state 4 water conditions is considered to satisfy the reasonably probable requirement.

(4) A sea state 4 is defined as a moderate sea with significant wave heights of 4 to 8 feet with a height-to-length ratio of:

(i) 1:12.5 for Category A rotorcraft.

(ii) 1:10 for Category B rotorcraft with Category A engine isolation.

(iii) 1:8 for Category B rotorcraft.

The source of the sea state definition is the World Meteorological Organization (WMO) Table. (See Table 337-1).

(5) Ditching certification encompasses four primary areas of concern: rotorcraft water entry, rotorcraft flotation and trim, occupant egress, and occupant survival.
(6) The rule requires that after ditching in reasonably probable water conditions, the flotation time and trim of the rotorcraft will allow the occupants to leave the rotorcraft and enter liferafts. This means that the rotorcraft should remain sufficiently upright and in adequate trim to permit safe and orderly evacuation of all personnel.

(7) For a rotorcraft to be certified for ditching, emergency exits must be provided which will meet the requirements of § 29.807(d).

(8) The safety and ditching equipment requirements are addressed in §§ 29.1411, 29.1415, and 29.1561 and specified in the operating rules (Parts 91, 121, 127, and 135). As used in § 29.1415, the term ditching equipment would more properly be described as occupant water survival equipment. Ditching equipment is required for extended overwater operations (more than 50 nautical miles from the nearest shoreline and more than 50 nautical miles from an offshore heliport structure). However, ditching certification should be accomplished with the maximum required quantity of ditching equipment regardless of possible operational use.

(9) Current practices allow wide latitude in the design of cabin interiors and consequently, the stowage provisions for safety and ditching equipment. Rotorcraft manufacturers may deliver aircraft with unfinished (green) interiors that are to be completed by the purchaser or modifier. These various "configurations" present problems for certifying the rotorcraft for ditching.

(i) In the past, "segmented" certification has been permitted to accommodate this practice. That is, the rotorcraft manufacturer shows compliance with the flotation time, trim, and emergency exit requirements while the purchaser or modifier shows compliance with the equipment provisions and egress requirements with the completed interior. This procedure requires close cooperation and coordination between the manufacturer, purchaser or modifier, and the FAA/AUTHORITY.

(ii) The rotorcraft manufacturer may elect to establish a "token" interior for ditching certification. This interior may subsequently be modified by a supplemental type certificate or a field approval. Compliance with the ditching requirements should be reviewed after any interior configuration and limitations changes where applicable.

(iii) The Rotorcraft Flight Manual and supplements deserve special attention if a "segmented" certification procedure is pursued.

b. Procedures. The following guidance criteria has been derived from past FAA/AUTHORITY certification policy and experience. Demonstration of compliance to other criteria may produce acceptable results if adequately justified by rational analysis. Model tests of the appropriate ditching configuration may be conducted to demonstrate satisfactory water entry and flotation and trim characteristics where satisfactory correlation between model testing and flight testing has been established. Model tests and other data from rotorcraft of similar configurations may be used to satisfy the ditching requirements where appropriate.

(1) Water entry.

(i) Tests should be conducted to establish procedures and techniques to be used for water entry. These tests should include determination of optimum pitch attitude and forward velocity for ditching in a calm sea as well as entry procedures for the highest sea state to be demonstrated (e.g., the recommended part of the wave on which to land). Procedures for all engines operating, one engine inoperative, and all engines inoperative conditions should be established. However, only the procedures for the most critical condition (usually all engines inoperative) need to be verified by water entry tests.

(ii) The ditching structural design consideration should be based on water impact with a rotor lift of not more than two-thirds of the maximum design weight acting through the center of gravity under the following conditions:

(A) For entry into a calm sea –

(1) The optimum pitch attitude as determined in 337(b)(1)(i) with consideration for pitch attitude variations that would reasonably be expected to occur in service;
(2) Forward speeds from zero up to the speed defining the knee of the height-velocity (HV) diagram;

(3) Vertical descent velocity of 5 feet per second; and

(4) Yaw attitudes up to 15°.

(B) For entry into the maximum demonstrated sea state –

(1) The optimum pitch attitude and entry procedure as established in (b)(1)(i);

(2) The forward speed defined by the knee of the HV diagram reduced by the wind speed associated with each applicable sea state;

(3) Vertical descent velocity of 5 feet per second; and

(4) Yaw attitudes up to 15°.

(C) The float system attachment hardware should be shown to be structurally adequate to withstand water loads during water entry when both deflated and stowed and fully inflated (unless in-flight inflation is prohibited). Water entry conditions should correspond to those established in Paragraphs 337(b)(1)(ii)(A) and (B). The appropriate vertical loads and drag loads determined from water entry conditions (or as limited by flight manual procedures) should be addressed. The effects of the vertical loads and the drag loads may be considered separately for the analysis.

(D) Probable damage due to water impact to the airframe/hull should be considered during the water entry evaluations; i.e., failure of windows, doors, skins, panels, etc.

(2) Flotation Systems.

(i) Normally inflated. Fixed flotation systems intended for emergency ditching use only and not for amphibian or limited amphibian duty should be evaluated for:

(A) Structural integrity when subjected to:

(1) Air loads throughout the approved flight envelope with floats installed;

(2) Water loads during water entry; and

(3) Water loads after water entry at speeds likely to be experienced after water impact.

(B) Rotorcraft handling qualities throughout the approved flight envelope with floats installed.

(ii) Normally deflated. Emergency flotation systems which are normally stowed in a deflated condition and inflated either in flight or after water contact during an emergency ditching should be evaluated for:

(A) Inflation. The float activation means may be either fully automatic or manual with a means to verify primary actuation system integrity prior to each flight. If manually inflated, the float activation switch should be on one of the primary flight controls and should be safeguarded against spontaneous or inadvertent actuation for all flight conditions.

(1) The inflation system design should minimize the probability of the floats not inflating properly or inflating asymmetrically. This may be accomplished by use of a single inflation agent container or multiple container system interconnected together. Redundant inflation activation systems will also normally be required. If the primary actuation system is electrical, a mechanical backup actuation system will usually provide the necessary reliability. A Secondary electrical actuation system may also be acceptable if adequate electrical system independence and reliability can be documented.
(2) The inflation system should be safeguarded against spontaneous or inadvertent actuation for all flight conditions. It should be demonstrated that float inflation at any flight condition within the approved operating envelope will not result in a hazardous condition unless the safeguarding system is shown to be extremely reliable. One safeguarding method that has been successfully used on previous certification programs is to provide a separate float system arming circuit which must be activated before inflation can be initiated.

(3) The maximum airsteeds for intentional in-flight actuation of the float system and for flight with the floats inflated should be established as limitations in the RFM unless in-flight actuation is prohibited by the RFM.

(4) The inflation time from actuation to neutral buoyancy should be short enough to prevent the rotorcraft from becoming more than partially submerged assuming actuation upon water contact.

(5) A means should be provided for checking the pressure of the gas storage cylinders prior to takeoff. A table of acceptable gas cylinder pressure variation with ambient temperature and altitude (if applicable) should be provided.

(6) A means should be provided to minimize the possibility of overinflation of the float bags under any reasonably probable actuation conditions.

(7) The ability of the floats to inflate without puncture when subjected to actual water pressures should be substantiated. A full-scale rotorcraft immersion demonstration in a calm body of water is one acceptable method of substantiation. Other methods of substantiation may be acceptable depending upon the particular design of the flotation system.

(B) Structural Integrity. The flotation bags should be evaluated for loads resulting from:

(1) Airloads during inflation and fully inflated for the most critical flight conditions and water loads with fully inflated floats during water impact for the water entry conditions established under Paragraph 337(b)(1)(ii) for rotorcraft desiring float deployment before water entry; or

(2) Water loads during inflation after water entry.

(C) Handling Qualities. Rotorcraft handling qualities should be verified to comply with the applicable regulations throughout the approved operating envelopes for:

(1) The deflated and stowed condition;

(2) The fully inflated condition; and

(3) The in-flight inflation condition.

(3) Flotation and Trim. The flotation and trim characteristics should be investigated for a range of sea states from zero to the maximum selected by the applicant and should be satisfactory in waves having height/length ratios of 1:12.5 for Category A rotorcraft, 1:10 for Category B rotorcraft with Category A engine isolation, and 1:8 for Category B rotorcraft.

(i) Flotation and trim characteristics should be demonstrated to be satisfactory to at least sea state 4 conditions.

(ii) Flotation tests should be investigated at the most critical rotorcraft loading condition.

(iii) Flotation time and trim requirements should be evaluated with a simulated, ruptured deflation of the most critical float compartment. Flotation characteristics should be satisfactory in this degraded mode to at least sea state 2 conditions.

(iv) A sea anchor or similar device should not be used when demonstrating compliance with the flotation and trim requirements but may be used to assist in the deployment of liferafts. If the basic flotation system has demonstrated compliance with the
minimum flotation and trim requirements, credit for a sea anchor or similar device to achieve stability in more severe water conditions (sea state, etc.) may be allowed if the device can be automatically, remotely, or easily deployed by the minimum flightcrew.

(v) Probable rotorcraft door/window open or closed configurations and probable damage to the airframe/hull (i.e. failure of doors, windows, skin, etc.) should be considered when demonstrating compliance with the flotation and trim requirements.

(4) Float System Reliability. Reliability should be considered in the basic design to assure approximately equal inflation of the floats to preclude excessive yaw, roll, or pitch in flight or in the water.

(i) Maintenance procedures should not degrade the flotation system (e.g., introducing contaminants which could affect normal operation, etc.).

(ii) The flotation system design should preclude inadvertent damage due to normal personnel traffic flow and excessive wear and tear. Protection covers should be evaluated for function and reliability.

(5) Occupant Egress and Survival. The ability of the occupants to deploy liferafts, egress the rotorcraft, and board the liferafts should be evaluated. For configurations which are considered to have critical occupant egress capabilities due to liferaft locations and/or ditching emergency exit locations and floats proximity, an actual demonstration of egress may be required. When a demonstration is required, it may be conducted on a full-scale rotorcraft actually immersed in a calm body of water or using any other rig/ground test facility shown to be representative. The demonstration should show that floats do not impede a satisfactory evacuation.

(6) Rotorcraft Flight Manual. The Rotorcraft Flight Manual is an important element in the approval cycle of the rotorcraft for ditching. The material related to ditching may be presented in the form of a supplement or a revision to the basic manual. This material should include:

(i) The information pertinent to the limitations applicable to the ditching approval. If the ditching approval is obtained in a segmented fashion (i.e., one applicant performing the aircraft equipment installation and operations portion and another designing and substantiating the liferaft/lifevest and ditching safety equipment installations and deployment facilities), the RFM limitations should state “Not Approved for Ditching” until all segments are completed. The requirements for a complete ditching approval not yet completed should be identified in the “Limitations” section.

(ii) Procedures and limitations for flotation device inflation.

(iii) Recommended rotorcraft water entry attitude, speed, and wave position.

(iv) Procedures for use of emergency ditching equipment.

(v) Ditching egress and raft entry procedures.
### TABLE 337-1

**SEA STATE CODE**

(WORLD METEOROLOGICAL ORGANIZATION)

<table>
<thead>
<tr>
<th>Sea State Code</th>
<th>Description of Sea</th>
<th>Significant Wave Height</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calm (Glassy)</td>
<td>0</td>
<td>0-3</td>
</tr>
<tr>
<td>1</td>
<td>Calm (Rippled)</td>
<td>0 to 0.1</td>
<td>0 to 1/3</td>
</tr>
<tr>
<td>2</td>
<td>Smooth (Wavelets)</td>
<td>0.1 to 0.5</td>
<td>1/3 to 1 2/3</td>
</tr>
<tr>
<td>3</td>
<td>Slight</td>
<td>0.5 to 1.25</td>
<td>1 2/3 to 4</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>1.25 to 2.5</td>
<td>4 to 8</td>
</tr>
<tr>
<td>5</td>
<td>Rough</td>
<td>2.5 to 4</td>
<td>8 to 13</td>
</tr>
<tr>
<td>6</td>
<td>Very Rough</td>
<td>4 to 6</td>
<td>13 to 20</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>6 to 9</td>
<td>20 to 30</td>
</tr>
<tr>
<td>8</td>
<td>Very High</td>
<td>9 to 14</td>
<td>30 to 45</td>
</tr>
<tr>
<td>9</td>
<td>Phenomenal</td>
<td>Over 14</td>
<td>Over 45</td>
</tr>
</tbody>
</table>

**INTENTIONALLY BLANK**
5.1 **JAR 29.807 Passenger Emergency Exits**

(a) Type. For the purpose of this Part, the types of passenger emergency exit are as follows:

(1) Type I. This type must have a rectangular opening of not less than 609.6 mm wide by 1.219 m (24 inches wide by 48 inches) high, with corner radii not greater than one-third the width of the exit, in the passenger area in the side of the fuselage at floor level and as far away as practicable from areas that might become potential fire hazards in a crash.

(2) Type II. This type is the same as Type I, except that the opening must be at least 508 mm wide by 1.12 m (20 inches wide by 44 inches) high.

(3) Type III. This type is the same as Type I, except that -

(i) The opening must be at least 508 mm wide by 914.4 mm (20 inches wide by 36 inches) high; and

(ii) The exits need not be at floor level.

(4) Type IV. This type must have a rectangular opening of not less than 482.6 mm wide by 660.4 mm (19 inches wide by 26 inches) high, with corner radii not greater than one-third the width of the exit, in the side of the fuselage with a step-up inside the rotorcraft of not more than 736.6 mm (29 inches). Openings with dimensions larger than those specified in this section may be used, regardless of shape, if the base of the opening has a flat surface of not less than the specified width.

(b) Passenger emergency exits: side-of-fuselage. Emergency exits must be accessible to the passengers and, except as provided in sub-paragraph (d) of this paragraph, must be provided in accordance with the following table:

<table>
<thead>
<tr>
<th>Passenger Seating Capacity</th>
<th>Emergency Exits For Each Side of The Fuselage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Type I)</td>
</tr>
<tr>
<td>1 to 10</td>
<td></td>
</tr>
<tr>
<td>11 to 19</td>
<td></td>
</tr>
<tr>
<td>20 to 39</td>
<td>1</td>
</tr>
<tr>
<td>40 to 59</td>
<td>1</td>
</tr>
<tr>
<td>60 to 79</td>
<td>1</td>
</tr>
</tbody>
</table>

(c) Passenger emergency exits; other than side-of-fuselage. In addition to the requirements of sub-paragraph (b) of this paragraph -

(1) There must be enough openings in the top, bottom, or ends of the fuselage to allow evacuation with the rotorcraft on its side; or

(2) The probability of the rotorcraft coming to rest on its side in a crash landing must be extremely remote.

(d) Ditching emergency exits for passengers. If certification with ditching provisions is requested, ditching emergency exits must be provided in accordance with the following requirements and must be proven by test, demonstration, or analysis unless the emergency exits required by sub-paragraph (b) of this paragraph already meet these requirements:

Study I 107
(1) For rotorcraft that have a passenger seating configuration, excluding pilots seats, of nine seats or less, one exit above the waterline in each side of the rotorcraft, meeting at least the dimensions of a Type IV exit.

(2) For rotorcraft that have a passenger seating configuration, excluding pilots seats, of 10 seats or more, one exit above the waterline in a side of the rotorcraft meeting at least the dimensions of a Type III exit, for each unit (or part of a unit) of 35 passenger seats, but no less than two such exits in the passenger cabin, with one on each side of the rotorcraft. However, where it has been shown through analysis, ditching demonstrations, or any other tests found necessary by the Authority, that the evacuation capability of the rotorcraft during ditching is improved by the use of larger exits, or by other means, the passenger seat to exit ratio may be increased.

(3) Flotation devices, whether stowed or deployed, may not interfere with or obstruct the exits.

(e) Ramp exits. One Type I exit only, or one Type II exit only, that is required in the side of the fuselage in sub-paragraph (b) of this paragraph, may be installed instead in the ramp of floor ramp rotorcraft if -

(1) Its installation in the side of the fuselage is impractical; and

(2) Its installation in the ramp meets JAR 29.813.

(f) Tests. The proper functioning of each emergency exit must be shown by test.

5.2 Advisory Circular 29-2B JAR 29.807 Passenger Emergency Exits

340. § 29.807 (Amendment 29-12) PASSENGER EMERGENCY EXITS.

a. Explanation. The normal passenger exits (type and number in each side of fuselage) are specified as follows:

(1) For overland operations.

<table>
<thead>
<tr>
<th>Passenger Seating Capacity</th>
<th>Emergency exits (rectangular with corner radii of width/3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For each side of the fuselage</td>
</tr>
<tr>
<td>Floor level</td>
<td>Step-up –29° Max</td>
</tr>
<tr>
<td>Type I</td>
<td>Type II</td>
</tr>
<tr>
<td>24” x 48”</td>
<td>20” x 44”</td>
</tr>
<tr>
<td>1 through 10</td>
<td>1</td>
</tr>
<tr>
<td>11 through 19</td>
<td></td>
</tr>
<tr>
<td>20 through 39</td>
<td>1</td>
</tr>
<tr>
<td>40 through 59</td>
<td>1</td>
</tr>
<tr>
<td>60 through 79</td>
<td>1</td>
</tr>
</tbody>
</table>

(2) For overwater operations (related to ditching an optional standard).

<table>
<thead>
<tr>
<th>Passenger Seating Capacity</th>
<th>Emergency exits (rectangular with corner radii of width/3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For each side of the fuselage</td>
</tr>
<tr>
<td></td>
<td>Threshold Above Waterline</td>
</tr>
<tr>
<td>Type III</td>
<td>Type IV</td>
</tr>
<tr>
<td>20” x 36”</td>
<td>19” x 26” w/step-up – 29” MAX</td>
</tr>
<tr>
<td>1 through 9</td>
<td>1</td>
</tr>
<tr>
<td>10 through 35</td>
<td>1*</td>
</tr>
<tr>
<td>Each Additional or Partial Unit of 35</td>
<td>1*</td>
</tr>
</tbody>
</table>

*The passenger seat-to-exit ratio may be increased by using larger exits if proven by analyses or tests.
(3) For crash rollover conditions. Sufficient top, bottom, or ends of fuselage exits are to be provided for evacuation unless the probability of the rotorcraft coming to rest on its side in a crash landing is extremely remote.

(4) Ramp exits to replace Type I or II exits are permitted.

(5) Each emergency exit must be functionally tested.

b. Procedures

(1) The number and size of overland and overwater operation exits will be as specified. The use of oversize exits is allowed if the threshold is flat and of the specified width.

(2) The top, bottom, or end fuselage exits should be provided unless features of design are provided which prevent the rotorcraft from coming to rest on its side in a crash landing, and unless sufficient fail-safe and fatigue tests and analyses are conducted of the landing gear and support structure to show it is unlikely that the rotorcraft will come to rest on its side as a result of a single structural failure. An analysis is generally necessary to prove compliance with § 29.807(c).

(3) Ramp exits may be used in place of one Type I or one Type II exit if the required Type I or Type II exit is impractical, and if the § 29.813 exit access requirements are met by ramp exits.

(4) Each emergency exit is to be opened from the inside and the outside as a functional test. Interior panels and seats should be installed for the exit functional tests to check for interferences and other effects. Section 29.813 pertains to access to the exits.

29.807 Emergency Exits

340A. § 29.807 (Amendment 29-30) EMERGENCY EXITS.

a. Explanation. Amendment 29-30 added § 29.807(d)(3) which requires proof that all ditching configuration exits will be free of interference from emergency flotation devices, whether stowed or deployed (inflated). The threshold for each of these “ditching” exits should be above the water line in calm water.

b. Procedures.

(1) Test, demonstration, compliance inspection, or analysis is required to show freedom from interference from stowed and deployed emergency flotation devices. In the event an analysis is insufficient or a given design is questionable, a demonstration may be required. Such a demonstration would consist of an accurate, full-size replica (or true representation) of the rotorcraft and the flotation devices while stowed and after their deployment.
<table>
<thead>
<tr>
<th>Report Number:</th>
<th>LAX83FA277</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date:</td>
<td>06/10/1983</td>
</tr>
<tr>
<td>City:</td>
<td>Goleta (CA)</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>Bell BHT-212-XXX</td>
</tr>
<tr>
<td>Weight Class:</td>
<td>C (FAR 29)</td>
</tr>
<tr>
<td>Registration Number:</td>
<td>59636</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 4 Knots. Assumed Sea State 1 based on wind speed.</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>As the helicopter approached the oil rig and reduced power to begin descent the tail rotor pedals began to vibrate. Pilot further reduced power and planned his decent so that the helicopter was closer to the water in case of complete tail rotor failure. The aircraft unexpectedly hit the water and immediately rolled over.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Substantial. The main rotor and tail rotor assemblies, vertical fin and upper transmission were not recovered</td>
</tr>
<tr>
<td>Flotation System:</td>
<td>The impact with the water occurred before the pilot armed the automatically actuated Emergency Flotation Bags. The bags are made from nylon. It is assumed they are located on the skids as shown in figure 16 of the FAA report.</td>
</tr>
<tr>
<td>Casualties:</td>
<td>Two passengers died. The pilot and another passenger had minor injuries.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 1: Flotation system activated.</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>A, B</td>
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<tr>
<td><strong>Report Number:</strong></td>
<td>FTW84LA166</td>
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<tr>
<td><strong>Date:</strong></td>
<td>03/12/1984</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-L1</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>1076N</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind speed 25 Knots, blowing spray and rain. Assumed Sea State 5 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was preparing to leave the oil rig. The engine was being started when it was blown off the platform and into the water by a gust of wind. The aircraft impacted the water in a tail first attitude. Given that the engine had only just been started it is assumed that the pilot had not armed the emergency flotation system.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>6 Floats capable of in flight inflation were fitted on this helicopter. They need to be armed using a switch mounted on the overhead console. The system is activated using a trigger switch on the collective stick.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>4 fatalities, 1 passenger seriously injured.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated.</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td>Report Number:</td>
<td>LAX85FA091</td>
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<tr>
<td>Date:</td>
<td>12/28/1984</td>
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<tr>
<td>City:</td>
<td>San Diego (CA)</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>Bell BHT-47-G3B</td>
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<tr>
<td>Weight Class:</td>
<td>B (FAR 29)</td>
</tr>
<tr>
<td>Registration Number:</td>
<td>474MP</td>
</tr>
</tbody>
</table>

**Sequence of Events:**
Helicopter landed on a moored tuna boat. After touchdown the helicopter appeared to be repositioning when the main rotor blades contacted a crane being used to load the boat. It is assumed that the helicopter then hit the water and the floats were not deployed.

**Damage:** Substantial

**Flotation System:**
There was a flotation system fitted on the helicopter. It is assumed that the flotation bags are located on the skids in the positions shown in figure 14 of the FAA report.

Assumed that the emergency flotation system required the pilot to arm it and that this was not done given the unexpected collision.

**Casualties:** 1 fatality, 1 serious injury.

**Stage of Failure:** Stage 1: Flotation system activated

**Relevant Modifications:** A, B
<table>
<thead>
<tr>
<th><strong>Report Number:</strong></th>
<th>DCA85AA020</th>
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<tbody>
<tr>
<td><strong>Date:</strong></td>
<td>04/26/1985</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>New York (NY)</td>
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<tr>
<td><strong>Make/Model:</strong></td>
<td>Aerospatiale SA-360-C</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>C (FAR 29)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>49505</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind speed 16 Knots. Assumed Sea State 3 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was taking off from a heliport on the west bank of the river. As the aircraft climbed there was a ‘popping’ sound and there was a loss of engine power and main rotor rpm. Aircraft began settling but impacted the water, rolled over and sank.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Substantial</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>Pilot attempted to deploy the emergency floats but did not have time.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>One passenger did not egress and drowned with seat belt fastened. The other passengers and crew received either minor or no injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>LAX86MA050A</td>
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<tr>
<td><strong>Date:</strong></td>
<td>11/30/1985</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>San Pedro (CA)</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-L1</td>
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<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
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<tr>
<td><strong>Registration Number:</strong></td>
<td>5759Y</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind speed 7 Knots. Assumed Sea State 2 based on wind speed</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>Mid air collision between two helicopters approaching a floating restaurant. 5759Y impacted the water. 3913Z hit the edge of the heliport and rolled over. It is assumed that the pilot did not arm/activate emergency flotation system because attention was directed to controlling the aircraft following the in flight collision.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>An emergency flotation system was fitted to the helicopter. Assumed flotation bags mounted on the skids as shown in FAA report for Bell 206.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>1 passenger died, four had serious injuries, 7 minor</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
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<tr>
<td><strong>Report Number:</strong></td>
<td>LAX87FA017</td>
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<tr>
<td><strong>Date:</strong></td>
<td>10/16/1986</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Lompoc (CA)</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-B</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>3182V</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 7 Knots. Assumed Sea State 2 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>On taking off from the helipad deck at the stern of a barge the helicopter's left skid became caught in a rope net. The helicopter came free but banked to left and collided with the structures on the barge. It then fell overboard and sank. Assumed the emergency flotation system was either not armed or not activated because the pilot had not yet taken off.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed. The skids and other wreckage were found caught up on the davit.</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>Pontoons or stowed floats capable of in-flight inflation are available on this helicopter as optional kits. There was an emergency flotation system fitted on the helicopter. If the flotation system was armed given the damage to the skids it is unlikely the flotation bags would have inflated.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>2 fatalities, 2 serious injuries</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>FTW87LA057</td>
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<tr>
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<tr>
<td><strong>Date:</strong></td>
<td>02/05/1987</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-L1</td>
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<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
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<tr>
<td><strong>Registration Number:</strong></td>
<td>5012Z</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter took off from an oil rig shortly afterwards the pilot transmitted a ‘Mayday’. The pilot told a passenger to get the raft out and the helicopter subsequently impacted rough water and sank.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Substantial</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The flotation bags are located on the skids on the 206. The helicopter was not recovered but a float inflation bottle was found. It was fully charged and the squib had not been fired. It cannot be confirmed that the failure of the inflation bottle to discharge the gas was due to a mechanical failure. The system could not have been armed. It is assumed that the flotation system was not armed or not activated.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>All occupants of the helicopter were retrieved although 2 later died from injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A+B</td>
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<td><strong>Report Number:</strong></td>
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<tr>
<td><strong>Date:</strong></td>
<td>08/21/1987</td>
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<tr>
<td><strong>City:</strong></td>
<td>Washington DC</td>
</tr>
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<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-B</td>
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<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>83080</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 3 Knots. Assumed Sea State 0 based on wind speed.</td>
</tr>
</tbody>
</table>

**Sequence of Events:**
The helicopter was on a sightseeing flight. Whilst hovering over the Potomac River, the engine lost power. The pilot initiated an autorotation and deployed the emergency floats. The aircraft impacted the water and rolled over. Given the sea state it is unlikely that the helicopter overturning was initiated by a wave. Therefore, the floats deployed unevenly due to an equipment failure. The helicopter was hovering at 200' when it lost power. The flight manual recommends that hovering at this height should be avoided to allow for successful autorotation landing in the event of a power loss. This implies that the autorotation carried out could cause damage to the aircraft. Therefore, it is assumed that the failure of the floats to deploy evenly was due to impact damage.

**Damage:** Destroyed

**Flotation System:** Pontoons or stowed floats capable of in-flight inflation are available on this helicopter as optional kits. The helicopter was supported upside down in the water by the floats.

**Casualties:** All 3 passengers died, the pilot had serious injuries.

**Stage of Failure:** Stage 4: Floats partially survive impact.

**Relevant Modifications:** G, J, I, H
<table>
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<tr>
<th><strong>Report Number:</strong></th>
<th>NYC88FA133</th>
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<tr>
<td><strong>Date:</strong></td>
<td>05/01/1988</td>
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<tr>
<td><strong>City:</strong></td>
<td>Long Island City</td>
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<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-XXX</td>
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<td><strong>Weight Class:</strong></td>
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<tr>
<td><strong>Registration Number:</strong></td>
<td>7094J</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 8 Knots. Assumed Sea State 2 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was on a sightseeing flight when it experienced a low rotor rpm situation. The pilot made a forced landing in the river. The pilot and 3 passengers exited the aircraft and clung to the floats.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The floats were inflated and separated from the aircraft. Assumed that the floats separated from the aircraft during impact.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>One passenger did not escape and died of drowning. The other occupants experienced minor injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 4: Floats survive impact</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>G, J, I, H</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
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<tr>
<td><strong>Date:</strong></td>
<td>07/14/1988</td>
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<tr>
<td><strong>City:</strong></td>
<td>Gulf of Mexico</td>
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<tr>
<td><strong>Make/Model:</strong></td>
<td>SNIAS SA-330-J</td>
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<td><strong>Weight Class:</strong></td>
<td>D (FAR 29)</td>
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<tr>
<td><strong>Registration Number:</strong></td>
<td>47307</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 10 Knots. Assumed Sea State 2 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>During take off from an oil rig the helicopter began a slow uncommanded left turn. The pilot attempted corrective action but the helicopter impacted the water in a left bank, nose down attitude. Given that the pilot was concentrating on controlling the helicopter and it was in take off it is assumed that the EFS was either not armed or not activated. The latter is more likely as arming the EFS is a take-off pre-flight check.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The floats were not inflated.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>1 fatality, 1 serious injury, 14 occupants had no injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
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<tr>
<td><strong>Date:</strong></td>
<td>11/04/1988</td>
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<tr>
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<td>Gulf of Mexico</td>
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<tr>
<td><strong>Make/Model:</strong></td>
<td>Aerospatiale AS-355-F1</td>
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<td><strong>Weight Class:</strong></td>
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<td><strong>Registration Number:</strong></td>
<td>355EH</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 25 Knots. Assumed Sea State 5 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was taking off from an offshore platform when it experienced a complete loss of tail rotor and helicopter control. Recovery was not possible. It is assumed the emergency flotation system was either not armed or not activated. The latter is more likely as arming the EFS is a take-off pre-flight check.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>There was a flotation system fitted on the helicopter.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>4 fatalities, 2 serious injury</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated.</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
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<td>Report Number:</td>
<td>MIA90FA081</td>
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<td>Date:</td>
<td>03/08/1990</td>
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<tr>
<td>City:</td>
<td>Miami</td>
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<tr>
<td>Make/Model:</td>
<td>SNIAAS AS-350-D</td>
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<td>Weight Class:</td>
<td>B (FAR 27)</td>
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<tr>
<td>Registration Number:</td>
<td>5778W</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 20 Knots, rough water. Assumed Sea State 4 based on wind speed.</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>The helicopter was in cruise flight over the ocean when it experienced a loss of engine power. At 100 feet above the water the pilot deployed the emergency floats and successfully landed the helicopter. A wave hit the helicopter and it rolled over. Assumed that floats deployed evenly and the wave caused it to turn over.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Destroyed</td>
</tr>
<tr>
<td>Flotation System:</td>
<td></td>
</tr>
<tr>
<td>Casualties:</td>
<td>Two passengers died from drowning. The pilot survived but suffered serious injuries.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 5: Craft remains upright</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>J</td>
</tr>
<tr>
<td>Report Number:</td>
<td>FTW91FA155</td>
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<tr>
<td>Date:</td>
<td>08/26/1991</td>
</tr>
<tr>
<td>City:</td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>Bell BHT-412-XXX</td>
</tr>
<tr>
<td>Weight Class:</td>
<td>D (FAR 29)</td>
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<tr>
<td>Registration Number:</td>
<td>3909F</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 3 Knots. Assume Sea State 0 based on wind speed.</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>The helicopter was on a final approach to an oil rig when tail rotor authority and directional control were lost. The crew began an autorotation to the water when the helicopter spun out of control to the right. It made 2 or 3 revolutions and impacted the water. The helicopter rolled over.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Substantial</td>
</tr>
<tr>
<td>Flotation System:</td>
<td>The right flotation gear deployed. The left flotation gear did not deploy because the pneumatic lines were pulled apart during impact.</td>
</tr>
<tr>
<td>Casualties:</td>
<td>One passenger was incapacitated due to injuries from the impact and drowned. The other 10 occupants received some injuries.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 3: Gas enters some floats.</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>E, F</td>
</tr>
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<td><strong>Report Number:</strong></td>
<td>FTW94LA021</td>
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<td><strong>Date:</strong></td>
<td>10/29/1993</td>
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<td><strong>City:</strong></td>
<td></td>
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<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-B</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>360S</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 35 knots. Assumed Sea State 6 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The Pilot was attempting to fly to an off shore platform when he encountered bad weather. In an attempt to avoid the weather he set up an orbit. During the orbit he slowed the aircraft down and it began to descend. A 15 foot swell struck the aircraft and it rolled into the water. Pilot was not in an emergency situation so it is assumed that the flotation system was either not armed or activated. The latter is more likely as arming the EFS is a take-off pre-flight check.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>An emergency flotation system was fitted on the aircraft.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>1 Fatality and 2 minor injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>BFO94FA013</td>
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<td>------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>11/19/1993</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Portland</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-L1</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>911ME</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 13 Knots. Water rough. Assumed Sea State 4 based on wave height.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter experienced a loss of engine power due to fuel exhaustion. The helicopter ditched in the ocean. The helicopter landed hard in “rough water” with 6 foot waves. It inverted and sank. It was assumed that the EFS operated with some success as the helicopter inverted. It was also assumed that there was sufficient time for some occupants to escape before the helicopter sank</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>During the autorotation the pilot deployed the floats attached to the skids.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>All 3 passengers died, the pilot received serious injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 5: Craft remains upright</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>J</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>FTW99FA001A</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>10/05/1998</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-407-XXX</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>403PH</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 25 knots. Assumed Sea State 5 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>403PH collided in flight with 5792H. 403PH executed an autorotation landing into the water. The float system was deployed. The helicopter stayed upright for about thirty seconds and then rolled over. Assumed roll over was caused by wave.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The emergency flotation bags were mounted on the skids.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>The pilot of 5792H died, the pilot of 403PH survived.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 5: Craft remains upright</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>J</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>LAX98LA079</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>01/24/1998</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Pacific Ocean</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Hughes HU-369-D</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>521ZZ</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 15 knots. Assumed Sea State 3 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter crashed into the ocean and sank. This was due to pilot error.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>One float broke off the other was seriously damaged.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>The pilot died, the other crew member was uninjured.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 4: Floats survive impact</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>G, J, I, H</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>FTW99FA094</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>03/17/1999</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Aerospatiale AS-350-B2</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>6100R</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind speed 11 Knots. Assumed Sea State 3 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>N6100R was destroyed following a loss of control while departing an oil platform. The helicopter rolled inverted and dropped into the ocean. Witnesses saw the floats deploy.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>The commercial pilot and one passenger sustained serious injuries, and two passengers were fatally injured.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 5: Craft remains upright</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>J</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>FTW00RA039</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>12/01/1999</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Cabinda, Republic of Angola</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-206-L1</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>B (FAR 27)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>5005B</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>Following a loss of engine power during takeoff from an offshore oil platform the helicopter impacted the water.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Substantial</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The emergency float system was not activated. Stowed floats capable of in flight inflation are available on this helicopter.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>The pilot and one passenger were seriously injured. Another passenger was fatally injured.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 1: Flotation system activated</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>A, B</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>FTW00RA003</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>10/02/1999</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Dhahran, Saudi Arabia</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Bell BHT-214-ST</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>D (FAR 29)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>704H</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 8 Knots. Assumed Sea State 2 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was substantially damaged upon impact with the water during take off from an offshore platform. The helicopters entry into the water was described as ‘soft and gentle’ by witnesses. The helicopter rolled and inverted in the water. It is assumed that some of the floats did not survive the impact and that is the reason for the craft inverting. The sea state is unlikely to produce a wave that would overturn the aircraft.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Substantial</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>The floats of the helicopter inflated during the accident sequence.</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>The 2 crew members and 10 passengers died. The other 8 passengers received minor injuries.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 4: Floats survive impact (Part)</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>G, J, I, H</td>
</tr>
</tbody>
</table>
## Appendix E  Cost Benefit Study – UK Accident Report Summaries

<table>
<thead>
<tr>
<th>Report Number:</th>
<th>Aircraft Accident Report 10/82</th>
</tr>
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<tbody>
<tr>
<td>Date:</td>
<td>08/12/1981</td>
</tr>
<tr>
<td>City:</td>
<td>Dunlin Alpha Platform</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>Bell 212</td>
</tr>
<tr>
<td>Weight Class:</td>
<td>C (FAR 29)</td>
</tr>
<tr>
<td>Registration Number:</td>
<td>G-BIJF</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 17 Knots. Assumed Sea State 4 based on wind speed.</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>The helicopter was flying between the Brent Field and the Dunlin Platform when it encountered an area of reduced visibility and the decision was made to turn back. During the turn, control of the helicopter was lost. It began yawing rapidly to the right and descending and struck the sea.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Substantial damage from impact and immersion. Aircraft considered beyond economical repair.</td>
</tr>
<tr>
<td>Flotation System:</td>
<td>Four inflatable floats were fitted to the fuselage. The emergency flotation bags were deployed from their stowages. The floats on the right side were deflated. The front left was fully inflated. The flexible pipe on the right hand side was ruptured.</td>
</tr>
<tr>
<td>Casualties:</td>
<td>1 Fatality, 2 serious injuries, 11 minor/none Assumed causes of fatalities:</td>
</tr>
<tr>
<td></td>
<td>0 – Due to primary impact.</td>
</tr>
<tr>
<td></td>
<td>1 – Died outside the helicopter due to exposure.</td>
</tr>
<tr>
<td></td>
<td>0 – Assumed to be due to not having sufficient time to escape from the helicopter.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 3: Gas enters some floats.</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>F</td>
</tr>
<tr>
<td>Report Number:</td>
<td>Aircraft Accident Report 2/93</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Date:</td>
<td>03/14/1992</td>
</tr>
<tr>
<td>City:</td>
<td>Cormorant 'A' Platform, East Shetland Basin</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>AS 332L Super Puma</td>
</tr>
<tr>
<td>Weight Class:</td>
<td>D (FAR 29)</td>
</tr>
<tr>
<td>Registration Number:</td>
<td>G-TIGH</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 54-64 Knots. Assumed Sea State 8</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>The helicopter was shuttling personnel from an oil production platform to a nearby accommodation 'Flotel'. Following takeoff from the platform the helicopter climbed to a height of 250 feet and began a right turn. The pilot reduced power and raised the nose of the aircraft. This reduced the airspeed to zero and a rate of descent built up. This could not be arrested and the helicopter struck the sea. It rolled onto its right side before inverting and sinking within a minute or two.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Destroyed</td>
</tr>
<tr>
<td>Flotation System:</td>
<td>The helicopter was fitted with an emergency flotation system. Two inflatable bags on the nose of the aircraft and one on each sponson. The system was armed and available but was not activated.</td>
</tr>
<tr>
<td>Casualties:</td>
<td>11 fatalities, 1 serious injury, 5 minor/nearly</td>
</tr>
<tr>
<td>Assumed causes of fatalities:</td>
<td>0 – Due to primary impact. 6 – Died outside the helicopter due to exposure. 5 – Assumed to be due to not having sufficient time to escape from the helicopter.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 1: Flotation system activated.</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>A+B</td>
</tr>
</tbody>
</table>

Study 1  
132
<table>
<thead>
<tr>
<th>Report Number:</th>
<th>Aircraft Accident Report 8/84</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date:</td>
<td>07/16/1983</td>
</tr>
<tr>
<td>City:</td>
<td>St Mary’s Aerodrome, Isles of Scilly</td>
</tr>
<tr>
<td>Make/Model:</td>
<td>Sikorsky S-61N</td>
</tr>
<tr>
<td>Weight Class:</td>
<td>D (FAR 29)</td>
</tr>
<tr>
<td>Registration Number:</td>
<td>G-BEON</td>
</tr>
<tr>
<td>Conditions:</td>
<td>Wind Speed 2-5 Knots. Assumed Sea State 1 based on wind speed.</td>
</tr>
<tr>
<td>Sequence of Events:</td>
<td>The helicopter was on a scheduled flight from Penzance to the Isles of Scilly. Whilst on the approach to St Mary’s Aerodrome the helicopter gradually descended from its intended height of 250 feet without either pilot being aware of this and flew into the water.</td>
</tr>
<tr>
<td>Damage:</td>
<td>Destroyed</td>
</tr>
<tr>
<td>Flotation System:</td>
<td>The inflatable flotation gear was attached to the sponsons. The sponsons broke off making the emergency flotation gear unavailable.</td>
</tr>
<tr>
<td>Casualties:</td>
<td>20 fatalities, 2 serious injuries, 4 minor/none Assumed causes of fatalities: 0 – Due to primary impact. 3 – Died outside the helicopter due to exposure. 17 – Assumed to be due to not having sufficient time to escape from the helicopter.</td>
</tr>
<tr>
<td>Stage of Failure:</td>
<td>Stage 4: Floats survive impact.</td>
</tr>
<tr>
<td>Relevant Modifications:</td>
<td>G, I, J, H</td>
</tr>
<tr>
<td><strong>Report Number:</strong></td>
<td>Aircraft Accident Report 2/91</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td><strong>Date:</strong></td>
<td>07/25/1990</td>
</tr>
<tr>
<td><strong>City:</strong></td>
<td>Brent Spar, East Shetland Basin</td>
</tr>
<tr>
<td><strong>Make/Model:</strong></td>
<td>Sikorsky S61N</td>
</tr>
<tr>
<td><strong>Weight Class:</strong></td>
<td>D (FAR 29)</td>
</tr>
<tr>
<td><strong>Registration Number:</strong></td>
<td>G-BEWL</td>
</tr>
<tr>
<td><strong>Conditions:</strong></td>
<td>Wind Speed 5 Knots or less. Assumed Sea State 1 based on wind speed.</td>
</tr>
<tr>
<td><strong>Sequence of Events:</strong></td>
<td>The helicopter was manoeuvring to land on the Brent Spar offshore platform. The tail rotor blade contacted a handrail on the installation crane ‘A’ frame. The helicopter crashed onto the helideck before falling into the sea and sinking.</td>
</tr>
<tr>
<td><strong>Damage:</strong></td>
<td>Destroyed</td>
</tr>
<tr>
<td><strong>Flotation System:</strong></td>
<td>Attached to damaged sponsons, not deployed</td>
</tr>
<tr>
<td><strong>Casualties:</strong></td>
<td>6 fatalities, 7 survivors. Assumed causes of fatalities:</td>
</tr>
<tr>
<td></td>
<td>2 – Due to primary impact.</td>
</tr>
<tr>
<td></td>
<td>0 – Died outside the helicopter due to exposure.</td>
</tr>
<tr>
<td></td>
<td>4 – Assumed to be due to not having sufficient time to escape from the helicopter.</td>
</tr>
<tr>
<td><strong>Stage of Failure:</strong></td>
<td>Stage 4: Floats survive impact</td>
</tr>
<tr>
<td><strong>Relevant Modifications:</strong></td>
<td>G, J, I, H</td>
</tr>
</tbody>
</table>
Appendix F  Cost Benefit Study – Worked Example

1. Introduction
Cost benefit study, worked example for "Modification A+B: Automatic arming and activation".

2. Determine System Functional Effectiveness With No Modifications
Determine base-line probabilities with no modifications from the EFS deployment Tree (Figure 36)

\[
\begin{align*}
\text{Psink}_0 & := 0.5 + (0.5 \cdot 0) + (0.5 \cdot 1 \cdot 0) + (0.5 \cdot 1 \cdot 0.17 \cdot 0) + (0.5 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.4) & \text{Psink}_0 &= 0.67 \\
\text{Pinvert}_0 & := 0.5 \cdot 1 \cdot 1 \cdot 0.17 \cdot 1 + (0.5 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.33) + (0.5 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.67 \cdot 1) & \text{Pinvert}_0 &= 0.33 \\
\text{Pairpocket}_0 & := 0.5 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.67 \cdot 0 & \text{Pairpocket}_0 &= 0
\end{align*}
\]

3. Determine Functional Effectiveness With Modification A+B In Place

\[
\begin{align*}
\text{Psink}_{AB} & := 0 + (1 \cdot 0) + (1 \cdot 1 \cdot 0) + (1 \cdot 1 \cdot 1 \cdot 0.17 \cdot 0) + (1 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.4) & \text{Psink}_{AB} &= 0.33 \\
\text{Pinvert}_{AB} & := 1 \cdot 1 \cdot 1 \cdot 0.17 \cdot 1 + (1 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.33) + (1 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.67 \cdot 1) & \text{Pinvert}_{AB} &= 0.67 \\
\text{Pairpocket}_{AB} & := 1 \cdot 1 \cdot 1 \cdot 0.83 \cdot 0.6 \cdot 0.67 \cdot 0 & \text{Pairpocket}_{AB} &= 0
\end{align*}
\]

4. Determine Change in Functional Effectiveness Due to Modification A+B

\[
\begin{align*}
\Delta \text{Psink}_{AB} & := \text{Psink}_{AB} - \text{Psink}_0 & \Delta \text{Psink}_{AB} &= -0.33 \\
\Delta \text{Pinvert}_{AB} & := \text{Pinvert}_{AB} - \text{Pinvert}_0 & \Delta \text{Pinvert}_{AB} &= 0.33 \\
\Delta \text{Pairpocket}_{AB} & := \text{Pairpocket}_{AB} - \text{Pairpocket}_0 & \Delta \text{Pairpocket}_{AB} &= 0
\end{align*}
\]

5. Calculate "Occupant Survival Number" For Modification A+B
Modifications which result in reduced sinkings are assumed to be 50% effective at saving occupants who would have drowned if no modifications were used.

Modifications which result in increased chances of an air pocket in the cabin with an overwater escape route are assumed to be 90% effective at saving occupants who would have drowned if no modifications were used.

\[
\text{Occupant}_{AB} = \left( 0.5 \cdot \Delta \text{Pinvert}_{AB} \right) + \left( 0.9 \cdot \Delta \text{Pairpocket}_{AB} \right) \quad \text{Occupant}_{AB} = 0.17
\]
6. Calculate Fatality Rate Per Year From UK Accident History

Search period 1980 to 1999, 20 years

Number of relevant fatalities (26)

\[
\text{FatalityRateUK} := \frac{\text{Fatilities}_\text{UK}}{\text{Period}}
\]

\[
\text{FatalityRateUK} = 1.3
\]

7. Calculate Number of Estimated Fatalities For UK Fleets Remaining Service Life

Estimated remaining life of UK fleet is 20 years

\[
\text{Life}_{\text{RemainingUK}} := 20
\]

\[
\text{TotalFatality}_{\text{FutureUK}} := \text{FatalityRateUK} \times \text{Life}_{\text{RemainingUK}}
\]

\[
\text{TotalFatality}_{\text{FutureUK}} = 26
\]

8. Calculated Potential Lives Saved By Modification A+B

Modification A+B will save 17% of the occupants who can be expected to escape from the helicopter.

\[
\text{LivesSaved}_{AB} := \text{TotalFatality}_{\text{FutureUK}} \times \text{Occupant}_{AB}
\]

\[
\text{LivesSaved}_{AB} = 4.34
\]

9. Calculate Cost of Modification A+B

Number of Helicopters in UK fleet is 79

\[
\text{Fleet size} := 79
\]

Cost of Modification (A+B). 7% of EFS

\[
\text{Mod}_{AB} := 0.07 \times 200000
\]

Overall cost for fleet

\[
\text{Cost}_{\text{TotalAB}} := \text{Fleet size} \times \text{Mod}_{AB}
\]

\[
\text{Cost}_{\text{TotalAB}} = 1106000.00
\]

10. Calculate Cost per Live Saved of Modification A+B

\[
\text{CostPerLifeSaved}_{AB} := \frac{\text{Cost}_{\text{TotalAB}}}{\text{LivesSaved}_{AB}}
\]

\[
\text{CostPerLifeSaved}_{AB} = 254721.33
\]
Study II (Supplementary Study)

Prepared by BMT Fluid Mechanics Ltd
Executive Summary

The main purpose of this investigation was to assess the range of impact loads experienced by typical emergency flotation systems, installed within the sponsons or beneath fuselage panels of helicopters, during controlled ditchings and impacts onto water. The calculations were performed using a Monte Carlo simulation procedure, based on simplified empirical and theoretical formulae for estimating the impact force. Failure of the flotation system was deemed to occur whenever the load on the sponson or fuselage panel exceeded its design value. Four different types of incident were considered: a controlled ditching, vertical descent (low horizontal speed), loss of control (intermediate horizontal and vertical speeds) and fly-in (low vertical speed). The calculations were performed in representative central North Sea wave conditions and in calm water.

The results showed, as expected, that there is a very low probability of exceeding the design load in a controlled ditching incident. Flotation equipment is designed to survive a normal ditching. The base case investigation showed a relatively high probability of exceeding design loads on both the sponson and fuselage panel during vertical descent and loss of control crash scenarios. This result suggested that substantial increases in design loads would be required in order to avoid major structural damage to flotation systems in these two types of incident. A follow-up sensitivity study confirmed that a 100% increase in design loads would result in only a modest improvement in crashworthiness.

Major structural failures have occurred during actual fly-in accidents in the past. The simulations nonetheless predicted that the risks of exceeding design loads on both the sponson and fuselage panel during a fly-in are relatively low. There are two likely reasons for this unexpected result. Firstly, drag and planing forces make major contributions to the total predicted load during a fly-in. These forces are poorly understood, and the simplified formulae used in the present analysis may not be reliable. Secondly, the model considers loads on an individual sponson or panel in isolation, and does not consider failure of the surrounding hull structure. The design of flotation equipment should in practice consider the design and strength of the supporting hull structure.

Sea state conditions had little effect on the results obtained from the investigation as a whole. They had a significant effect on results obtained in severe sea conditions, however, and increased the range of loads substantially during controlled ditching and fly-in incidents.

The impact force proved to be sensitive to variations in several different parameters. It may therefore be difficult to characterise helicopter impact incidents in terms of a small number of deterministic scenarios.

Impact loads were sensitive to variations in the helicopter's mean speed and descent angle at the moment of impact. The drag force coefficient was also an important parameter. The helicopter's mean pitch angle and the planing force coefficient only affected loads experienced during ditching and fly-in incidents.

Investigations into float redundancy demonstrated that there are clear benefits, in terms of crashworthiness, from having additional floats on the upper cabin walls. Benefits emerged regardless of whether they were measured in terms of reducing the number of occasions when the helicopter sank, making it float on its side, or providing a satisfactory air space in the cabin. The largest improvement came when the first upper cabin float was added. There are possible advantages in this asymmetric float configuration, because it gives the
helicopter a preferred stable attitude in the water, eliminating the risk of a second rotation while the occupants are trying to escape.

Alternative methods for improving crashworthiness might also be considered, such as designing a ‘crumple zone’ or other energy-absorbing device into the support structure. Whatever solution is adopted, however, the structure must retain sufficient integrity to serve its primary function of providing buoyancy.

There may be potential for reducing impact loads during a fly-in incident by modifying the shape of the hull or sponson, and avoiding large flat areas.

The present investigations considered all-year wave conditions in the central area of the North Sea. It is likely that selecting a more severe wave climate (e.g. West of Shetland) would significantly increase the loads predicted during controlled ditching and fly-in incidents. Suitable design procedures would be needed to take account of increases in water impact loading due to waves.

BMT recommends that further work should be done to investigate the importance of drag and planing type forces in the water impact loading process, and the feasibility of representing these loads better in the calculations. These forces turned out to be more significant than originally anticipated, and simplifications in existing calculation procedures may have resulted in unrealistically low predicted forces during fly-in incidents.
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1    INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Terms of Reference</td>
<td>2</td>
</tr>
<tr>
<td>2    BACKGROUND AND KEY STAGES</td>
<td>2</td>
</tr>
<tr>
<td>2.1 Analysis of Loads on Flotation Systems</td>
<td>2</td>
</tr>
<tr>
<td>2.2 Key Stages</td>
<td>3</td>
</tr>
<tr>
<td>3    KEY RESULTS FROM THE LITERATURE REVIEW</td>
<td>4</td>
</tr>
<tr>
<td>3.1 Procedures for Estimating Loads on Seaplanes and Helicopters</td>
<td>4</td>
</tr>
<tr>
<td>3.2 General Considerations</td>
<td>5</td>
</tr>
<tr>
<td>3.3 Impact Loads on Circular Cylinders</td>
<td>7</td>
</tr>
<tr>
<td>3.4 Impact Loads on Wedge Sections</td>
<td>9</td>
</tr>
<tr>
<td>4    THEORETICAL BASIS</td>
<td>11</td>
</tr>
<tr>
<td>4.1 Assumptions</td>
<td>11</td>
</tr>
<tr>
<td>4.2 Monte-Carlo Simulation Procedure</td>
<td>12</td>
</tr>
<tr>
<td>4.3 Input Parameters</td>
<td>12</td>
</tr>
<tr>
<td>4.4 Initial Water Impact Forces</td>
<td>13</td>
</tr>
<tr>
<td>4.4.1 Maximum Impact Force on the Sponson</td>
<td>14</td>
</tr>
<tr>
<td>4.4.2 Maximum Impact Force on the Fuselage Panel</td>
<td>15</td>
</tr>
<tr>
<td>4.5 Structure Loads</td>
<td>16</td>
</tr>
<tr>
<td>4.6 Drag and Planing Forces</td>
<td>17</td>
</tr>
<tr>
<td>4.6.1 Drag Forces on the Sponson</td>
<td>18</td>
</tr>
<tr>
<td>4.6.2 Planing Forces on the Fuselage Panel</td>
<td>18</td>
</tr>
<tr>
<td>5    MAIN STUDY</td>
<td>19</td>
</tr>
<tr>
<td>5.1 Helicopter Details</td>
<td>20</td>
</tr>
<tr>
<td>5.2 Impact Loading Scenarios</td>
<td>20</td>
</tr>
<tr>
<td>5.3 Conditions Represented</td>
<td>21</td>
</tr>
<tr>
<td>5.3.1 Sea Conditions</td>
<td>21</td>
</tr>
<tr>
<td>5.3.2 Impact Force on the Sponson</td>
<td>22</td>
</tr>
<tr>
<td>5.3.3 Impact Force on the Fuselage Panel</td>
<td>23</td>
</tr>
<tr>
<td>5.3.4 Impact Scenarios</td>
<td>23</td>
</tr>
<tr>
<td>5.3.5 Modelling the Sponson</td>
<td>24</td>
</tr>
<tr>
<td>5.3.6 Modelling the Fuselage Panel</td>
<td>26</td>
</tr>
<tr>
<td>5.4 Results</td>
<td>27</td>
</tr>
<tr>
<td>5.4.1 Correlation Plots</td>
<td>27</td>
</tr>
<tr>
<td>5.4.2 Load Exceedance Distributions</td>
<td>28</td>
</tr>
<tr>
<td>6    SENSITIVITY STUDY</td>
<td>29</td>
</tr>
<tr>
<td>6.1 Scope of Work</td>
<td>29</td>
</tr>
<tr>
<td>6.2 Results from the Sensitivity Study</td>
<td>31</td>
</tr>
<tr>
<td>7    TWO-FLOAT REDUNDANCY STUDY</td>
<td>36</td>
</tr>
<tr>
<td>7.1 Scope of Work</td>
<td>36</td>
</tr>
<tr>
<td>7.2 Impact Loads on Sponsons</td>
<td>37</td>
</tr>
<tr>
<td>7.3 Impact Loads on Fuselage Panels</td>
<td>37</td>
</tr>
<tr>
<td>7.4 General Conclusions from Two-Float Redundancy Study</td>
<td>38</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

BMT Fluid Mechanics Limited (BMT) was commissioned by the Civil Aviation Authority (CAA) to carry out an investigation into the crashworthiness of helicopter emergency flotation systems during a crash or ditching onto water. BMT’s work formed part of a broader study, undertaken by WS Atkins Science and Technology (WSA), which included a literature review of past accidents, a finite element modelling study, a review of emergency flotation equipment design and its failure modes, a cost/benefit study on proposed modifications, and a review of current regulations. The results from this broader study are presented in a companion WSA report [1].

The main purpose of BMT's investigation was to estimate the range of water impact loads experienced by typical flotation systems, installed within the sponsors or beneath fuselage panels of helicopters, during controlled ditching, vertical descent, loss of control and fly-in incidents. The first phase of BMT's investigation [2] involved a literature review of model test results and impact force calculation methods, the development of a Monte Carlo simulation procedure based on simplified empirical and theoretical formulae for estimating the impact force, and a simulation study based on a number of agreed ditching and accident scenarios. Failure of the flotation system was deemed to occur whenever the load on the sponsor or fuselage panel exceeded its design value. The calculations were performed in representative central North Sea wave conditions and in calm water.


Input data parameters and design loads used during the initial investigation and subsequent sensitivity study were based on information for the Sea King helicopter, supplied by GKN Westland Helicopters Limited (GKN WHL). The Cormorant Alpha and Brent Spar investigations were based on input parameters and models agreed with WSA, which were ultimately derived from information contained in relevant reports of the Air Accidents Investigation Branch (of the UK Department of Transport).

The final phase of work involved a redundancy study on a multi-float system, based on the EH101 helicopter with additional upper cabin flotation units.

It is assumed that the flotation system remains uninflated until after contact with the water, and will fail to deploy if the relevant sponsor or cover panel suffers structural damage on impact. The loading range is characterised in terms of the exceedance probability distribution of maximum water impact forces on the sponsor or panel.

These calculations were based on a simplified water impact loading model, which treats each flotation component in isolation, ignoring the effects of the surrounding hull structure. This type of model should be sufficient to demonstrate trends and sensitivity levels, but it is not easy to estimate the absolute accuracy of the predicted forces. Comparisons with results from the WSA finite element model-based analysis

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1 A full list of references may be found in Section 12 on page 60.
(reported separately by WSA [1]) have nonetheless shown an encouraging level of agreement.

The following report summarises results from the literature review, outlines the theoretical basis for BMT's Monte Carlo simulation procedure, and presents key results and conclusions from the project as a whole. Further details and additional results may be found in references [2] and [3].

1.1 Terms of Reference

BMT's scope of work and terms of reference for this investigation are defined in reference [6].

2 BACKGROUND AND KEY STAGES

Previous work on the analysis of helicopter crashes onto water [7, 8, 9, 10, 11] concluded that the primary cause of loss of life following water impact is drowning, and that improvements in the capability of helicopters to remain afloat after impact, long enough for occupants to escape, is the major factor in increasing occupant survivability. The CAA therefore commissioned a research project aimed at establishing the feasibility of improving the crashworthiness of helicopter emergency flotation systems. This project was undertaken by WS Atkins Science and Technology (WSA), with support from the BMT investigation reported in this document.

2.1 Analysis of Loads on Flotation Systems

GKN WHL had previously carried out an analysis [8] of the accelerations and loads sustained by the main helicopter fuselage during impact onto water using the MSC/DYNA program. DYNA is essentially a structural analysis program, and the water surface was modelled in an idealised manner (i.e. as a material with a given density and a specified relationship between its pressure and volume). This type of model is likely to predict the peak impact pressure occurring immediately after a vertical impact onto a smooth and still water surface quite well, when the forces are largely determined by the inertia of the fluid and by acoustic pressures. It is not obvious how to model the effects of free surface waves, water surface roughness and aeration, however, and it is difficult to model quasi-steady processes, such as viscous drag and planing forces, which are likely to become important during impacts at high forward speeds.

WSA have now undertaken a further numerical finite element modelling study, based around three actual accident scenarios. These three accidents occurred near the Cormorant Alpha platform in 1992, at the Brent Spar platform in 1990, and near the Scilly Isles in 1983. The results from WSA's investigations are presented in a separate companion report [1]. WSA's analysis aimed to predict detailed structural loads within the helicopter's hull during a small number of specific water impact events.

BMT have adopted a more pragmatic approach, which aims to define the range of loads occurring during many such impact events, but using a simplified water impact loading model to describe each such event. BMT's investigations were therefore intended to complement WSA's analysis by establishing trends and levels of sensitivity, and thus help to place WSA's results within a broader context.
BMT’s approach is based on an empirical description of the impact loading process, rather than on a purely theoretical model. Experimental work has repeatedly demonstrated that water impact loads are extremely variable and sensitive to the shape and roughness of the structure and water surfaces, to the amount of air entrapment, and to the entry angle and velocity on impact. BMT have therefore adopted a probabilistic approach which recognises the highly random nature of the impact loading process, and its sensitivity to fairly small changes in the impact conditions. The loading model has also been adapted to represent simplified drag and planing forces as well as the initial impact.

The simplifications and assumption within this model have to be borne in mind when assessing the results. The main purpose of this investigation was to identify trends and the sensitivity of impact loads to variations in the helicopter's condition and sea state at the instant of impact, rather than to obtain high absolute accuracy in the predicted impact loads, or to identify the structural consequences.

Appendix A describes results from an investigation which allowed direct comparisons to be made between impact loads estimated by BMT and WSA. This investigation was based on the Brent Spar and Cormorant Alpha accident scenarios, and was intended to provide guidance on the accuracy, reliability and limitations of both types of model. The results from this comparison study are described in the accompanying WSA report [1].

2.2 Key Stages

The key stages of this investigation were as follows:

- a literature search and review aimed at identifying suitable procedures for estimating water impact loads on a sponson or fuselage panel during each of the four specified types of incident (Section 3);

- development of a Monte Carlo simulation procedure, based on selected load calculation methods, to establish probability distributions of water impact loads in each type of incident (Section 4);

- calculations based on Brent Spar and Cormorant Alpha accident scenarios, which enabled comparisons to be made with WSA’s results (Appendix A);

- the definition of four base case scenarios describing ranges of ditching, vertical descent, loss of control and fly-in incidents, and an analysis based on those scenarios (Section 5);

- a sensitivity study to investigate the effects of varying the helicopter's condition and the sea state at the instant of impact (Section 6);

- an initial two-float redundancy study to investigate the effects of making alternative assumptions about the number of flotation units required to keep the helicopter afloat (Section 7);

- an interpretation and assessment study to help draw appropriate conclusions about prospects for enhancing the crashworthiness of emergency flotation equipment (Section 8);
• a multi-float redundancy study, based on the EH101 helicopter with additional upper cabin flotation units (Section 9).

3 KEY RESULTS FROM THE LITERATURE REVIEW

3.1 Procedures for Estimating Loads on Seaplanes and Helicopters

Early procedures for predicting water impact forces on seaplanes and helicopters were based on a theoretical model developed by von Karman [12] to describe forces on a wedge descending vertically onto smooth water. Von Karman's theory was subsequently extended by Wagner [13], who took account of the rise in the water surface on either side of the descending wedge. Models of this type effectively assume that the velocity on impact is normal to the keel, and ignore the forward speed of the hull through the water.

Later investigators recognised that any significant forward motion of the hull through the water causes a loss of momentum in the downwash, and in the sheet of water that is thrown forwards and away from the craft. These momentum changes result in ‘planing’ forces, which are not represented in simple vertical impact models. Various empirical or intuitive modifications were made to the theory during the late 1940s and 1950s in order to take account of forces associated with forward motion.

Some of the earliest references considered during this review were three NACA reports [14, 15, 16] relating to the landing of seaplanes and helicopters on water. These are part of an extensive series of NACA papers and reports which investigated both impulsive slam-type loads and planing loads on cylindrical and V-shaped hull-sections, using empirical formulae and intuitive modifications to theoretical solutions. Theoretical predictions were also compared with results from extensive programmes of model tests.

NACA Technical Note 1008 [14] reviewed the von Karman and Wagner models, and considered a number of proposed improvements to the theory. It then proposed an intuitive modification to the theory to take account of forward speed and planing forces. Maximum forces predicted using this modified theory agreed favourably with measured forces on a V-shaped hull model.

NACA Report 1103 [15] developed a ‘strip theory’ procedure for estimating forces and moments on seaplane hulls, based on the force prediction formula proposed in [14]. The flow was assumed to be two-dimensional in each transverse flow plane, and an aspect ratio correction was applied to take account of three-dimensional flow effects. The loads were characterised in terms of a so-called ‘approach’ parameter, which depended on the craft’s trim angle and flight path angle on impact. Predicted moments on seaplane hulls and the resulting motions agreed favourably with measurements.

NACA Technical Note 2889 [16] presented a theoretical procedure for estimating water impact loads on helicopters, which were modelled as elliptical cylinders. The theoretical model was based on the Wagner wedge impact theory, and forward speed was taken into account using the approach proposed in [15]. Predicted pressures agreed reasonably well with measurements on a dropped circular cylinder. These measurements have now been largely superseded by the more extensive Campbell data set discussed in Section 3.3.
A more recent Aeronautical Research Council report [17] reviewed these and other prediction procedures for seaplane impact, and compared predicted results with experimental data. Once again, an important distinction was made between impact forces and planing forces. The impact force was associated with the component of flow normal to the aircraft keel, whereas planing forces were associated with the component of flow parallel to the keel. Both types of forces were found to be important in cases where the aircraft had a significant forward speed and descent speed on contact with the water. Section 3 of [17] presented various alternative theoretical procedures for estimating the effects of planing and impact forces on seaplanes. Comparisons with experimental measurements on a Sunderland flying boat were somewhat inconclusive, however, and none of the theoretical solutions convincingly fitted both the model and full-scale experimental evidence. Certain discrepancies were attributed to experimental error, but the paper concluded that it might be necessary to determine three-dimensional planing forces and pressures experimentally on models of individual hull forms.

3.2 General Considerations

The initial objective of this study was to assess the range of possible impact loads occurring when the helicopter sponson or fuselage first contacts the water. At that stage the problem was seen as one of impact loading, rather than one of gradual immersion and the development of planing and drag forces. During the course of the project, however, it became clear that different physical processes are involved, depending on whether the helicopter falls vertically onto the water surface, or flies into the water at a high forward speed. In the latter case, planing and drag-type forces seem to be at least as important as the initial impact force and the physical processes are highly complex, three-dimensional in character, and not amenable to a straightforward theoretical analysis.

BMT was discouraged from adopting any of the seaplane impact models described in Section 3.1, partly by the apparent complexity of implementing such a model within a Monte Carlo simulation procedure, and partly by comments in [17] about the uncertain level of correlation between theoretical models of this type and experimental data.

With the initial goal of predicting water impact loads only, BMT therefore decided to develop a theoretical model based on conventional design procedures for estimating slam loading on objects impacted by sea waves. Such models are well established in engineering design, are relatively straightforward to implement, and have been validated against measurements.

As in most other water impact loading studies, it was assumed that the peak water impact load on a typical sponson or fuselage panel may be characterised using a slam force equation of the form:

\[ F_{\text{max,imp}} = \frac{1}{2} C_s \rho A u_p |u_r| \]

where \( F_{\text{max,imp}} \) is the peak impact force, \( C_s \) is the impact force coefficient, \( \rho \) is the water density, \( A \) is the presented area across which the impact occurs, \( u_p \) is the relative velocity of water particles resolved normal to the component, and \( u_r \) is the relative velocity of the water surface resolved normal to the component.
An equation of the same general form as (1) is recommended in the Health and Safety Executive's (HSE) Guidance Notes [18] for calculating wave slam loading on members of offshore structures, and similar formulae are widely used in other water impact loading problems, such as slamming on ships' hulls.

The background report to the HSE's Guidance Notes [19] contains extensive guidance on the selection of slam force coefficients for particular applications, and on the use of this formula in design. It also points out, however, that there is considerable variability in values of the slam force coefficient, $C_s$, that have been obtained from measurements. It is important to take this variability in $C_s$ into account in the design process, together with the variability in other parameters, such as the impact velocities, $u_p$ and $u_e$, and the impact angle $\xi$.

The slam force coefficient $C_s$ in equation (1) has several sources of variability, associated with:

- variations in the angle between the structural component and water surface on impact,
- effects of the sea state and water surface roughness,
- inherent variability between different samples from nominally identical conditions.

BMT therefore undertook an extensive literature review [2] to find appropriate information on values of the slam force coefficient, its variability and dependence on the angle of impact and sea state conditions. This review included an initial literature search to identify papers and reports relating to impact forces on cylinders and other objects dropped onto the water surface, forces on fixed cylinders impacted by waves, breaking wave impact loads and slamming on ship hulls. The results contained in many of these papers and reports were considered to be of limited value for this investigation because of:

- the generally high levels of scatter in the results,
- evidence of severe contamination by natural period oscillations of the measurement equipment,
- little information that could be regarded as sufficiently systematic, extensive and reliable,
- and little data that had been analysed sufficiently to allow prediction formulae to be developed.

A small number of reports were investigated in detail, and key results are summarised in Sections 3.3 and 3.4. These particular papers and reports relate to water impact loads on circular cylinders and wedge sections. Further information about papers considered during this review study may be found in Appendix A of reference [2].
3.3 Impact Loads on Circular Cylinders

The procedure adopted here (see Section 4.4.1) for estimating water impact loads on the sponson was based primarily on an empirical equation proposed by Ridley [20] for estimating water impact forces on a circular cylinder. Ridley's formula was in turn based on results from an unusually extensive, thorough and systematic series of experiments on circular cylinders dropped onto still water. These experiments were performed by Campbell and colleagues [21, 22] at the Wolfson Unit (Southampton University).

These experiments measured both total forces and pressure distributions. Special care was taken to make the model very stiff (with a high natural frequency of 550 Hz), and to minimise (and correct for) effects of the model's dynamic response. Systematic tests covered cylinders of various diameters, horizontal and oblique water entry, smooth and disturbed water surfaces, smooth and fouled cylinder surfaces, and aerated water.

Campbell [21, 22] proposed an empirical formula for predicting the force time history during a horizontal impact with a smooth water surface, and an associated procedure for estimating impact loads during an inclined impact. This procedure took the form of a 'strip theory', in which the cylinder was treated as many short cylindrical segments, entering the water in succession.

Ridley [20] proposed an alternative formula for predicting the impact force time history, which also fitted the measured data well (see Figure 1). Ridley's formula has since become the basis of a widely-used procedure [19] for estimating wave slamming forces on tubular members of offshore structures. This formula is therefore well-established in offshore design, and seemed to offer a reasonable basis for estimating water impact loads on a helicopter sponson. BMT therefore developed a procedure for estimating loads on the sponson based on Ridley's impact force formula combined with Campbell's 'strip theory' approach.

Key results from Campbell's investigations were as follows:

(a) When a perfectly horizontal cylinder impacted onto perfectly still water the measured impact force time histories could all be collapsed onto a single curve, as illustrated in Figure 1. The vertical bars in this Figure show the low level of variability between different tests, and represent one standard deviation either side of the mean value at each point in the time-history.

(b) The maximum value of $C_i$ was found to be very sensitive to small changes in the angle between the cylinder axis and water surface on impact. The peak value of $C_i$ reduced from 5.3 to 2.6 as the cylinder inclination angle changed from 0° to only 1°. Small variations in the angle of impact are likely to be responsible for much of the observed variability in results obtained from slamming experiments in waves.

(c) Measured values of $C_i$ for inclined cylinder impacts and with a disturbed water surface could be predicted quite well from the time-history of force for horizontal impacts together with 'strip theory'.

(d) The peak value of $C_i$ for aerated water, and the time at which the peak occurred, were almost identical to those measured in still water, except when the angle of
impact was less than 0.5°. (Campbell’s reports do not make it clear whether $C_i$ was calculated using the density of aerated or unaerated water.) The effects of aerated water were ignored during the present study.

Campbell’s experiments gave no indication of the effects of wave steepness and breaking. Measurements of slamming loads made by other researchers in very steep and breaking waves (e.g. reference [23]) have generally produced very variable results, which were difficult to interpret and use. The unsystematic nature of test programmes and questionable data quality made it generally difficult to see how to convert published measured data into suitable prediction formulae.

There was nonetheless evidence that the impact force coefficient $C_i$ is more variable when impacts occur in rough water. BMT therefore decided to make the pragmatic assumption that Ridley’s formula applies in rough sea conditions, but that the standard deviation of $C_i$ should simply be increased to 1.0.

It was assumed that the sea state could be described as ‘rough’ or ‘smooth’, depending on whether the significant wave steepness, $S_s$, lay above or below a certain threshold value, $S_{lim}$. The significant wave steepness is defined as:

$$S_s = \frac{2\pi H_s}{g T_s^2}$$

(2)

where $H_s$ is the significant wave height, and $T_s$ is the mean zero up-crossing wave period.

Model tests have shown that the effects of entrained air and compressibility become very significant when the water and structure surfaces are smooth and almost parallel at the moment of impact [24]. The impact force varies substantially, depending on the amount of air entrapment, water surface roughness, and the precise angle of impact. It is assumed that the surfaces have sufficient curvature to allow circular cylinder data and formulae to be used.

Results from a numerical study [25] lent support to the assumption that the impact force would be proportional to the local radius of curvature of the structure surface. Forces on cylinders of circular and parabolic section had been predicted using a numerical finite difference model. Maximum forces on the two parabolic models were lower than the maximum force on the circular model, almost exactly in proportion to the radius of curvature of the section at its lowest point.

Figure 1 shows the time history of the force on a smooth horizontal circular cylinder, of diameter $D$, falling with velocity $u$ onto still water of density $\rho$. The Figure compares Ridley’s [20] empirical formula with Campbell’s measured data [21]. Ridley expressed the force per unit length of the cylinder, $F(t)$, in terms of a non-dimensional quantity, $\Phi_s(t)$, and as a function of time $t$:

$$F(t) = \frac{1}{2} \rho u^2 D \Phi_s(t)$$

(3)

where:

$$\Phi_s(t) = C_i \left\{ a_0 + a_1 \exp\left(-b_1 \frac{u t}{D}\right) + a_2 \exp\left(-b_2 \frac{u t}{D}\right) \right\}$$

(4)
with the following fitted parameters: mean \( C_i = 5.3, a_0 = 0.14, a_1 = 0.59, a_2 = 0.27, b_1 = 9.9 \) and \( b_2 = 54.9 \). The first term in equation (4) represents the steady drag force, and \( C_i a_0 \) is effectively the drag force coefficient. The two exponentially decaying terms in equation (4) represent the effects of the initial impact.

Campbell's experiments considered the vertical drop scenario only, and did not consider the effects of forward speed. BMT therefore made simple intuitive adjustments to the theoretical model to allow for forward speed, based on physical arguments about the nature of the initial impact and drag forces, and about relationships between these forces and the relative velocity between the water and structure surfaces.

Details of procedures used to estimate both the initial impact force and quasi-steady drag force on the sponson are presented in Sections 4.4.1 and 4.6.

3.4 Impact Loads on Wedge Sections

The procedure adopted here for estimating the maximum impact load on a fuselage panel was based on Wagner's [13] wedge impact theory. Wagner's theory is based on a simple expanding flat plate model, and has been applied to a variety of water entry problems. Wagner's theory tends to over-predict maximum impact forces and pressures, when compared with measurements, and there is generally also significant scatter in the measured data, especially when the impact angle between the body and water surface is very small.

Chuang [26] reported results from an extensive and systematic programme of local impact pressure measurements on wedges and cones dropped onto both calm water and regular waves. The results from the tests in waves are of particular interest because wave slamming forces are known to be very sensitive to the shape of the water surface, its roughness and the amount of air entrapment. Figure 22 of Chuang's report [26], reproduced as Figure 2, summarises the results obtained from all of Chuang's tests in regular waves, and compares the results with his own empirical prediction formula (shown as a dashed line). The experimental data show considerable scatter (as is usual in experiments of this type in waves), but the empirical curve lies above the majority of the data.

The coefficient \( k \), shown in Figure 2, is in an unconventional set of units, and is not the same as the usual maximum pressure coefficient, \( C_{p,\text{max}} \), which may be obtained by setting:

\[
C_{p,\text{max}} = \frac{p_{\text{max}}}{\frac{1}{2} \rho u^2} = 288 k
\]

where \( p_{\text{max}} \) is the maximum measured pressure, \( \rho \) is the water density, and \( u \) is the relevant impact velocity. The angle \( \xi \) in Chuang's figure represents the effective impact angle between the structure surface and water surface, taking account of the vessel's trim and heel and the local slope of the water surface.

Entrapped air has a pronounced 'cushioning' effect at small angles of impact, and the impact pressure is very sensitive to small changes in the angle between the structure and water surfaces, to local changes in the surface shape and roughness, and to the degree of aeration. This is the reason why Chuang's empirical curve, shown in Figure 2, falls when the impact angle is small, whereas Wagner's theoretical model...
predicts a very steep rise. It is also the reason for the much-increased level of scatter seen in the measured data at small impact angles.

Figure 3 compares maximum pressure coefficients predicted using Wagner's theoretical model [13] with those predicted using Chuang's empirical formula. The pressure coefficient, $C_{\text{pmax}}$, has been plotted against the impact angle, $\xi$. The two curves approach each other when $\xi$ is greater than 15°, but behave in a very different manner when the impact angle is small. This Figure also shows the highest values of $C_{\text{pmax}}$ obtained during Chuang's experiments. These highest values are very scattered, and are up to twice the values predicted by Chuang's formula.

Chuang's experiments measured local impact pressures rather than the impact force acting over the entire wedge surface. Impact pressures vary very rapidly with time, and vary spatially across the wedge face. This means that measurements of maximum local impact pressures give little indication of the magnitude of the impact force. The impact force on the panel as a whole cannot therefore be estimated reliably from Chuang's formulae and data, although it is possible to infer trends and draw some general conclusions.

It seems likely, in fact, that Wagner's theory will predict maximum total impact forces better than maximum local pressures, with less scatter. Chuang's data indicated that Wagner's model should predict maximum impact pressures satisfactorily when the impact angles is greater than about 10° to 15°. Maximum forces will probably be predicted satisfactorily down to lower impact angles.

Wagner's theory predicts that the force will tend to infinity as the impact angle tends to zero. The predicted behaviour is clearly unrealistic, and the force must be limited in practice by physical effects such as water compressibility. The force is therefore likely to level off at small impact angles. The calculation procedure used here was therefore based on Wagner's theoretical model [13], with a constant upper limit value at small impact angles.

The maximum impact force on the fuselage panel, $F_{\text{max imp}}$, was expressed in the form:

$$F_{\text{max imp}} = \frac{1}{2} C_o \rho u_p u_s WL \Phi_w(\xi)$$  \hspace{1cm} (6)

where the non-dimensional quantity, $\Phi_w$, has the form:

$$\Phi_w(\xi) = F_w(\xi) \text{ for } \xi \geq \xi_{\text{min}}$$ \hspace{1cm} (7)

$$\Phi_w(\xi) = F_w(\xi_{\text{min}}) \text{ for } \xi < \xi_{\text{min}}$$ \hspace{1cm} (8)

and $F_w(\xi)$ is the corresponding expression given by Wagner's theory. The minimum angle $\xi_{\text{min}}$ was set equal to 2 degrees, which is the limit at which the Chuang formula starts to fall to zero.

The mean value of $C_o$ in equations (7) and (8) was set equal to 1.0. $C_o$ was then allowed to vary at each step in the simulation process, by use of a random sampling procedure, in order to represent random variability in the impact loading process.

Figure 4 compares values of $\Phi_w(\xi)$, defined using equations (7), (8) and (15), with the equivalent values obtained using the original Wagner theory.
Wagner’s theory represents the initial impact force in vertical drop conditions only, and does not consider the effects of forward speed. Mayo [14] and Arlott et al. [17] reviewed some of the many attempts made to enhance Wagner’s theory and take account of forward speed. None of these enhancements seem to have been entirely satisfactory when compared with measured data. BMT therefore made simple intuitive adjustments to the theoretical model to allow for forward speed, based on physical arguments about relationships between the impact force and the relative velocity between the water and structure surfaces.

Mayo’s and Arlott’s reviews indicated that planing forces are likely to become important when the helicopter has a high forward speed on contact with the water. A planing force term was therefore added, based on a simple theoretical model of a planing flat plate (equation 6.13.20 of [27]).

Procedures used to estimate both the initial impact force and quasi-steady planing force on the fuselage panel are described in Sections 4.4.2 and 4.6.

4 THEORETICAL BASIS

4.1 Assumptions

As in most other studies on wave slamming, such as [20], it is assumed that the surface of the water is an inclined flat plane, and that the water surface velocity is effectively uniform over the area spanned by the relevant structural component (i.e. the sponson or fuselage panel). These assumptions effectively mean that the dimensions of this component are small compared with distances over which the water surface slope varies. Local variations in water surface conditions, such as surface roughness and broken water, will be taken into account by varying the slam coefficient, \( C_s \), rather than by varying the flow conditions.

The helicopter hull, sponson and water surface have complex three-dimensional surfaces, and it is impractical to model these in detail. The structure and water surfaces were therefore simplified in order to make the problem manageable:

- the water surface was assumed to be flat, but inclined to the horizontal,

- the sponson was modelled using ‘strip theory’ as a number of circular cylinder and cone segments with a common axis,

- the fuselage panel was modelled as an inclined flat plate.

The dynamic behaviour of the helicopter as a whole was ignored. The impact duration was assumed to be short enough for changes in helicopter speed, descent angle and attitude to be ignored, at least up to the instant when the maximum impact load occurs.

The maximum total impact force, \( F_{\text{max, tot}} \), was assumed to be the sum of a maximum initial impact force, \( F_{\text{max, imp}} \), and a quasi-static drag or planing force, \( F_d \):

\[
F_{\text{max, tot}} = F_{\text{max, imp}} + F_d \tag{9}
\]
The analysis considered scalar force magnitudes only, and took no account of the vector directions in which the forces act.

Effects of hull shielding are treated in a very simplified manner. The sponsons are assumed to be far enough from the hull to experience no benefits from shielding whatsoever. The panels are assumed to be part of the hull, however, and are assumed to be totally protected by the helicopter's hull if impact occurs while they are inclined upwards, away from the water surface. In these circumstances the impact force is set to zero. No other shielding effects are represented, because the model knows nothing about the remainder of the hull. Clearly this is a highly simplified way in which to treat what is really a very complex hydrodynamic phenomenon.

It is difficult to know what the real effects of shielding are likely to be, and the present model may either overstate or understate the benefits of shielding, depending on where the panels and sponsons are located, and how the hull hits the water. In one respect BMT's model overstates the benefits, because it assumes that an upward-facing panel will survive a high speed impact, whereas the hull itself would fail in these circumstances.

4.2 Monte-Carlo Simulation Procedure

A Monte Carlo simulation procedure was used to develop probability distributions of maximum water impact loads on the sponson and fuselage panel. This procedure involved calculating maximum impact loads based on random samples from probability distributions of the various input parameters. The impact force corresponding to a given set of input parameters was calculated in a deterministic manner.

The main steps in the Monte Carlo simulation procedure were as follows:

(a) sample randomly from each of the relevant distributions of input parameters,

(b) calculate (deterministically) the maximum hydrodynamic impact force and structural force corresponding to this particular random combination of selected parameters,

(c) repeat this sampling process a large number (20,000) of times,

(d) derive probability distributions of the resulting maximum forces, and the probability of exceeding a specified design value.

4.3 Input Parameters

The maximum impact force depends on a range of parameters describing the speed, descent angle and attitude of the helicopter at the instant of impact, and local water surface conditions. Random variations in each of the following input parameters were considered:

- the impact force coefficient,
- the forward speed of the helicopter,
• its angle of descent,
• its roll, pitch and yaw angles on entry into the water,
• its heading angle relative to waves,
• the joint distribution of significant wave heights and periods, representing all sea states in which the impact may occur,
• individual values of wave steepness and phase angle in each sea state.

Most of these parameters were assumed to be normally distributed, and the distributions were defined in terms of mean values and standard deviations. Random samples from each of these distributions were obtained by standard numerical sampling procedures. There is no particular evidence to suggest that many of these parameters are normally distributed in practice, and one might in fact expect some of them (such as the helicopter's forward speed) to be skewed. Normal distributions were nonetheless assumed for reasons of convenience and consistency, and in the absence of an obvious alternative model. The main aim was to achieve a representative amount of variability, and a representative mean value of each parameter.

4.4 Initial Water Impact Forces

Details of the formulae and procedures used to calculate maximum impact loads on the sponson and fuselage panel may be found in Appendices B to H of reference [2]. Key equations only are reproduced here.

The maximum initial impact force was calculated using an approach recommended by the UK Health and Safety Executive (HSE) for calculating wave slamming loads on members of offshore structures [18, 19]. The peak hydrodynamic impact force, $F_{\text{max, imp}}$, on a typical sponson or fuselage panel was represented by a slam force equation of the form:

$$ F_{\text{max, imp}} = \frac{1}{2} C_s \rho A u_p \left| u_s \right| $$

(10)

where $C_s$ is the slam force coefficient, $\rho$ is the water density, $A$ is the presented area across which the impact occurs, $u_p$ is the relative velocity of water particles resolved normal to the component, and $u_s$ is the relative velocity of the water surface resolved normal to the component.

Figure 5 illustrates typical relationships between the helicopter velocity, $u_h$, the water surface velocity, $u_w$, the relative particle velocity, $u_p$, the relative surface velocity, $u_s$, and the resolved components, $u_p$ and $u_s$. The formulae used to calculate these parameters may be found in Appendices B and C of [2].

The two velocities $u_p$ and $u_s$ have similar magnitudes in circumstances where the helicopter descends almost vertically into the water, but have very different magnitudes when the helicopter has a high forward speed and low rate of descent at the instant of impact. It is therefore important to distinguish clearly between $u_p$ and $u_s$, and appropriate adjustments were made to various empirical formulae in order to represent these two velocities correctly.
The initial impact force depends on the rate of change of fluid added mass as the helicopter enters the water. The rate of entry into the water depends on the relative velocity between the structure surface and water surface, and therefore depends on \( u_s \). The added mass at any given immersion depth depends on the relative velocity between water particles and the structure surface, and therefore depends on \( u_p \). The rate of change of added mass (and therefore the impact force) therefore depends on the product of these velocities, \( u_p u_s \).

Extending this intuitive argument further, it is reasonable to assume that the immersion time and impact duration will depend on the rate of entry into the water, and therefore on \( u_s \) alone. The impulse (defined as the force integrated over time, and representing the change of fluid momentum on impact) will depend on the total change in fluid added mass, and therefore on \( u_p \) alone.

4.4.1 Maximum Impact Force on the Sponson

The maximum impact force on the sponson was calculated using empirical equations describing the slam force on a horizontal circular cylinder dropped onto smooth water. As discussed in Section 3.3, these equations were proposed by Ridley [20], and were based on experimental measurements by Campbell and colleagues [21, 22]. These equations, (3) and (4), contain both constant and impulsive terms. The constant term, involving \( a_0 \), represents the drag force, which develops as the cylinder becomes fully immersed. The two exponentially decaying terms, involving \( a_1 \) and \( a_2 \), represent the initial impact force. The quasi-steady and impulsive terms are considered separately in the analysis.

Campbell [21] found that measured peak impact forces on inclined cylinders agreed very well with predictions based on a ‘strip-theory’ procedure combined with force coefficients for horizontal impacts. A similar approach has therefore been adopted here. The total force on a cylinder inclined to the water surface was calculated as the sum of contributions from short longitudinal segments or ‘strips’ of the cylinder. The force on each short segment was calculated as if its axis was parallel to the water surface on impact.

The impact force on a short segment of the cylinder was therefore calculated using equations (3) and (4). The force on the complete cylinder was then calculated by adding contributions from all the short segments, taking account of the fact that they enter the water in succession. The impact force on a horizontal cylinder is at a maximum when it first makes contact with the water, whereas the impact force on an inclined cylinder rises initially, then approaches a constant value until it becomes fully immersed. The maximum impact force in this second case occurs when the cylinder is just fully immersed.

Using equation (3) and (4), it may be shown (see Appendix D of [2]) that the maximum initial impact force, \( F_{\text{max, imp}} \), on a cylindrical component of length \( L \) and diameter \( D \) inclined with its axis at an angle \( \beta \) to the water surface, is given by the formula:

\[
F_{\text{max, imp}} = \frac{1}{2} C_s \rho u_s u_p D \Phi_\varepsilon (L, \beta)
\]

(11)

where:
\[
\Phi_c (L, \beta) = \left[ \frac{a_1 D}{b_1 \tan \beta} \left( 1 - \exp \left( -b_1 \frac{L \tan \beta}{D} \right) \right) + \frac{a_2 D}{b_2 \tan \beta} \left( 1 - \exp \left( -b_2 \frac{L \tan \beta}{D} \right) \right) \right] \tag{12}
\]

Special limiting forms of this equation have to be considered when \( \beta \) approaches 0 or 90 degrees.

The impulse associated with immersing a length \( L \) of the cylinder is:

\[
J = \frac{1}{2} C_s \rho u_p D^2 L \left\{ \frac{a_1}{b_1} + \frac{a_2}{b_2} \right\} \tag{13}
\]

The sponson was modelled as a parallel-sided cylinder, together with a ‘nose cone’. The force on the nose cone was calculated in the same manner as on the circular cylinder but using velocity components, \( u_s \) and \( u_p \), normal to the cone’s surface at the point of first impact, rather than velocity components normal to the cylinder axis.

The impact force coefficient, \( C_s \), was assumed to have the mean value proposed by Ridley [20], but was allowed to vary in a random manner about that mean in order to allow for the variability observed in practice. Greater variability was assumed to occur in steeper wave conditions.

4.4.2 Maximum Impact Force on the Fuselage Panel

As noted in Section 3.4, the Wagner theoretical model [13] seemed to be a reasonable basis from which to calculate impact forces on the fuselage panel. The theory was nonetheless modified, as shown in equations (7) and (8), by imposing a minimum impact angle, \( \xi = \xi_{\text{min}} \), below which the impact force coefficient was assumed to remain constant. Intuitive arguments were then used to extend Wagner's theory from vertical impacts onto a horizontal surface to non-vertical impacts with forward speed onto an inclined water surface.

In accordance with equations (6), (7) and (8), the maximum impact force, \( F_{\text{max, imp}} \), on a panel of width \( W \) and length \( L \), inclined at an angle \( \xi \) to the water surface, was expressed in the form:

\[
F_{\text{max, imp}} = \frac{1}{2} C_o \rho u_p W L \Phi_w (\xi) \tag{14}
\]

where (see Appendix E of [2]):

\[
\Phi_w (\xi) = \frac{\pi^2}{2sz cz} \tag{15}
\]

\[
sz = \sin \xi \quad \text{when} \quad |\sin \xi| \geq sz_{\text{min}} \tag{16}
\]

\[
sz = sz_{\text{min}} \quad \text{when} \quad |\sin \xi| < sz_{\text{min}}\]

\[
cz = \cos \xi \quad \text{when} \quad |\cos \xi| \geq cz_{\text{min}} \tag{17}
\]

\[
cz = cz_{\text{min}} \quad \text{when} \quad |\cos \xi| < cz_{\text{min}}\]

\[
sz_{\text{min}} = \sin \xi_{\text{min}} \tag{18}
\]
The impulse, \( J \), is given by:

\[
J = \frac{\pi \rho u_w W^2 L}{4}
\]  

(19)

The purpose of the parameter \( C_o \) in equation (14) was to allow the impact force to vary in a random manner. \( C_o \) was sampled from a normal distribution with a mean value of 1.0. The standard deviation of the distribution was chosen to represent the level of variability observed in practice. Greater variability was assumed to occur in steeper wave conditions.

4.5 Structure Loads

Equations (11) and (14) describe hydrodynamic forces acting externally on the sponson and panel surfaces. The maximum force experienced within the structure depends on the duration of the external force, and on the way in which the structure responds. These in turn depend on the helicopter's structural properties.

The relationship between the impact force and the structure's response is complex, even when the structure is a simple single-degree-of-freedom, linear, spring/mass/damper system. The maximum response depends on the time-history of the impact force as well as on the characteristics of the structure. BMT therefore undertook an initial feasibility study to find a practical and justifiable procedure for estimating the maximum structure force analytically, without having to calculate the full response time history, and bearing in mind the necessary structural simplicity of the model. Initial attempts were based on use of the Laplace transform of the impact force history, and an assumed delay time between the initial impact and the maximum response. It quickly became clear, however, that the relationship between the force history and maximum response is complex, involving various different time scales, and simple assumptions about the delay time proved to be unsatisfactory.

A more straightforward and approximate approach was therefore adopted, based on considering both ends of the range of impact loading types. The structural loading process was assumed to be either impulsive or quasi-static in character, depending on whether the impact duration was short or long compared with the structure's natural response period.

The impact duration was estimated from the maximum impact force and the impulse (change in fluid momentum) associated with the impact. The response was assumed to be quasi-static in character if the impact duration was less than the natural response period divided by \( \pi \), and impulsive in character if greater than the natural response period divided by \( \pi \). The factor \( \pi \) was introduced simply in order to avoid discontinuities where the two load type ranges meet. If the response was considered to be quasi-static in character, then the structure force was set equal to the impact force. If it was impulsive in character, the maximum deflection of the structure was estimated, assuming a delta-function (i.e. an instantaneous ‘spike’) type of loading, and a linear spring/mass/damper system with low damping.

According to equation (2.63) of Bartrop and Adams [28], the response \( x(t) \) of a single-degree-of-freedom linear system, which has mass \( m \) and damping ratio \( \zeta \), to an impulse \( f \) is:
\[ x(t) = \left( \frac{J}{m\omega_d} \sin \left( \omega_d t \right) \right) \exp \left( -\zeta \omega_n t \right) \]  

(20)

where \( \omega_d \) and \( \omega_n \) are the undamped and damped natural frequencies respectively. If the response is lightly damped, \( \zeta \) is small and \( \omega_d = \omega_n \). The maximum deflection is then:

\[ x_{\text{max}} = \frac{J}{m\omega_n} = \frac{\omega_n J}{c} \]  

(21)

and the maximum structural force is:

\[ F_{r\text{max}} = c x_{\text{max}} = \omega_n J \]  

(22)

These equations apply only when the duration of the impact force, \( T_{\text{imp}} \), is short compared with the structure’s natural response period, \( T_n \). If \( T_{\text{imp}} \) is long compared with \( T_n \), the response is quasi-static and a better approximation to the maximum structure force is:

\[ F_{r\text{max}} = F_{\text{max imp}} \]  

(23)

The impact duration may be estimated assuming that the impact force history is triangular in form. In this case:

\[ T_{\text{imp}} = \frac{2J}{F_{\text{max imp}}} \]  

(24)

It may then be shown (see Appendix F of [2]) that the maximum structure force is approximately:

\[ F_{r\text{max}} = \omega_n J \quad \text{when} \quad T_n > \pi T_{\text{imp}} \]  

(25)

\[ F_{r\text{max}} = F_{\text{max imp}} \quad \text{when} \quad T_n \leq \pi T_{\text{imp}} \]  

(26)

These equations assume that the impact duration is either very short or very long, and that there is no possibility of structural resonance causing dynamic amplification of the structural load. They are intended to provide a simple means of estimating a typical magnitude (rather than the precise value) of the maximum structural force. These assumptions mean that the calculated maximum structure force, \( F_{\text{max imp}} \), is never greater than the maximum hydrodynamic impact force, \( F_{\text{max imp}} \).

The kinetic energy transferred to the water and the energy absorbed by the structure were calculated from the impulse, entry speed and structure response. The relevant equations may be found in Appendix F of [2].

4.6 Drag and Planing Forces

Drag and planing forces are likely to become important when the helicopter has a high horizontal speed on entry into the water. These forces have a quasi-steady character, and continue to act while the helicopter moves through the water.
The physical processes giving rise to drag and planing forces are very different from those associated with the initial impact force, despite the outwardly similar forms of the force formulae. Drag and planing forces depend on the instantaneous values of particle velocities around the structure, but are relatively insensitive to its rate of immersion. They are therefore likely to depend on the normal component of the particle velocity squared, $u_p^2$, rather than on the product of the particle velocity and immersion velocity $u_p u_s$. Both types of forces were therefore assumed to have the form:

$$F = \frac{1}{2} C_f \rho A u_p^2$$  \hspace{1cm} (27)

where $C_f$ is the relevant force coefficient, and $A$ is the area presented to the flow.

The full importance of drag and planing forces was recognised at a fairly late stage in the development of BMT's simulation model. Available evidence suggested a fairly complex relationship between these forces and the helicopter's flight parameters, but the form of this relationship was not clear. A simple and intuitive relationship was therefore assumed in the simulation model, more to ensure that drag and planing forces were included than to represent them in an accurate quantitative manner. Thus drag forces alone were assumed to act on the sponson, and planing forces alone on the fuselage panel, on the grounds that these were considered likely to be the dominant components of quasi-steady loading in each case.

4.6.1 Drag Forces on the Sponson

The drag force on a cylindrical component of the sponson, of diameter $D$ and length $L$, is assumed to have the form:

$$F_d = \frac{1}{2} C_d \rho D L u_p^2$$  \hspace{1cm} (28)

where the drag force coefficient, $C_d$, is related to the parameters $C_s$ and $a_b$ in Ridley's formula (equations (3) and (4)) using $C_d = C_s a_b$. Ridley's proposed mean values of these two parameters ($C_s = 5.3$ and $a_b = 0.14$) result in $C_d = 0.74$, which is a typical value of the drag force coefficient for a smooth cylinder.

The drag force is represented here as a quasi-steady component of the impact force. This means that the drag force coefficient, $C_d$, varies in the same random manner as the impact force coefficient, $C_s$. This is an artificial assumption but probably had relatively little effect on the end results, bearing in mind the model's relative insensitivity to variations in $C_s$ (see Tables 6.2 and 6.3).

The drag force reaches a maximum value when the cylinder is just fully immersed, if speed losses during impact are ignored. Maximum impact and drag forces are therefore likely to occur at approximately the same time, justifying the simple addition of these two components so as to obtain an estimate of the 'total' impact force.

4.6.2 Planing Forces on the Fuselage Panel

Several alternative formulae have been proposed in the past [17] for estimating planing and combined impact-planing forces. The choice of appropriate formulae is complex, and was considered to be beyond the scope of the present project. The force was therefore assumed to have the same form as the drag force, and was
estimated using a theoretical solution (equation 6.13.20 of [27]) for the force on a planing plate of width \( W \) and length \( L \), with a void behind it, inclined at an angle \( \alpha \) to a steady flow with incident velocity \( u \). This force is:

\[
F_{pi} = \frac{\pi \sin^2 \alpha}{\pi \sin \alpha + 4} \rho \ u^2 \ L \ W
\]  

(29)

The normal component of the incident velocity, \( u_p \), is effectively \( u \sin \alpha \), and so the planing force may be written:

\[
F_{pi} = \frac{\pi}{\pi \sin \alpha + 4} \rho \ u_p^2 \ L \ W
\]  

(30)

where:

\[
\alpha = \sin^{-1} \left( \frac{u_p}{|u_p|} \right)
\]  

(31)

This formula for the planing force on a flat plate has a lift component, at right angles to the flow direction. Lift forces were otherwise ignored.

Wagner's theory shows that the impact force reaches a maximum value when the panel is just fully immersed. The planing force also reaches a maximum value when the panel becomes fully immersed, if speed losses during impact are ignored. The 'total' impact force was therefore calculated by simply adding the maximum impact and planing forces.

Equation (30) may be written in the same general form as equation (27):

\[
F_{pi} = \frac{1}{2} \ C_{pi} \ \rho \ L \ W \ u_p^2
\]  

(32)

where the planing force coefficient, \( C_{pi} \), is defined as:

\[
C_{pi} = \frac{2\pi}{\pi \sin \alpha + 4}
\]  

(33)

The planing force coefficient was therefore regarded as a fixed quantity during this investigation, with no random variations of any kind. Bearing in mind the comment made earlier about variability in \( C_d \), however, it seems likely that ignoring the variability in \( C_{pi} \) probably had relatively little effect on the end results.

5 MAIN STUDY

The next stage of the investigation took the form of a case study, based on data for the Sea King helicopter. Sample calculations were performed to identify the range of water impact loading on a typical sponson and fuselage panel, covering a range of alternative water impact scenarios and types of incidents considered to be survivable. Four basic types of incident were considered, and the case study considered a range of helicopter speeds, descent angles, attitudes and sea states at the instant of impact.
These calculations were performed using a computer model to perform Monte Carlo simulations of many thousands of such impacts in order to develop probability distributions of the impact force, and to provide an understanding of relationships between the impact force, the helicopter's condition, sea state and other parameters. The theoretical basis of this simulation model is described in Section 4, and results from a simulation study performed using this model are presented in Section 5.4.

The main aims of this part of the investigation were to help identify:

(a) which parameters are important and which are unimportant in each of the four incident scenarios,

(b) the range of impact load variability,

(c) whether the risks of exceeding design load values are large or small,

(d) the likely cost-effectiveness of design modifications.

5.1 Helicopter Details

Information about the Sea King helicopter, and about a typical fuselage-mounted emergency flotation system, were supplied by GKN Westland Helicopters Limited (GKN WHL) [29]. GKN WHL also provided basic information about the sponsons of the civil Sikorsky S61N helicopter, stating that they believed the sponson system of the Sea King to be similar to that of the S61N in terms of structure strength and failure characteristics. GKN WHL noted, however, that the breadth of the sponson on the S61N is 1.31m, which is substantially wider than the 0.84m sponson breadth on the Sea King, and is therefore likely to attract higher impact loads.

Two types of emergency flotation equipment were considered during this investigation. Flotation equipment is typically located in two sponsons, which are part of the wheel support assembly, and under two panels, one on either side of the nose section of the fuselage. These two flotation unit locations are illustrated in Figure 6. Figure 7 shows plan and side views of the starboard sponson on the Sea King.

The flotation equipment was assumed to be uninflated when the craft impacted onto the water surface. Failure was therefore considered to be due to structural failure of the sponson support assembly, or failure of the fuselage panel cover.

5.2 Impact Loading Scenarios

Following discussions with the CAA it was agreed that four basic types of incident should be considered:

(a) a controlled ditching,

(b) a vertical descent incident, representing a helicopter falling off the helideck of an offshore platform,

(c) a loss of control incident, where the helicopter descends into the water following mechanical failure or pilot error,

(d) a fly-in incident, at a high forward speed and shallow descent angle.
These four scenarios, and the parameters used to describe them, were initially based on incident types and descriptions in a GKN WHL report [8]. The parameter ranges were adjusted following discussions with the CAA, and the values finally selected are described in Section 5.3. Parameter ranges for the last three incident types were adjusted to identify them more closely with actual events: the *Brent Spar* accident in July 1990, the *Cormorant Alpha* accident in March 1992, and the *Scilly Isles* accident in July 1983, which were considered representative of vertical descent, loss of control and fly-in types of incident respectively. These three incidents were also being used as the basis for the associated WS Atkins study [1].

Ranges of horizontal and vertical craft speeds, attitudes and angles of impact were considered in each of these cases. The analysis also considered variations in the significant wave height and period, the steepness of individual waves, the degree of water surface roughness, and the inherent variability of the impact force coefficient, \( C_s \). Variations in each of these parameters resulted in a range of possible impact loads for each selected incident scenario.

A Monte Carlo simulation procedure was developed in order to sample randomly from probability distributions of each of these parameters, and thus obtain a large number of random samples of water impact loads. These samples were then analysed to obtain probability distributions of impact loads, together with the associated structure loads, impulses and kinetic energies. The predicted impact load distributions were then compared with structural design load values for the *Sea King* helicopter, supplied by GKN WHL. These design load values included maximum total forces that can be resisted by the main sponson support struts, and the maximum design pressure for the fuselage panel.

### 5.3 Conditions Represented

#### 5.3.1 Sea Conditions

Two alternative sets of sea conditions were considered during this investigation in order to demonstrate the effects of waves on the impact loading process:

- (a) all-year conditions for the central area of the North Sea,
- (b) a completely calm sea with no waves.

The calculations for the central area of the North Sea were based on the all-year, all-directions scatter table of significant wave heights, \( H_s \), and zero-crossing periods, \( T_z \), obtained from BMT’s *PC-Global Wave Statistics* database. It was assumed for present purposes that there are no weather restrictions on helicopter operations, and sea states were sampled randomly from the entire scatter table. The central North Sea scatter table used in this analysis is shown in Table 5.1.
Table 5.1: Scatter table of significant wave heights and zero-crossing periods: central North Sea, all-year, all-directions.

<table>
<thead>
<tr>
<th>Sig.</th>
<th>AREA No. 12</th>
<th>Jan - Dec</th>
<th>ALL DIRECTIONS</th>
<th>100.00% Obs.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hgt. (m)</td>
<td>2</td>
<td>36</td>
<td>161</td>
<td>293</td>
<td>272</td>
</tr>
</tbody>
</table>

European Database

<table>
<thead>
<tr>
<th>Sig.</th>
<th>AREA No. 12</th>
<th>Jan - Dec</th>
<th>ALL DIRECTIONS</th>
<th>100.00% Obs.</th>
<th>Obs.</th>
</tr>
</thead>
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<tr>
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<td>36</td>
<td>161</td>
<td>293</td>
<td>272</td>
</tr>
</tbody>
</table>

5.3.2 Impact Force on the Sponson

The maximum initial impact and drag forces on the sponson elements were calculated using equations (11), (12) and (28). The parameters in these equations took the values: mean $C_i = 5.3$, $a_i = 0.14$, $a_d = 0.59$, $a_e = 0.27$, $b_1 = 9.9$ and $b_2 = 54.9$. These equations and the parameter values were based on an empirical equation (3) proposed by Ridley [20]. Table 5.2 summarises the impact force equation parameters used in the simulations.

Very little information was available about the way in which the force coefficients vary when the water surface is broken. There was nonetheless evidence that the impact force coefficient $C_i$ is more variable when impacts occur in rough water. Following results in [21, 20], the standard deviation of the force coefficient was assumed to be 0.15 when the water was reasonably 'smooth', and was increased to 1.0 in 'rough' water. There is no precise dividing line between smooth and rough water conditions, and a limiting upper bound value of the significant wave steepness, $S_s$, shown in equation (2), for 'smooth' water was assumed (somewhat subjectively) to be $S_{lim} = 0.07$. Sea states with $S_s$ less than 0.07 were regarded as 'smooth', and sea states with $S_s$ greater than 0.07 were regarded as 'rough'.

Study II 22
### Table 5.2: Impact force equation parameters for the sponson

<table>
<thead>
<tr>
<th></th>
<th>‘Smooth’ water</th>
<th>‘Rough’ water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $C_r$ standard</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>deviation $a_0$</td>
<td>0.15</td>
<td>1.0</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$a_2$</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>$b_2$</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>$S_{lim}$</td>
<td>54.9</td>
<td>54.9</td>
</tr>
</tbody>
</table>

5.3.3 Impact Force on the Fuselage Panel

The maximum impact and planing forces on the fuselage panel were calculated using equations (14), (15) and (30). Table 5.3 summarises the impact force equation parameters used in the simulations. The Wagner theory applies only when the impact angle, $\xi$, is larger than a specified lower limit value, $\xi_{min}$. This lower limit value was set equal to 2 degrees, as discussed in Section 3.4.

The mean value of $C_r$ in equation (14) was set equal to 1.0, in order to make the mean force equal to that obtained using the Wagner theoretical model. The standard deviation of $C_r$ was set equal to 0.2 in ‘smooth’ water, and 0.4 in ‘rough’ water. Once again the limiting value of the significant wave steepness, shown in equation (2), for smooth water was assumed to be $S_{lim} = 0.07$.

### Table 5.3: Impact force equation parameters for the fuselage panel

<table>
<thead>
<tr>
<th></th>
<th>‘Smooth’ water</th>
<th>‘Rough’ water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $C_r$ standard</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>deviation $\xi_{min}$</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>$S_{lim}$</td>
<td>2.0°</td>
<td>2.0°</td>
</tr>
</tbody>
</table>

5.3.4 Impact Scenarios

Eight base case Monte Carlo simulation runs were performed in order to calculate the probability distributions of water impact loads on:

- the selected sponson and fuselage panel,
- in the four selected incident scenarios outlined in Section 5.2 (controlled ditching, vertical descent, loss of control, and fly-in),
- in central North Sea wave conditions.
Codes used to identify these eight base-case simulation runs are listed in Table 5.4.

<table>
<thead>
<tr>
<th>Table 5.4: Simulation run identification codes: central North Sea conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Sponson</td>
</tr>
<tr>
<td>Fuselage panel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.5: Parameters used to describe impact scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Mean speed standard deviation</td>
</tr>
<tr>
<td>Mean descent angle standard deviation</td>
</tr>
<tr>
<td>Mean roll angle standard deviation</td>
</tr>
<tr>
<td>Mean pitch angle standard deviation</td>
</tr>
<tr>
<td>Mean yaw angle standard deviation</td>
</tr>
<tr>
<td>Mean angle to waves standard deviation</td>
</tr>
</tbody>
</table>

The simulations covered ranges of helicopter speeds, attitudes and descent angles considered to be representative of each of these four scenarios. Table 5.5 summarises key parameters used in the calculations. The actual value used at each step in the Monte Carlo simulation was obtained by sampling from a normal distribution with the specified mean value and standard deviation. 20,000 alternative combinations of the input parameters were considered during each simulation run. Exceedance probability distributions of water impact loads were then constructed for each incident scenario.

It was assumed that the helicopter pilot will normally attempt to land head into waves during a controlled ditching, but the heading relative to waves will be more random during vertical descent, loss of control or fly-in incidents.

5.3.5 *Modelling the Sponson*

The starboard sponson of the *Sea King* helicopter was modelled as a circular cylinder with a ‘nose cone’. The total length and breadth of this model are the same as those of the actual *Sea King* sponson, which is illustrated in Figure 7. Key information about the sponson was supplied in two GKN WHL faxes [29], dated 6 February and 27 February 1997.
The total length of the sponson is 2.58m, and its breadth is 0.84m. It is modelled as two segments:

(a) a cylinder with parallel sides representing the rear 2.12m of the sponson’s length,

(b) a ‘nose-cone’ representing the forward 0.46m of the sponson’s length, with the nose cone sides inclined at an angle of 30° to the cylinder axis.

The sponson is attached to the helicopter fuselage through two struts. According to GKN WHL [29], these struts are designed for the following maximum failure loads: 207 kN in the vertical direction, 164 kN in the fore-aft direction, and 239 kN in the transverse direction.

The corresponding maximum deflections of the sponson under failure loading are: 6mm in the vertical direction, 46mm in the fore-aft direction, and 24mm in the transverse direction.

For the purpose of estimating stiffnesses and natural frequencies of the sponson mounting system it was assumed that the load/deflection relationships are linear, so that the stiffnesses are: 35.5 MN/m in the vertical direction, 3.6 MN/m in the fore-aft direction, and 9.9 MN/m in the transverse direction. Discussions with GKN WHL suggested that the design deflections include some plastic deformation, although the linear load/deflection assumption is likely to be sufficiently accurate for the purposes of this study.

The natural periods depend on the mass of the sponson system, including its added mass when in contact with the water. The added mass is likely to represent a large part of the total mass, and varies continuously as the sponson enters the water. For present purposes it is assumed that the total mass of the sponson system is half of its total displaced mass. If the sponson is an ellipsoid with principal axes of lengths 2.58m, 0.84m and 0.84m, half of its displacement mass in sea water is approximately 0.5 tonnes. The natural periods of the sponson are therefore approximately: 0.02s in the vertical direction, 0.07s in the fore-aft direction, and 0.04s in the transverse direction.

A single characteristic value of stiffness and natural period had to be selected for use in the calculations. It was not immediately obvious which values should be chosen, because the sponson is inclined at about 11° to the horizontal (upwards at the front), and the analysis took no account of force direction. It was decided to use the fore-aft component, however, on the grounds that the sponson supports are most flexible in this direction, and so dynamic effects are likely to be most apparent in this direction. Table 5.6 therefore summarises key sponson parameters used in the analysis.
Table 5.6: Summary of key sponson parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>2.58m</td>
</tr>
<tr>
<td>Breadth</td>
<td>0.84m</td>
</tr>
<tr>
<td>Inclination to horizontal</td>
<td>11°</td>
</tr>
<tr>
<td>Design maximum load (fore-aft)</td>
<td>164 kN</td>
</tr>
<tr>
<td>Design maximum deflection</td>
<td>46 mm</td>
</tr>
<tr>
<td>Stiffness (fore-aft)</td>
<td>3.6 MN/m</td>
</tr>
<tr>
<td>Natural period (fore-aft)</td>
<td>0.07 s</td>
</tr>
</tbody>
</table>

5.3.6 Modelling the Fuselage Panel

Details of the fuselage panel were contained in two GKN WHL faxes, dated 6 February and 14 May 1997 [29]. A single panel on the starboard side of the helicopter’s nose was modelled.

The area of the fuselage panel was approximately $0.165 \text{ m}^2$, and it was approximately 0.6m long. The effective panel width was therefore 0.275m. The panel was considered to have failed if the pressure exceeded 0.1288 N/mm$^2$. The failure force was therefore approximately 21.3 kN.

The attitude of the panel was described by three inclination angles, representing successive clockwise rotations of an initially vertical panel facing to starboard, about axes pointing forwards, to starboard, and downwards. The panel was inclined at an angle of $14^\circ$ to starboard, $0^\circ$ (level) in the fore-aft direction, and $-10^\circ$ relative to the forward direction.

Associated maximum displacements of the panel were not available. It was therefore assumed that the natural period of the panel and its supports was approximately 0.01s, and its effective mass was the added mass of a flat plate with the same area. The effective total mass was therefore approximately 0.02 tonnes, the panel's effective stiffness was approximately 7.2 MN/m, and the displacement associated with the failure load was 3mm. Discussions with GKN WHL suggested that these were reasonable order-of-magnitude estimates, and should be sufficient for the purposes of this study.

Table 5.7 summarises key panel parameters used in the calculations.
Table 5.7: Summary of panel parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>0.6m</td>
</tr>
<tr>
<td>Width</td>
<td>0.275m</td>
</tr>
<tr>
<td>Inclination about roll axis</td>
<td>14°</td>
</tr>
<tr>
<td>Inclination about pitch axis</td>
<td>0°</td>
</tr>
<tr>
<td>Inclination relative to forward direction</td>
<td>-10°</td>
</tr>
<tr>
<td>Design maximum load</td>
<td>21.3 kN</td>
</tr>
<tr>
<td>Estimated maximum deflection</td>
<td>3 mm</td>
</tr>
<tr>
<td>Stiffness</td>
<td>7.2 MN/m</td>
</tr>
<tr>
<td>Natural period</td>
<td>0.01 s</td>
</tr>
</tbody>
</table>

5.4 Results

Results from each Monte Carlo simulation run were presented [2, 3] in two alternative ways:

- correlation plots illustrating relationships between the total impact force and other simulation parameters, based on the first 200 points from each simulation,

- exceedance probability distributions of the total hydrodynamic impact force, based on the full 20,000-point simulation.

5.4.1 Correlation Plots

Figures 8 to 15 illustrate relationships between simultaneous estimates of the maximum total hydrodynamic impact force on the sponson and corresponding estimates of the maximum structure force and drag force. These correlation plots are based on the first 200 samples from each 20,000-point simulation run. Each quantity is plotted against the corresponding value of the maximum total impact force.

Corresponding results for the fuselage panel are shown in Figures 16 to 23. These figures show relationships between estimates of the maximum total impact force and corresponding estimates of the structure force and planing force.

Figures 24 to 27 show sample results illustrating relationships between the maximum total impact force, impact duration, the impact velocities $u_p$ and $u_s$, and the impact angle $\beta$ for the sponson in a vertical descent incident. Corresponding results for the fuselage panel are shown in Figures 28 to 31.

Equation (24) suggests an approximately inverse relationship between the duration and severity of an impact. This seems intuitively reasonable. The maximum force on a panel or sponson tends to increase rapidly as its surface becomes more parallel to the water surface on impact, but at the same time it enters the water more quickly, reducing $T_{imp}$. Figures 24 and 28 therefore show the inverse of the impact duration, $1/T_{imp}$, plotted against the maximum impact force, $F_{max imp}$. 
A number of conclusions were drawn from the correlation plots:

- The duration of each impact event was generally longer than the relevant natural period. The structural load predicted by the simple structural response model was therefore equal to the hydrodynamic impact load, suggesting that the loading would be essentially quasi-static in character.

- Drag forces on the sponson were found to represent a large proportion of the total impact force in all four types of incident. Planing forces represented only a small proportion of the total force on the fuselage panel in ditching, vertical descent and loss of control types of incident, but about half the total in a fly-in incident.

- The results confirm that there is an approximately inverse relationship between the impact duration and maximum impact force. Very high impact loads were associated with very short impact durations, thus keeping the impulse and energy within reasonable bounds.

- As expected, there was a fairly high level of correlation between the impact velocities, $u_i$ and $u_i'$, and the maximum total impact force, although the highest forces on the sponson were generally associated with moderate impact velocities. The highest forces on the panel were generally associated with high impact velocities.

- A very small number of impacts were much more severe than the remainder. Severe impacts on both the sponson and fuselage panel were generally associated with small impact angles. These very severe impacts may not be modelled satisfactorily by the present procedure because no attempt has been made to represent, in detail, the effects of air entrapment or acoustic pressure limits.

- The distribution of impact angles during ditching and fly-in incidents lay in a band about the panel inclination angle. The band of impact angles was much broader during vertical descent and loss of control incidents, reflecting the broader range of attitudes of the helicopter in these conditions.

- The degree of scatter in ditching and fly-in incidents was noticeably greater in central North Sea conditions, compared with calm water. Wave conditions had a less significant effect on results obtained from the vertical descent and loss of control incidents, as had been expected.

### 5.4.2 Load Exceedance Distributions

The maximum impact loads occurring in the 20,000 individual impact events represented in each simulation run were assembled together in the form of a load exceedance probability distribution. Each distribution shows the range of variability of total impact loads occurring in each incident scenario, and the probability of exceeding a given impact load level.

Load exceedance distributions obtained during this initial base case study were presented in reference [2]. A selection of these distributions will be compared in
Section 6.2 with corresponding results obtained during the sensitivity study. A number of conclusions were drawn during the initial base case study:

- Flotation equipment is designed to survive normal ditching incidents, and the simulation results confirmed that the risk of exceeding the design load in these circumstances is small. There are significant risks of exceeding design loads for both the sponson and fuselage panel, however, in vertical descent and loss of control incidents. These results confirmed initial expectations.

- The results obtained from the simulation model of fly-in incidents were more unexpected. The simulations suggested that there should be a relatively low risk of exceeding design load values for the sponson and fuselage panel in a fly-in incident. Considerable structural damage has occurred during such incidents in the past, however, and one must question whether the simulation represents forces occurring during a fly-in realistically.

- The simulation model represents drag and planing forces, as well as the initial impact force. The drag force represented almost all of the force acting on the sponson, and about half the total force acting on the fuselage panel in a large number of impact events. The present investigation was originally intended to consider impact loading only, however. Drag and planing forces were added almost as an after-thought, and are represented in a very simplified manner. The physical processes involved in the development of these forces during a fly-in incident are extremely complex, and are poorly understood. No fully established and validated theoretical model is known to exist. Predicted fly-in loads are therefore of very uncertain accuracy and reliability.

- There are further difficulties in modelling the fly-in scenario. BMT’s simulation model considers loads on a single sponson or fuselage panel in isolation, and does not consider loads on the surrounding hull structure. A fuselage panel is in practice an integral part of the hull structure, however, and some parts of the helicopter’s nose are likely to experience much higher loading than the fuselage panel. Failure of the fuselage panel in a fly-in incident is likely to occur as a result of over-loading the surrounding nose structure rather than over-loading the panel itself. Failure of the surrounding hull structure was specifically excluded from consideration during the present study.

6 Sensitivity Study

6.1 Scope of Work

The initial base case study, described in Section 5, assumed specific mean values and standard deviations of parameters describing the helicopter’s condition at the instant of impact, and specific values of the impact force coefficients. There are large uncertainties in some of these assumed values, however, and the effects of varying these parameters were not obvious. A sensitivity study was therefore undertaken in order to discover how changes in these assumed parameter values would affect the impact load distributions and conclusions from the study.
Table 6.1 identifies parameters (marked with a ✓ symbol) that were varied during this investigation. Other parameters were left unchanged during this investigation, because they were considered to be of secondary importance or interest. These cases are identified by the symbol ✗ in Table 6.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Controlled ditching</th>
<th>Vertical descent</th>
<th>Loss of control</th>
<th>Fly-in incident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm water conditions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mean speed standard deviation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mean descent angle standard deviation</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mean roll angle standard deviation</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Mean pitch angle standard deviation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mean yaw angle standard deviation</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Beam waves</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Following waves standard deviation of heading</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Drag/planing force coefficient</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Impact force coefficient standard deviation</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

The following variations in parameter values were considered:

- Mean values of the helicopter speed and descent angle were increased by 20% above base case values.
- Mean pitch angles were increased by 2 degrees.
- Values of standard deviations are generally more uncertain than mean values, and these were all increased by 50%.
- There are also large uncertainties in the drag and planing force coefficients, $C_d$ and $C_{pl}$, and these were both increased by 50%.

The effects of ditching the helicopter beam-on to waves (90° heading angle) and in following waves (180° heading angle) were also considered. A head on (0° heading angle) condition was assumed during the base case ditching investigation.

The above calculations were performed on both the sponson-mounted and fuselage-mounted flotation systems, making 92 sets of calculations in total.
Eight base case conditions were considered during the main sensitivity study, and are listed in Table 5.4. Model details and values of key parameters assumed in these eight cases are summarised below, and are described more fully in reference [2]. Definitions of symbols and variable names may be found in the ‘Nomenclature’ section of reference [2].

Only one parameter at a time was varied during this sensitivity study, leaving all other parameters unchanged at their base case values. Base case values assumed during this investigation are defined in Section 5.3.

6.2 Results from the Sensitivity Study

The results from each simulation run were presented in the form of an exceedance probability distribution of ‘total’ impact loads. The full set of results obtained during the sensitivity study are presented in reference [3]. Only a small sample of key results are presented here.

Figures 32 to 55 show exceedance distributions of the total impact force on the sponson in each of the above incident scenarios. Figures 56 to 81 show corresponding results for the fuselage panel. The exceedance distribution shows the range of variability of the total impact load within each incident scenario.

In each case the result of varying each parameter in turn (shown as a dashed line) is overlaid on top of the corresponding distribution obtained from the base case simulation (shown as a solid line).

The simulation model assumes that the maximum ‘total’ impact force may be represented as the sum of the maximum initial impact force and the maximum quasi-steady drag or planing force. Drag forces are assumed to act on the sponson, and planing forces on the fuselage panel. The initial impact force has an impulsive character, and is likely to reach its maximum value approximately when the sponson or panel becomes fully immersed, and will then die away to zero. The drag and planing forces are likely to increase as the sponson or panel becomes more deeply immersed, and will continue to act while the helicopter moves through the water. The simulation model makes the conservative assumption that the maximum impact force and the maximum drag or planing force occur at the same instant of time, and that these forces act in the same direction.

The correlation study described in Section 5.4 indicated that loads on the sponson and panel were essentially quasi-static in character, thus justifying the decision to compare distributions of total (hydrodynamic) impact forces directly with (structural) design load values provided by GKN WHL. These comparisons may be used to assess the cost-effectiveness of possible design changes to improve crashworthiness.

Design loads for the sponson in the vertical, fore-aft and transverse directions were therefore superimposed on relevant distributions of maximum impact forces, and are shown in each figure as three vertical bars. No attempt was made to calculate the directions associated with individual impact forces, and all three design load values are therefore shown in the figures. The design load for the fuselage panel, based on maximum design pressures, was superimposed on corresponding panel force distributions.
Table 6.2 summarises results from all calculations on the sponson in the form of a single table. Table 6.3 summarises corresponding results for the fuselage panel. These tables show whether each individual parameter change resulted in a general increase (+) or decrease (−) in impact loading across the entire range of the distribution, or whether the changes in loading were insignificant or variable (∼). One such symbol (+, − or ∼) indicates a small change in impact loads, two symbols (++ or ∼∼) indicates a more substantial change, and three symbols (+++ or ∼∼∼) indicates a large change. Three symbols therefore indicate high sensitivity to a change in the relevant parameter, whereas one symbol indicates little or no sensitivity.

These symbols were chosen on the basis of the visual appearance of the distribution, rather than on any calculated difference parameter. Differences occurring in the upper and lower tails of the distributions were generally ignored when making this assessment. A change of less than about 10% in maximum impact loads was generally regarded as insignificant, and a change of more than 20% was regarded as large in this context.

Bearing in mind the different formulations adopted for estimating impact loads on the sponson and fuselage panel, there is a remarkable level of consistency between the two sets of results.

Impact load distributions obtained from simulations in calm water were compared with those obtained in base case conditions (i.e. all-year central North Sea waves). Wave conditions had a significant effect on the load distributions obtained in ditching and fly-in incidents, but relatively little effect on distributions obtained in vertical descent and loss of control incidents. Ditching and fly-in generally involve relatively high forward speeds and shallow descent angles, and the sea state was expected to have a significant effect on maximum impact loads in these circumstances. As expected, waves tended to increase the range of possible loads. The vertical descent and loss of control scenarios typically involved lower forward speeds, higher vertical speeds and steeper angles of descent, and the sea state was expected to be less important in these circumstances.

Increasing the mean speed on impact caused a major increase in the impact load in all cases. This is because the maximum impact load depends on the square of the relative velocity at the instant of impact.

Increasing the drag coefficient resulted in a major increase in loads experienced by the sponson in all conditions. The same percentage increase in planing loads on the fuselage panel resulted in a somewhat smaller increase in total impact loads, mainly in the controlled ditching and fly-in scenarios. The importance of drag and planing forces was not anticipated at the start of the project, and the present model represents these in a highly simplified and approximate manner. This model is probably sufficient to show the relative importance of drag, planing and impact loads, but may not represent accurate numerical values.

Increasing the mean descent angle also resulted in increased impact loads. Increasing the mean pitch angle had a more variable effect. It increased loads on the sponson and fuselage panel during controlled ditching and fly-in incidents, but not during vertical descent or loss of control incidents.
As expected, an increase in the standard deviation of an input parameter generally broadened the resulting impact load distribution, resulting in a wider range of possible loads.

Changes in a single parameter often seemed to have relatively little effect on the shape of the probability distribution. Lack of sensitivity does not necessarily mean that this parameter is unimportant, because the variability in the load often comes from the combined effect of several such parameters. The results are generally insensitive to changes in the value of the standard deviation of any single parameter. This clearly does not mean that the same results will be obtained if all parameters are set at their fixed mean values. It merely shows that no single parameter dominates the spread of the distribution.

The effects of doubling the mean value and standard deviation of the wave heading angles (assumed during vertical descent, loss of control and fly-in incidents) were also considered, even though these cases were not part of the agreed scope of work, and are therefore not listed in Table 6.1. The resulting impact load probability distributions were almost indistinguishable from the base case distributions, confirming that the assumed base case parameters adequately represented randomly chosen wave headings.

The probability distributions often approach a limit less than 1.0 as the force tends to zero. This simply indicates that the sponson or panel in question sometimes fell ‘upside down’, or else the random sampling procedure sometimes resulted in a non-physical parameter value (e.g. a ‘negative’ impact force coefficient). The impact force on a fuselage panel would genuinely be zero if it fell ‘upside down’, because it would then be sheltered behind the hull. The situation is less clear for a sponson, although this too would probably experience a much reduced load if it were sheltered behind the hull on impact. In all such cases the impact force was set to zero, resulting in a step change in the exceedance probability distribution at this point. These zero values were included in the exceedance distribution analysis because they either represented events that genuinely resulted in zero or small impact loads, or else represented valid (though non-physical) samples from the specified distributions of input parameters.
<table>
<thead>
<tr>
<th>Parameter variation</th>
<th>Controlled ditching</th>
<th>Vertical descent</th>
<th>Loss of control</th>
<th>Fly-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Calm water</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~~~</td>
</tr>
<tr>
<td>2. Mean speed × 1.2</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>3. St dev speed × 1.5</td>
<td>~</td>
<td>~</td>
<td>~~~</td>
<td>~~~~~</td>
</tr>
<tr>
<td>4. Mean descent angle × 1.2</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>~</td>
</tr>
<tr>
<td>5. St dev descent angle × 1.5</td>
<td>~</td>
<td>~</td>
<td>~~~</td>
<td>~</td>
</tr>
<tr>
<td>6. St dev roll × 1.5</td>
<td>~</td>
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<td>7. Mean pitch + 2 deg</td>
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**Key:**  
+++ large increase, ++ moderate increase, + small increase  
---- large decrease, -- moderate decrease, – small decrease  
~~~ major variation, ~~ moderate variation, ~ little or no variation
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<th>Vertical descent</th>
<th>Loss of control</th>
<th>Fly-in</th>
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</thead>
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<td>5. St dev descent angle × 1.5</td>
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**Key:**  
+++ large increase,  
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---- large decrease,  
--- moderate decrease,  
-- small decrease  
~~~ major variation,  
~~ moderate variation,  
~ little or no variation
TWO-FLOAT REDUNDANCY STUDY

7.1 Scope of Work

The two main stages of this investigation, described in Sections 5 and 6, considered impact loads on a single fuselage panel or sponson in isolation, and were therefore concerned with risks to a particular item of flotation equipment, rather than risks to the helicopter and its occupants as a whole.

The risk to the helicopter as a whole depends on many additional factors, including levels of redundancy and independence between flotation units. The following calculations were performed to demonstrate the principles and potential benefits of having some degree of redundancy between flotation units. In this simplified example the helicopter was assumed to have only two flotation units: one on each side of the craft.

The ‘no redundancy’ scenario was assumed to represent the situation where both units have to remain intact, whereas the ‘one unit redundant’ scenario represented the situation where only one unit is needed to keep the craft afloat. The following calculations demonstrated that the risk of failure of both units simultaneously may be significantly lower than the risk of failure of a single unit in isolation, whereas the risk of failure of either one of two units may be correspondingly higher than the risk of failure of a single unit.

The main investigation (Section 5) considered impact loads on a starboard panel or sponson only. Impact load distributions for the port panel were expected to be identical to those obtained for the starboard panel, because the scenario itself is essentially symmetric. The mean yaw and roll angles of the helicopter were zero, and the forward and backward faces of the wave surface were symmetric. The calculations presented below did in fact confirm that impact loads on the port and starboard fuselage panels had identical probability distributions.

Impact loads occurring on port and starboard panels during any individual impact event are different, however, depending on the roll and yaw angles of the helicopter, and on the wave slope at the instant of impact. This means that the probability of system failure depends on whether it is based on failure of a single flotation unit alone, failure of either one of the two units, or failure of both units simultaneously.

In the ‘no redundancy’ scenario, the system fails if the load on either unit exceeds its design value. This scenario may therefore be characterised by constructing a probability distribution based on the maximum of the loads experienced by the two units during each individual impact event.

In the ‘one unit redundant’ scenario, however, the system fails only if the loads on both units exceed their design values. This scenario may therefore be characterised by constructing a probability distribution based on the minimum of the loads experienced by the two units during each individual impact event.

The following four exceedance probability distributions of maximum impact loads were therefore calculated and compared:
• impact loads on the starboard flotation unit alone;

• impact loads on the port flotation unit alone;

• maximum loads experienced by either of the two units (representing the ‘no redundancy’ scenario, where both units are necessary to keep the helicopter afloat);

• minimum loads experienced by either of the two units (representing the ‘one unit redundant’ scenario, where one unit alone is sufficient to keep the helicopter afloat).

7.2 Impact Loads on Sponsons

In BMT’s simulation model the port and starboard sponsons are identical, and are symmetric about their centralines. The simulation model therefore predicts identical impact loads on both the port and starboard sponsons during any individual impact event. This means that if one sponson fails during a particular impact event, then so too does the other. The risk of one sponson failing on its own is therefore the same as the risk of both sponsons failing simultaneously. According to this simplified model, there is no benefit from having redundancy in the system or avoiding common failure modes. The risks to the flotation system and to the helicopter as a whole are determined by the risk of failure of a single sponson.

These conclusions are a direct consequence of artificial assumptions made within the theoretical model. Different loads would be experienced by the two sponsons of a real helicopter, and this would in practice affect the probability of survival, depending on whether both sponsons have to remain intact, or one alone is sufficient. Some benefit is therefore to be expected in practice from having redundancy in the flotation system, and in avoiding common failure modes.

7.3 Impact Loads on Fuselage Panels

The simulation model predicts different loads on the port and starboard panels of a fuselage-mounted system, however, and the results show that there are significant differences between risks of failure, depending on whether both panels have to remain intact, or one alone is sufficient. Probability distributions of impact loads were calculated on the port and starboard panels individually, and also based on the maximum and minima of the two, using exactly the same sequence of impact events in all four cases. The sequence of impact events was identical to that already chosen for earlier base case and sensitivity studies.

Figure 82 compares the four resulting exceedance distributions of maximum impact loads in the controlled ditching scenario. The load distribution for the ‘starboard panel’ alone is identical to that obtained during the base case study. As expected, the results for the ‘starboard panel’ and ‘port panel’ alone are almost indistinguishable.

The distribution identified as the ‘maximum of the two’ always lies well above the first two curves, because it is based on the higher of the impact loads occurring on the port and starboard panels during each impact incident. This distribution is used to characterise the probability of system failure in circumstances where survival of the system as a whole depends on both panels remaining intact.
The distribution identified as the ‘minimum of the two’ always lies well below all the others, because it is based on the lower of the impact loads occurring on the port and starboard panels during each impact incident. This distribution is used to characterise the probability of system failure in circumstances where survival depends on only one panel remaining intact.

Figures 83, 84 and 85 show similar sets of results obtained in scenarios representing fly-in, loss of control and vertical descent incidents respectively.

7.4 General Conclusions from Two-Float Redundancy Study

The above calculations are based on results from an analysis where the flotation comes from two fuselage panels mounted on either side of the helicopter. They demonstrate that there is a significantly higher risk of helicopter loss if survival depends on both fuselage panels remaining intact, compared with a situation where a single intact panel is sufficient to keep the helicopter afloat. In the latter case the crashworthiness of the flotation equipment may be enhanced significantly by eliminating sources of common-mode failure between the two flotation units.

The simplifications implicit in this model should be borne in mind when interpreting these results. The effects of hull shielding are, in particular, treated in a very simplified manner. The sponsons are assumed to be far enough from the hull to experience no benefits from shielding. The model therefore predicts identical loads on both sponsons and no benefits from sponson redundancy. The loads on two sponsons of a real helicopter would be different in practice, and sponson redundancy should therefore provide some benefit. The fuselage panels in BMT’s model are assumed to be part of the hull, and are assumed to be totally protected if impact occurs while they are inclined upwards, away from the water surface. Once again this represents a very simplified way in which to treat what is really a very complex hydrodynamic phenomenon. The results from this study should therefore be regarded as indicative, rather than being a precise quantitative measure of the benefits of redundancy.

The above results may be generalised further without running actual simulations. In cases where the helicopter has more than two flotation units, it should be possible to enhance crashworthiness by having more redundancy in the flotation system, and by avoiding common-mode failures between separate units. Compared with a situation where all four units out of four have to remain intact, for example, the chances of survival are better if the helicopter is able to remain afloat with three out of four units intact, and better still if two out of four units are sufficient. There is a law of diminishing returns, however, because it may be expensive to provide additional independent buoyancy units. A cost/benefit analysis would therefore be needed in order to decide on the most cost effective arrangement.

Results from a more realistic redundancy study, based on a helicopter with either four, five or six flotation units, may be found in Section 9.
DATA INTERPRETATION AND APPRAISAL STUDY

The earlier sensitivity study (Section 6) showed that the helicopter’s forward speed and descent angle on impact were two of the most significant parameters determining the maximum impact load. Impact velocity scatter plots were therefore constructed, bringing together results from simulations based on ditching, vertical descent, loss of control and fly-in incidents, and showing the helicopter's vertical and horizontal velocities during each individual impact event along the vertical and horizontal axes respectively. These scatter plots showed which individual events caused loads less than and greater than the design value, and were used to identify relationships between the flotation unit failure rate (expressed as a percentage of the total number of impact events) and the helicopter's speed on impact. Once again, the impact forces were characterised by maximum loads on an individual sponson or fuselage panel, and the four incident scenarios were those considered during the main base case study (Section 5).

This analysis assumed implicitly that all four types of incident are of equal importance. Equal numbers of each type of incident (4,000) were included in the analysis.

8.1 Base Case Conditions

8.1.1 Sponson Impact Loads

Figure 86 shows the velocity scatter plot obtained from simulations of maximum impact loads on the sponson in the four base case scenarios defined in Section 5.3. This scatter plot shows the first 4,000 impact events from each of the four simulation runs, representing ditching, vertical descent, loss of control and fly-in incidents. These data points have been split into two groups:

- green points indicate impact events where the maximum load was less than the design value,
- red points indicate impact events where the maximum load was greater than the design value.

The design value in this case was chosen to be the lowest (164 kN) of the three (fore-aft, vertical and transverse) design forces specified by GKN WHL for the sponson support struts. These three values are discussed in Section 5.3.5.

Four clusters of points may be seen in Figure 86:

- a compact group with horizontal velocities less than about 20 m/s, and low vertical velocities, representing ditching events,
- a further well-defined group, covering a small range of vertical velocities less than about 5 m/s, and a broad range of horizontal velocities, representing fly-in events,
- a broad cluster of points, with high vertical velocities, and moderate horizontal velocities of less than about 10 m/s, representing vertical descent events,
• a scatter of points, covering a broad range of vertical and horizontal speeds, representing loss-of-control incidents.

Two further curves are shown on this figure:

• a blue rectangular boundary, representing the ditching velocity limits specified in reference [9], with maximum forward and vertical speeds equal to 15.2 m/s (50 ft/s) and 1.5 m/s (5 ft/s) respectively;

• an elliptical curve, outlined in paler blue, which represents a boundary proposed by the Federal Aviation Authority (FAA) in Figure 5 of reference [9], within which 95% of human occupants should survive a crash onto water, according to the FAA’s accident statistics.

As noted in Section 5.4, very few ditching events caused impact loads above the design value.

Green points (impact loads below the design value) obtained during fly-in events tend to lie towards the bottom left side of the cluster, and red points (impact loads above the design value) tend to lie towards the top right side, but there is a broad area of overlap between these two distributions.

There is even more overlap between the distributions based on vertical descent and loss of control events, where the areas covered by red and green points are almost indistinguishable. This overlap occurs because impact loads depend on many parameters other than the helicopter’s vertical and horizontal velocities. They depend in particular on the helicopter’s attitude at the instant of impact, and this was highly variable during vertical descent and loss of control scenarios. Waves also caused some scatter in the distributions.

As noted earlier, the analysis was based on loads experienced by an individual sponson, and took no account of loads on the helicopter’s hull as a whole. Points lying in the upper right hand area of the figure represent severe impact events, which would cause a major hull failure, even though the present model suggests that an individual sponson would survive. In many of these cases the sponson survived simply because it entered the water in an axial direction, and the simulation model does not represent axial loads.

Figures 87 and 88 show the same information as Figure 86, but separated into points lying below and above the design value. From a practical viewpoint, the only points of concern are those lying above the design value. These points are shown in Figure 88, and will be regarded as ‘failure’ cases in the discussion below.

8.1.2 Impact Severity Index Curves

Elliptical curves were drawn on Figure 88 to provide a simple means of classifying impact events according to their severity, based on the observation that impact severity and survivability tend to depend more on the helicopter’s vertical velocity than on its horizontal velocity. The Brent Spar and Scilly Isles accidents were regarded as being two especially severe but survivable events. For present purposes these two events were regarded as being of comparable severity. Mean estimates of the vertical (22 m/s) and horizontal (46 m/s) impact speeds of the helicopters involved in the Brent Spar and Scilly Isles accidents were therefore used to define the
vertical and horizontal semi-axes, respectively, of a base case ellipse represented by
the chain-dotted curve in Figure 88. A number of further concentric ellipses were
then constructed (shown as dotted lines in Figure 88) by multiplying the semi-axes of
the base case ellipse by factors ranging from 0.1 to 1.4. These factors were then used
to define a simple ‘impact severity index’, with points around the boundary of each
eLLIPSE being regarded as being of comparable severity. Relationships between the
number of float failures and the impact severity index were then investigated by
counting up the number of failure cases within each of these elliptical boundaries.

The FAA’s 95% survivability boundary lies between curves corresponding to impact
severity index values 0.3 and 0.4. Very few failure cases lie within the FAA’s 95%
survivability boundary (significantly less than 5% of the total number of simulated
impact events). Incidents occurring within the FAA’s boundary may therefore be
regarded as moderate impact events.

Impacts occurring beyond impact severity index 0.7 are considered to be severe, and
impacts occurring beyond severity index 1.0 are generally likely to be unsurvivable.
The greatest benefits in terms of crashworthiness are likely to come from increasing
the survivability of floats when the impact severity index lies between 0.7 and 1.0.

8.1.3  Fuselage Panel Impact Loads

Figures 89 to 91 show corresponding results obtained from simulations of impact
loads on the fuselage panel in the four base case impact scenarios. Once again the
green points correspond to impacts where the load on the panel was less than the
design value (21.3 kN) defined in Section 5.3.6, and the red points denote ‘failure’
cases where the impact load was greater than the design value.

The results are broadly similar to those obtained from simulations of loads on the
sponson, although a smaller percentage of impact events resulted in failure of the
fuselage panel. Once again, very few failures occurred during ditching events, and
fly-in failures tended to occur at relatively high horizontal speeds. It is not clear,
however, whether the model represents fly-in loads adequately, and the results from
the fly-in simulation therefore have to be treated with caution.

Results obtained from simulations of vertical descent and loss of control scenarios
again show a broad area of overlap between points corresponding to loads above
and below the design value. A significant number of green points, corresponding to
impact loads below the design value, occur at very high vertical and horizontal
impact speeds. A number of these cases represent events where the panel was on the
protected side of the hull (i.e. on the side away from the point of impact), and
therefore experienced no loading. As noted earlier, the analysis considered loads on
a single panel on one side of the helicopter’s nose in isolation, ignoring loads on the
remainder of the hull. In many of these cases the hull itself would fail, even though
the analysis suggests that an individual panel will survive.

8.2  Calm Water Conditions

Figures 92 and 93 show corresponding impact velocity scatter plots for cases
representing sponson and panel failure in calm water.

Study II  41
Comparing these two figures with those obtained in corresponding central North Sea wave conditions (Figures 88 and 91), the calm water results show very few failure cases in the lower left area of the scatter plots. Ditching caused no impact loads above the design value. Fly-in speeds less than 30 m/s also caused relatively few failures. As noted earlier, however, the procedures for calculating impact loads in high forward speed conditions may not be accurate or reliable, and the results should again be treated with caution.

Once again the results show considerable scatter in results obtained during vertical descent and loss-of-control scenarios, where the impact load generally depended on the helicopter's attitude at the moment of impact rather than on the sea state.

8.2.1 Failure Case Distributions

The number of failure cases within each impact severity index curve was then counted, in order to determine the percentage of failure cases (relative to the total number of incidents) as a function of the impact severity index. Figure 94 compares percentages of sponson failure cases in both base case and calm water conditions, and Figure 95 shows corresponding results for the fuselage panel.

The sponson / panel failed on less than 5% of occasions when the impact severity index was less than 0.6 / 0.7 respectively. The failure probability distributions level off at high values of the severity index, simply because the number of incidents at high levels is small. Only 47% / 30% of all incidents resulted in sponson / panel failures respectively.

The base case and calm water curves are almost indistinguishable in both Figures, showing that overall (i.e. considering all four types of incidents together, and incidents randomly distributed throughout the year) the sea state had little effect on the probability of failure. The waves are nonetheless likely to have a significant effect on the impact load occurring in certain types of incident scenario, and in severe wave conditions.

8.3 Increased Design Load

Figures 96 and 97 show the velocity scatter plots obtained when design loads on the sponson and fuselage panel were increased by 100%. A 100% increase in the design load would generally require major modifications to the design and operational capability of the helicopter, and would therefore have major cost implications. Any such increase in design loads would therefore only be justified if it resulted in a correspondingly large crashworthiness benefit for the emergency flotation system.

These two figures show no failures during ditching events, and very few failures during fly-in events. As noted above, however, the results obtained from the fly-in scenario should be treated with caution. The number of failures has also reduced significantly during loss of control and vertical descent incidents, although the number of failure cases remains large when the vertical velocity exceeds about 7 to 10 m/s.

8.3.1 Failure Case Distributions

Relationships between float failures and the impact severity index were again assessed by counting the number of failure cases within each impact severity index
curve. Figures 98 and 99 compare the distributions obtained using base case design loads with those obtained when these loads were increased by 100%. As expected the total number of failure cases fell significantly: from 47% to 30% of the total number of impacts for the sponson, and from 30% to 20% for the fuselage panels.

The simulation model predicts that the sponson or panel will often survive in high speed impact conditions. Many of these high speed impacts would not be survivable in practice by human occupants. It was therefore considered more meaningful to judge improvements in crashworthiness in terms of the change in the impact severity index at which 95% of panels and sponsons survived (i.e. with a 5% level of float failures). Figures 98 and 99 show that the relevant value of the impact severity index increased from about 0.65 to 0.75 for both the sponson and panel. This means that a 100% increase in design loads resulted in only about 15% increase in the impact severity index associated with 5% of failures. This represents a poor gain in crashworthiness when considered in relation to such a major increase in design loads.

8.4 Results from Two-Float Redundancy Study

Section 7 describes results from a preliminary investigation into redundancy between floats installed under two fuselage panels, on the port and starboard sides of the helicopter. This investigation suggested that there might be crashworthiness benefits if the flotation unit under a single panel were sufficient to keep the helicopter afloat, over the situation where both flotation units have to remain intact.

The results from this preliminary investigation have now been assembled together in the form of velocity scatter plots. In the ‘no redundancy’ scenario, both panels have to remain intact on impact if the helicopter is to remain afloat. In this case an impact results in a ‘failure’ if either of the two fuselage panels fails. In the ‘one panel redundant’ scenario, a single panel is sufficient to keep the helicopter afloat. In this case a ‘failure’ (shown as a red cross) only occurs if both panels fail.

The resulting failure case scatter plots are shown in Figures 100 and 101. There are very obvious differences between these two scatter plots, which show a very significant reduction in the number of failure cases when only one panel is necessary for survival, compared with the ‘no redundancy’ scenario. This is particularly true at low and moderate impact speeds, which are considered to be the most survivable.

8.4.1 Failure Case Distributions

The number of failure cases within each severity index curve was again counted. The results are presented, as previously, in the form of failure case percentages as a function of the impact severity index.

Results from the two-panel redundancy study are shown in Figure 102. As indicated by the scatter plots, there are major reductions in the number of failure cases if only one out of the two panels is sufficient to keep the helicopter afloat, compared with the situation where both panels must remain intact. There are also major reductions compared with the failure rate for a single panel on its own. This is because many impact events caused one panel or the other to fail, but not both.

This analysis took no account of structural failure of the hull as a whole, however, and inevitably overestimated the number of survivable events at high impact speeds.
The analysis nonetheless suggests that, at the more realistic velocities associated with a 5% failure level, the impact severity index increases from about 0.6 to about 0.9, representing a significant enhancement in the level of crashworthiness.

9 **EH101 MULTI-FLOAT REDUNDANCY STUDY**

The main objective of this final stage of the investigation was to find out whether there are likely to be significant benefits, in terms of crashworthiness, from having redundancy between either four, five or six flotation units.

This phase of the work was originally envisaged as a simple extension of the two-float redundancy study described in Section 7, based simply on considering the number of floats remaining intact after impact, regardless of their location or size. After discussion, however, it was agreed that the study would be more realistic and would have greater practical value if:

- the model was based on the helicopter type (WG34/EH101) and flotation configuration previously tested in the HTC model basin [31];

- the analysis considered whether the floats remaining intact after an impact were sufficient to:

  (a) allow the helicopter to remain floating at the surface, albeit inverted,

  (b) enable the helicopter to float on its side,

  (c) provide a satisfactory air space in the cabin.

A conventional four-float arrangement was considered first. The floats were arranged as on the **EH101**, with two floats at the nose and the other two (main) floats located in sponsons attached directly to the hull. It was assumed that a four-float helicopter would always capsize and become inverted after impact, leaving the floor level at or below the water surface, and the cabin totally submerged. In these circumstances the occupants have little time to re-orient themselves and escape, because there is little or no air space in the cabin.

There will only be a satisfactory air space in the cabin, sufficient to allow the occupants to take breath before escaping, if the helicopter floats on its side (see Section 9.3). The benefits of adding either one or two extra floats on the upper cabin walls were therefore investigated. These asymmetric (five-float) and symmetric (six-float) configurations not only provide redundancy but also enable the helicopter to float on its side after capsize, usually with a satisfactory air space in the cabin, thereby improving chances of escape and survival. The dimensions and locations of these extra floats were based on ‘long units’ which had been model-tested at HTC [31], and had shown some promise in terms of providing a side-floating attitude after capsize.

As in earlier stages of this investigation, it was assumed that the floats would only deploy after impact with the water surface. A float was deemed to ‘fail’ if the impact force on its covering panel exceeded the design load. Each float was treated as a single entity, ignoring any internal sub-compartmentation. Consequences of hull damage, failure of the float itself and associated equipment were not considered.
9.1 **Panel Definition**

Tables 9.1 to 9.3 summarise the dimensions of the cover panels on all three different types of float, together with their inclinations and failure loads.

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<thead>
<tr>
<th>Table 9.1: Summary of forward panel parameters.</th>
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<td>Inclination about roll axis</td>
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<td>Inclination about pitch axis</td>
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<tr>
<td>Inclination relative to forward direction</td>
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<td>Design maximum load</td>
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<th>Table 9.2: Summary of main (sponson) panel parameters.</th>
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<td>Inclination about roll axis</td>
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<td>Design maximum load</td>
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<th>Table 9.3: Summary of upper cabin panel parameters.</th>
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<td>Length</td>
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<tr>
<td>Inclination about roll axis</td>
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<tr>
<td>Inclination relative to forward direction</td>
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<td>Design maximum load</td>
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</table>

It was considered adequate to estimate the dimensions of the forward and main (sponson) panels from photographs of the *EH101* helicopter [30]. Upper cabin floats do not exist on present-day helicopters, and so the dimensions of the upper cabin panels had to be estimated from the dimensions of the ‘long’ inflated floats.
considered during the HTC model tests [31]. The panel length and height were assumed to be equal to half the length and half the height of the inflated unit. ²

The orientations of the panels were also estimated from photographs. The sponson panel was assumed to be exactly vertical and parallel to the helicopter's longitudinal axis. The forward panel was assumed to be inclined downwards and forwards, with angles similar to those assumed during the earlier Sea King study (see Section 5.3.6). It seemed reasonable to assume that the upper cabin panel would be parallel to the helicopter's longitudinal axis, and inclined slightly upwards by 10 degrees. This panel was assumed to be flat despite its considerable length (3.1m).

Each panel was assumed to fail if the impact pressure exceeded 0.1288 N/mm². This failure pressure was the value supplied by GKN WHL in connection with the earlier Sea King study (see Section 5.3.6). The maximum design load on each panel was then equal to the failure pressure times the panel area.

9.2 Hull and Flotation Unit Buoyancy

9.2.1 Hull Buoyancy

The helicopter was assumed to float (or sink) depending on whether the total buoyancy from the hull and flotation units was greater than (or less than) the helicopter's weight. The main complication here was in deciding how much buoyancy should be attributed to the hull. Initial calculations showed that the buoyancy of the EH101 hull was significant and could not be ignored, even when all internal air spaces were flooded. The buoyancy of the hull will depend in practice on the amount of damage sustained in a crash, but it was not practical to take such variations into account. The hull buoyancy was therefore assumed to remain constant throughout, and was estimated from the displacement of the airframe and fuel tanks, assuming that all other internal spaces would flood.

The aim here was to obtain a realistic estimate of hull buoyancy, but one that erred slightly on the low side so as to increase slightly the predicted probability of sinking.

Two further assumptions, that the fuel tanks were full and remained intact on impact, were considered to have the following effects:

- An empty (or partially full) intact tank provides the same buoyancy as a full tank, but weighs less. Assuming a full tank therefore overestimated its net weight, slightly increasing the predicted probability of sinking.

- A ruptured tank tends to lose weight and buoyancy at similar rates, because aviation fuel is only slightly less dense than water, and lost fuel is replaced by the same volume of water. Assuming an intact tank would therefore have little effect on the predicted probability of sinking.

Previous studies had suggested that tail booms of helicopters often fail on impact with water. Loss of the tail boom was not considered to be an important factor in this study, however, because of its relatively small effect on the helicopter's net weight in water.

² Based on the dimensions of existing panels and floats on the EH101, where this ratio varies between 0.36 and 0.53.
Four alternative estimates of hull buoyancy were made, designated as follows:

- **Naval estimate**: 8,164 kg
- **Weight estimate**: 6,971 kg
- **Commando light weight estimate**: 6,421 kg
- **Combination estimate**: 5,474 kg.

The *naval estimate* came directly from a GKN WHL report on the naval version of the EH101 [32]. Certain parts of the helicopter were assumed to flood in GKN WHL’s analysis, and were not included in their buoyancy estimate.

The *weight estimate* was based on two values of the helicopter's weight quoted in an EEL report [33] for the civilian version of the EH101: 14,290 kg with the fuel tanks full, and 12,839 kg with them half full. This means that the weight of the full fuel tanks was 2,902 kg, and their buoyancy was therefore 3,718 kg. The light weight of the EH101 was estimated by subtracting the fuel weight and the weight of 25 people (each assumed to have an average weight of 100 kg) from the total helicopter weight (i.e., 14,290 - 2,902 - 2,500 = 8,888 kg). This estimate is very close to the operating weight when empty (8,993 kg) quoted by the helicopter designers [30]. Assuming that the average density of the airframe was that of aluminium, the airframe buoyancy was estimated to be 3,253 kg. The combined buoyancy of the airframe and full fuel tanks was then 6,971 kg.

An average airframe density had to be assumed, because no weight breakdown was available. Certain items, such as the main rotor, gear box and engines, are made of steel and are therefore much denser than aluminium. On the other hand certain other items are made of plastic, which is a less dense material. On average it therefore seemed reasonable to assume that the average density of the airframe would be that of aluminium.

The *Commando light weight estimate* came from a report on model ditching tests on the WG34 [34]. In this report the Commando version was stated to have a light weight of 16,281 lb. Assuming again that the airframe had the same average density as aluminium, and adding the buoyancy of the fuel tanks calculated using the method explained above, the total buoyancy was estimated to be 6,421 kg.

The *combination estimate* was based on a breakdown of buoyancy elements quoted in the naval EH-101 report (see *naval estimate* above) and the fuel buoyancy estimate (from the *weight estimate* above). All items relating to the fuel tank were subtracted from the naval estimate, giving a buoyancy equal to 1,756 kg. The fuel tank buoyancy found by the second method (3,718 kg) was then added, giving a total buoyancy equal to 5,474 kg.

There are substantial differences between the above four buoyancy estimates, but some are likely to be more reliable and relevant than others. The *naval, Commando light weight and combination estimates* are all based on military versions of the EH101, and may therefore represent variants with different weights and buoyancy. The *weight estimate* is probably the most relevant and reliable because it is based on documented all-up and fuel weights for the civilian version of the EH101. After discussion, however, it was agreed that a lower value should be assumed: making the combined buoyancy of the airframe and full fuel tanks equal to 6,000 kg. This value lies towards the lower end of the above range of estimates, and was considered to provide a conservative (i.e. pessimistic) view of flotation system requirements. The
aim of choosing a low value of hull buoyancy was to increase the relative importance of the floats, and increase the number of failure cases obtained from the analysis.

9.2.2 Float Buoyancy

The buoyancy provided by each float was assumed to be identical to the value stated in the HTC model test report [31]. The buoyancy of each forward float was 1,630 kg. That of each main float was 3,864 kg, and that of each upper cabin float was 4,058 kg.

9.3 Float Failure Consequences

A ‘consequence table’ was constructed, in order to describe the outcome of each combination of float failures. There are 64 (= 2^6) possible float failure combinations when six floats are installed, although symmetry reduces the number of different possibilities to 32. When only five or four floats are installed, the consequence table is a simple subset of the six-float table.

With only four conventional flotation units the helicopter cannot float on its side. There are only two possible outcomes in this case: the helicopter may either float or sink after impact.

Additional ‘consequence classes’ have to be considered, however, when five or six floats are installed. These classes distinguish between whether the floats remaining intact after each simulated crash event either:

(i) provide insufficient buoyancy, causing the helicopter to sink,

(ii) allow the helicopter to remain floating at the surface, albeit inverted,

(iii) enable the helicopter to float on its side,

(iv) provide a satisfactory air space in the cabin.

It was not always easy to predict the attitude of the helicopter after a crash, or to decide which attitudes represent side-floating conditions. The helicopter's attitude in the water could have been assessed by carrying out a hydrostatics analysis, but this option was rejected partly on grounds of cost, and partly because of the uncertain effects of internal flooding. It was therefore agreed that it would be adequate to assess the outcome of each panel failure scenario in a subjective manner. Most scenarios have a fairly obvious outcome, but six scenarios with less obvious outcomes are identified below.

Table 9.4 represents BMT’s best subjective assessment of the consequences of panel failure, and Figure 103 shows the float numbering system used during this analysis. This table should be interpreted as follows:

- When a cell below a Bag x column is red, it means that the relevant float has failed. A green cell means that the float is intact.

- ‘Sy&. Buoyancy’ represents the total available buoyancy of the helicopter’s hull plus remaining intact floats.
• The next three columns of the table represent the helicopter’s attitude with the particular combination of float failures indicated. If the cell in the first of these columns, labelled ‘sink’, is red, then the helicopter will sink. The helicopter will stay afloat if this cell is green.

• If the cell in the second of these three columns is green, then the helicopter will float on its side. It will invert if it is red.

• If the cell in the third column is green, there will be a satisfactory air space within the cabin.

• Note that if the helicopter sinks (first cell red) then the second and third cells will automatically be red (the helicopter cannot float on its side or provide a satisfactory air space in the cabin). Similarly, if the helicopter does not float on its side, it cannot provide a satisfactory air space.

Assuming that the earlier estimates of helicopter buoyancy and weight are realistic, then it is straightforward to decide whether the helicopter will float or sink. Confidence in this particular outcome is therefore high.

The system buoyancy in Table 9.4 represents the total amount available from the hull and all intact floats. This total is often greater than the weight of the helicopter. This simply means that part of the available flotation lies above the water surface. It is nonetheless fair to include this excess buoyancy in the calculation, because all floats have to sink below the surface, providing their full buoyancy, before the helicopter itself can sink.

There was generally little doubt in deciding whether the helicopter would float on its side. If the helicopter floated at all (this required at least three floats to be intact), then in general only one intact upper cabin float was needed to ensure side flotation. The only exceptions to this rule were cases 25 and 26, which are discussed below.

Most of the uncertainties lay in deciding whether there would be a satisfactory air space. After discussion, however, it was agreed that if an upper cabin float on one side, and a main float situated on the other side of the helicopter, are both intact, then there should generally be a satisfactory air space within the cabin.
Table 9.4: Consequence table based on the six-float configuration.

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</tbody>
</table>

Green cell denotes ‘float intact’ / ‘success’. Red cell denotes ‘failure’.

Study II

50
The outcomes of six scenarios were nonetheless considered to be especially uncertain and subjective, and are discussed in detail below:

- **Cases 25 and 26**: There was some doubt in these two cases about both the size of the air space and whether the helicopter would float on its side. With two upper cabin floats intact, together with one forward float, the final waterline is likely to be at mid-height through the two cabin floats, and most of the cabin would be under water. The forward float would probably provide enough buoyancy either to raise the nose of the helicopter, or to make it incline towards one side. If the helicopter has much of its buoyancy low down, in the area of the fuel tanks, then this too would tend to raise the nose or make the helicopter incline. Having little quantitative information on which to base a decision, however, a pessimistic outcome was assumed: that the helicopter would not float on its side, and in consequence would not provide a satisfactory air space.

- **Case 28, 29, 36 and 37**: In these cases one upper cabin float and the main float on the same side are intact, together with any one of the forward floats. In these four cases it was clear that the helicopter would float on its side, with the final waterline going through the main and cabin floats, with most of the helicopter under water. The question was then whether the forward float would have enough buoyancy to raise the nose, and thereby create a satisfactory air space. Although the cabin floats are likely to provide buoyancy fairly centrally, the main float would provide buoyancy in the aft part of the helicopter. Again, a pessimistic outcome was assumed: that the helicopter would lie on its side, with its nose inclined downwards.

A further conservative assumption was also made: that the helicopter would always capsize after impact, regardless of the type of incident. Past accident statistics [9] show that helicopters have capsized in the majority (80%) of survivable and partially survivable accidents on water. It therefore seemed reasonable to assume that the helicopter would always capsize after a crash. This assumption seemed more questionable in ditching conditions, however, because helicopters are designed to remain upright after ditching in a moderate sea. Whether they do in fact remain upright depends on a number of factors, including the severity of the sea state, the helicopter's attitude as it enters the water and any damage sustained. Representing all these factors would have added to the complexity of the model, without necessarily reducing key uncertainties. Bearing in mind that this investigation was concerned primarily with crashworthiness, and that ditchings represent only a quarter of the incidents in the simulation, accurate modelling of ditching events was considered to be of lesser importance.

The above assumption gives a pessimistic view of the helicopter's crashworthiness in the four-flap base line condition, but may as a result give a slightly optimistic view of the benefits of adding extra floats.

A further element of pessimism lies in the fact that a helicopter takes time to fill with water after a crash, and may remain afloat long enough for survivors to escape, even though simple static buoyancy and weight calculations show that it will eventually sink.
9.4 Results

The results from this investigation were analysed and presented in much the same way as in Section 8. As previously, four different types of water impact scenarios were simulated: controlled ditchings, vertical descent, loss of control and fly-in incidents. Four thousand individual impact events of each type were simulated, using the Monte Carlo simulation and sampling procedures described in Sections 4 and 5. The central North Sea wave scatter table was used, together with distributions of helicopter speed, descent angle, roll, pitch and yaw angles, wave incidence angle and impact force coefficients identical to those assumed in the earlier Sea King study. These distributions are defined in Tables 5.1, 5.3 and 5.5.

Results from these 4,000 simulations of four different types of impact events were then combined together into scatter plots showing the vertical and horizontal components of velocity corresponding to each impact event, and percentage probabilities of ‘failure’ within elliptical impact severity index curves, as described in Section 8. Three different types of ‘failure’ were considered in the analysis: when the helicopter failed to provide a satisfactory air space, failed to float on its side, or failed to float at all.

9.4.1 Criteria for Floating or Sinking

The first aspect investigated was whether the helicopter would float or sink after a water impact. The criterion used here was simply whether the total buoyancy from the hull and intact floats was greater than, or less than the total weight.

The analysis was performed first with a conventional configuration of four floats (two forward and two sponson floats). Figure 104 shows ‘failure’ cases (i.e. where the helicopter sank after impact) from four simulation runs, representing 4,000 separate ditching, vertical descent, loss of control and fly-in events. The red crosses in this figure show the vertical and horizontal components of the helicopter's velocity at the instant of impact, presented in the same form as in Section 8.

As previously there are four separate clusters of points:

- The broad spread of points around the vertical velocity axis corresponds to vertical descent incidents. The majority of these impacts resulted in float failures sufficient to make the helicopter sink.

- A second broad spread of points, near the centre of the figure, corresponds to loss of control incidents. Again, many of these incidents resulted in the helicopter sinking.

- The third cluster, just above the horizontal velocity axis (horizontal velocities between about 30 m/s and 50 m/s), correspond to fly-in incidents. Only a small proportion of these incidents resulted in the helicopter sinking. As previously, however, it should be noted that:
  
  (i) drag and planing loads were modelled in a simplified manner, and may not be represented satisfactorily in fly-in conditions;

  (ii) the analysis only considered direct loads on the flotation panel, and took no account of surrounding hull damage.
• Very few ditching incidents resulted in the helicopter sinking. Failures during ditching are represented by only four crosses at low vertical speeds, with horizontal velocities close to 15 m/s.

The analysis was then repeated with a single upper cabin float added on the starboard side (float 5 in Figure 103). Figure 105 shows incidents in which the helicopter sank with this five-float configuration. Adding one upper cabin float resulted in a substantial reduction in the number of failure cases. All four different types of incident (ditching, vertical descent, loss of control and fly in) benefited from having the additional float, but in varying proportions:

• the helicopter floated after every ditching incident;

• only a small number of fly-in incidents caused sinking;

• sinking occurred less often after vertical descent and loss of control incidents, although a significant number of failure cases remained.

No scatter plot is presented for the six-float configuration, because no ‘failures’ were recorded during any of the simulation runs. At least one main float, one upper cabin float and one other float remained intact on every occasion, providing sufficient buoyancy to keep the helicopter afloat.

Figure 106 shows the percentage of failure cases lying within each impact severity index curve for each float configuration. The solid line represents results obtained with the conventional four-float arrangement. The dashed line represents the five-float system, and the dotted line (along the horizontal axis) a six-float combination. Adding an upper cabin float significantly increased the probability of remaining afloat after a moderate to severe impact. In cases where the impact severity index was less than 0.8, the percentage of impact events in which the helicopter sank reduced from 12% for a conventional four-float system to 3% for the five-float system, and to zero for the six-float combination. Expressed in another way: the impact severity index below which there was a 5% probability of sinking increased from 0.7 to 0.9 when the first upper cabin float was added, and to a point well above the survivability limit when all six floats were present.

9.4.2 Probability of Sinking in a Severe Crash

In their accompanying cost-benefit study [1] WSA estimated that the probability of sinking in a severe (but otherwise partially survivable) water impact accident is about 0.65. This figure was based on accident statistics from the NTSB accident database between 1982 and 1989. Many assumptions had to be made when interpreting the NTSB data, and it was difficult to make a comparison with the results of the present study. An attempt was nonetheless made to find out whether WSA’s estimate was at all similar to the value obtained from the present model by considering the proportion of severe but partially survivable incidents which resulted in sinking with a conventional four-float system. In this context a severe but partially survivable incident was considered to be one where the impact severity index lay between 0.8 and 1.2. The total number of such incidents, from Figure 104, was 5,364, and the helicopter sank on 3,299 of these occasions. Sinking therefore occurred on 61% of occasions. Lowering the upper limit to 1.0 reduced the proportion to 58%, showing that the end result was not unduly sensitive to where the upper limit was set.
The similarity between WSA’s estimate (65%) and that obtained here (61%) is partly fortuitous, bearing in mind the very different underlying assumptions, but obtaining values which were even remotely similar gave some confidence that both estimates might be realistic.

9.4.3 Criteria for Side-Floating

It was assumed, for the purposes of this study, that a helicopter with a conventional four-float system would always capsize on impact. Because the helicopter could never float on its side, every impact event resulted in a ‘failure’.

Adding one upper cabin float gave a significant improvement in the ‘success’ rate, but also gave the somewhat surprising result that if the helicopter floated at all, it always floated on its side. This meant that the ‘failure’ scatter plot for side-floating ability was identical to that for floating ability (Figure 105). Another way of looking at this result is to say that any impact severe enough to damage the (relatively unexposed) upper cabin float also damaged enough other floats to make the helicopter sink.

There is also no difference between results based on floating and side-floating criteria with a six-float system. In this case the helicopter always floated on its side, regardless of the severity or type of impact. No impact caused both upper cabin floats to fail simultaneously, one float always remaining intact to make the helicopter float on its side.

Figure 107 shows the percentage of occasions when the helicopter failed to float on its side within each impact severity index curve. The curves corresponding to the five-float and six-float systems are identical to those shown in Figure 106, but the curve for the conventional four-float system has moved up to 100%.

9.4.4 Criteria for a Satisfactory Air Space

It was assumed, for the purposes of this study, that a helicopter with a conventional four-float system would always capsize and invert on impact. As a result there would never be a satisfactory air space in the cabin, and every impact event resulted in a ‘failure’.

Figure 108 shows incidents in which the helicopter, with a five-float system, failed to provide a satisfactory air space. Most of the results shown in this plot correspond to vertical descent and loss of control incidents, with very few fly-in cases. Figure 109 shows similar results for the six-float system.

Figure 110 shows the percentage of occasions when there was an unsatisfactory air space in the cabin, as the impact severity index varied. The solid line represents results obtained with a conventional four-float system. The dashed line represents a five-float system, and the dotted line a six-float combination. Adding a single upper cabin float greatly increased the probability of having a satisfactory air space in the cabin after a moderate to severe impact. When the impact severity index was less than 0.8, the air space was always unsatisfactory with a conventional four-float system, but on only 7% of occasions with the five-float system, and on 5% of occasions with the six-float combination. Expressed in another way, the impact severity index below which there was 5% probability of having an unsatisfactory air space increased from 0.75 to 0.85 when the second upper cabin float was added.
Measured in these terms, most of the gain in crashworthiness occurred when the first upper cabin float was added. The second upper cabin float resulted in only a small further improvement.

9.4.5 Float Failure Combinations

Tables 9.5 to 9.7 show how many times each panel failure combination occurred during each simulation run, broken down according to the type of impact incident (ditching, vertical descent, loss of control or fly-in). Cells in the first six columns of each table show (in red) the panels that failed and (in green) those that remained intact. Hatched cells indicate that the relevant float was not present (e.g. there were no upper cabin floats in the four-float system). The float numbering system used in these tables is the same as is shown in Figure 103.

Ten out of 16 possible float failure combinations occurred with the four-float system, but only 12 out of a possible 32 occurred with the five-float system, and 13 out of a possible 64 with the six-float system. Other failure combinations did not occur for one or another of the following reasons:

(a) the analysis only considered loading on an individual panel, and did not take account of damage to the surrounding hull and neighbouring panels;

(b) one or other of the two main sponson panels always faced away from the water surface on impact, and it was impossible to fail both simultaneously;

(c) their orientations were such that no more than three panels could face towards the water surface, and therefore fail, during any given impact event;

(d) the two upper cabin panels could only fail simultaneously if the helicopter were to fall onto the water surface upside down at high speed, and this very rare event never occurred.

The next four columns in each table show the number of times each failure combination occurred in 4,000 impact events representing each of the four types of incident. The last column shows the total number of times each failure combination occurred (out of a total of 16,000 impact events) when results from all four types of incident were combined.

Many of the numbers are repeated between one table and another without change. These repeated numbers generally correspond to combinations where an upper cabin float remained intact. Incidents in which an upper cabin float was damaged were not common, and only occurred when the helicopter landed on one side at a steep angle of inclination, leaving the floats on the other side intact.
### Table 9.5: Number of occurrences for each failure combination: four-float configuration.

<table>
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<th>Failure combination</th>
<th>Ditching</th>
<th>Vertical descent</th>
<th>Loss of control</th>
<th>Fly in</th>
<th>Total</th>
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### Table 9.6: Number of occurrences for each failure combination: five-float configuration.

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*Green cell denotes ‘float intact’. Red cell denotes ‘failure’.*
Table 9.7: Number of occurrences for each failure combination: six-float configuration.

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9.5 Conclusions from EH101 Multi-Float Redundancy Study

The objective of this investigation was to find out whether there are likely to be significant benefits, in terms of crashworthiness, from having additional redundant emergency flotation units installed. The benefits were judged in terms of whether the extra units would improve the helicopter's ability to float (inverted), float on its side, or provide a satisfactory air space in the cabin after water impact.

Adding one upper cabin float significantly improved the helicopter's crashworthiness, compared with a conventional four float system. An upper cabin float increased the probability that the helicopter would float, and enabled the helicopter to float on its side, which in most cases also provided a satisfactory air space in the cabin.

Adding a second cabin float improved crashworthiness further. It prevented sinking and inversion completely, at least in the circumstances considered during this study (where the possibility of hull damage was not taken into account). It also increased to some extent the number of occasions when there was a satisfactory air space.

Only a small proportion of the 64 possible float failure combinations occurred during this study. No more than three floats failed in any impact event. It was also rare for an upper cabin float to be damaged, because of its relatively protected location on the cabin wall. An upper cabin float only failed when the helicopter fell onto that side, leaving all floats on the opposite side intact.
Although this study made many simplifying assumptions, the general principles and conclusions seem intuitively to be valid. The study demonstrated that there are clear benefits, in terms of crashworthiness, from having additional floats on the upper cabin walls. Benefits emerged regardless of whether they were measured in terms of reducing the number of occasions when the helicopter sank, making it float on its side, or providing a satisfactory air space in the cabin. The largest improvement came when the first upper cabin float was added.

There are possible advantages in this asymmetric float configuration, because it gives the helicopter a preferred orientation in the water. Model tests at HTC [31] had shown that the six-float arrangement allowed two possible stable orientations of the hull after capsize. With a five-float arrangement, however, there was only one stable attitude, eliminating the risk of a second rotation while the occupants are trying to escape.

10 OVERALL CONCLUSIONS

Detailed conclusions from BMT’s initial investigations have already been presented in reference [2]. Conclusions from BMT’s subsequent sensitivity study, together with investigations based on the Brent Spar and Cormorant Alpha accident scenarios, were presented in reference [3]. The following overall conclusions are based on results from these initial investigations together with follow-up data assessment and float redundancy studies.

Each of the flotation units considered during this investigation was assumed to be mounted within either a sponson or fuselage panel, and was assumed to be uninflated at the moment of impact. The flotation unit was deemed to fail if the impact load on the sponson or fuselage panel exceeded its design value.

Impact, planing and drag forces on the sponson and panel were estimated by combining simple theoretical and empirical load calculation procedures. Exceedance probability distributions of water impact loads were then estimated using a Monte Carlo simulation procedure. This procedure took account of the randomness and variability in the impact scenario and in the loading process. Predicted exceedance distributions of maximum total impact loads were compared with typical design loads for the sponson and panel.

Key conclusions from this investigation were as follows:

- The probability of exceeding design loads in a controlled ditching incident was found to be very low, as had been expected. Flotation equipment is designed to survive a normal ditching.

- The base case investigation showed a relatively high probability of exceeding design loads on both the sponson and fuselage panel during vertical descent and loss of control incidents. This result suggested that substantial increases in design loads would be required in order to avoid major structural damage to flotation systems in these two types of incident.

- A follow-up sensitivity study confirmed that a 100% increase in design loads would result in only a modest improvement in crashworthiness.
• Major structural failures have occurred during actual fly-in accidents in the past. The simulations nonetheless predicted that the risks of exceeding design loads on both the sponson and fuselage panel during a fly-in are relatively low. There are two likely reasons for this unexpected result. Firstly, drag and planing forces make major contributions to the total predicted load during a fly-in. These forces are poorly understood, and the simplified formulae used in the present analysis may not be reliable. Secondly, the model considers loads on an individual sponson or panel in isolation, and does not consider failure of the surrounding hull structure. The design of flotation equipment should in practice consider the design and strength of the supporting hull structure.

• Severe impacts on the fuselage panel were typically associated with small angles of impact between the hull and water surfaces. These very severe impacts may not be modelled satisfactorily by the present procedure, because no attempt was made to represent in detail the effects of air entrapment or acoustic pressure limits.

• Sea state conditions had little effect on the results obtained from the investigation as a whole. They had a significant effect on results obtained in severe sea conditions, however, and increased the range of loads substantially during controlled ditching and fly-in incidents.

• The impact force proved to be sensitive to variations in several different parameters. It may therefore be difficult to characterise helicopter impact incidents in terms of a small number of deterministic scenarios.

• Impact loads were sensitive to variations in the helicopter’s mean speed and descent angle at the moment of impact. The drag force coefficient was also an important parameter. The helicopter’s mean pitch angle and the planing force coefficient only affected loads experienced during ditching and fly-in incidents.

• Investigations into float redundancy demonstrated that there are clear benefits, in terms of crashworthiness, from having additional floats on the upper cabin walls. Benefits emerged regardless of whether they were measured in terms of reducing the number of occasions when the helicopter sank, making it float on its side, or providing a satisfactory air space in the cabin. The largest improvement came when the first upper cabin float was added. There are possible advantages in this asymmetric float configuration, because it gives the helicopter a preferred stable attitude in the water, eliminating the risk of a second rotation while the occupants are trying to escape.

The results from this study suggested a number of further possible conclusions, although these issues were not considered in detail:

• Alternative methods for improving crashworthiness might also be considered, such as designing a ‘crumple zone’ or other energy-absorbing device into the support structure. Whatever solution is adopted, however, the structure must retain sufficient integrity to serve its primary function of providing buoyancy.

• There may be potential for reducing impact loads during a fly-in incident by modifying the shape of the hull or sponson, and avoiding large flat areas.
• The present investigations considered all-year wave conditions in the central area of the North Sea. It is likely that selecting a more severe wave climate (e.g. West of Shetland) would significantly increase the loads predicted during controlled ditching and fly-in incidents. Suitable design criteria would be needed to take account of increases in water impact loading due to waves.

• BMT recommends that further work should be done to investigate the importance of drag and planing type forces in the water impact loading process, and the feasibility of representing these loads better in the calculations. These forces turned out to be more significant than originally anticipated, and simplifications in existing calculation procedures may have resulted in unexpectedly low predicted forces during fly-in incidents.

11 ACKNOWLEDGEMENTS

BMT gratefully acknowledges assistance provided by GKN Westland Helicopters Limited, who supplied design information on the Sea King helicopter, and provided valuable advice and comments during the course of this project. BMT also gratefully acknowledges information provided by WS Atkins Science and Technology for the investigations based on the Brent Spar and Cormorant Alpha accident scenarios.

12 REFERENCES


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KEY NOMENCLATURE

$A$  
area presented to the flow

$a_0$, $a_1$, $a_2$  
coefficients in cylinder impact force equations (4) and (12)

$b_1$, $b_2$  
coefficients in cylinder impact force equations (4) and (12)

$c$  
structure stiffness

$C_d$  
drag force coefficient

$C_{pl}$  
planing force coefficient

$C_{p\text{ max}}$  
maximum pressure coefficient (equation (5))

$C_s$  
impact force coefficient (equation (1))

$C_v$  
variability parameter in panel impact force equation (14)

$F_d$  
drag force on the sponson (equation (28))

$F_{\text{max imp}}$  
maximum impact force on the sponson or fuselage panel (equations (11) and (14))

$F_{pl}$  
planing force on the fuselage panel (equation (30))

$F_{r\text{ max}}$  
maximum structure force in the sponson or fuselage panel assembly (equations (25) and (26))

$F_w$  
maximum non-dimensional panel force calculated using Wagner’s theory (equations (7) and (8))

$D$  
mean diameter of cylinder or cone segment

$g$  
acceleration due to gravity

$H_s$  
significant wave height

$I$  
impulse on the sponson segment or fuselage panel

$L$  
length of the sponson segment or fuselage panel

$S_{\text{lim}}$  
limiting value of significant wave steepness

$S_i$  
significant wave steepness (equation (2))

$t$  
time

$T_{\text{imp}}$  
impact duration

$T_n$  
natural response period of the sponson or fuselage panel assembly

$T_z$  
mean zero up-crossing wave period

$u_b$  
helicopter velocity vector

$u_p$  
relative water particle velocity vector

$u_r$  
relative water particle velocity, resolved normal to structure surface

$u_s$  
relative water surface velocity vector

$u_{sw}$  
relative water surface velocity, resolved normal to structure surface

$u_w$  
water surface velocity vector

$W$  
fuselage panel width

$\alpha$  
inclination of plate to flow (in planing force equation (30))
\( \beta \) angle between the sponson segment axis and water surface on impact
\( \Phi_c \) inclined cylinder impact force coefficient (equation (12))
\( \Phi_g \) non-dimensional cylinder impact force coefficient (equation (4))
\( \Phi_{aw} \) non-dimensional panel impact force coefficient (equation (15))
\( \rho \) water density
\( \xi \) impact angle between the fuselage panel and water surface
\( \xi_{\text{min}} \) minimum value of \( \xi \), used in panel impact force equation (15)
\( \omega_n \) angular natural frequency of the sponson or fuselage panel assembly

**ABBREVIATIONS**

AAIB Air Accidents Investigation Branch
BMT BMT Fluid Mechanics Limited
CAA Civil Aviation Authority
FAA Federal Aviation Authority
GKN WHL GKN Westland Helicopters Limited
HSE The Health and Safety Executive
HTC Hydrodynamic Test Centre
NACA National Advisory Committee for Aeronautics
NTSB National Transportation Safety Board
UK United Kingdom
WSA WS Atkins Science and Technology
Figures
Figure 1: Comparison between the theoretical force history and measured data for horizontal cylinder impacts on smooth water (reproduced from Ridley [20]).

\[ \phi_s = 5.3 \left[ 0.14 + 0.59 \exp(-9.9Vt/D) + 0.27 \exp(-54.9Vt/D) \right] \]

Comparison of the empirical fit with experimental data from Campbell (1982).
Figure 2: Comparison between measured and predicted maximum impact pressures from tests on wedges dropped onto waves (reproduced from Chuang [26]).
Figure 3: Comparison between Wagner and Chuang formulae for the maximum pressure coefficient.

Figure 4: Comparison between the impact force coefficient $\Phi_w(\xi)$ used in the present analysis with that predicted by Wagner's theory.
Figure 5: Typical relationships between helicopter, water surface and relative water particle velocities.

Figure 6: Typical sponson and fuselage panel locations assumed in base case and sensitivity studies.
Figure 7: Plan and side views of the Sea King sponson.
Correlation plots: maximum structure and drag forces against the total impact force on the sponson; all incident scenarios, base case conditions.
Figure 8: Correlation between maximum structure force and total impact force: sponson in controlled ditching incident, central North Sea waves.

Figure 9: Correlation between the drag force and maximum total impact force: sponson in controlled ditching incident, central North Sea waves.
Figure 10: Correlation between maximum structure force and total impact force: sponson in vertical descent incident, central North Sea waves.

Figure 11: Correlation between the drag force and maximum total impact force: sponson in vertical descent incident, central North Sea waves.
Correlation between structure force and total impact force: case SPNL C1

Figure 12: Correlation between maximum structure force and total impact force: sponson in loss of control incident, central North Sea waves.

Correlation between drag force and total impact force: case SPNL C1

Figure 13: Correlation between the drag force and maximum total impact force: sponson in loss of control incident, central North Sea waves.
Figure 14: Correlation between maximum structure force and total impact force: sponson in fly-in incident, central North Sea waves.

Figure 15: Correlation between the drag force and maximum total impact force: sponson in fly-in incident, central North Sea waves.
Correlation plots: maximum structure and planing forces against the total impact force on the fuselage panel; all incident scenarios, base case conditions.
Figure 16: Correlation between maximum structure force and total impact force: panel in controlled ditching incident, central North Sea waves.

Figure 17: Correlation between the planing force and maximum total impact force: panel in controlled ditching incident, central North Sea waves.
Figure 18: Correlation between maximum structure force and total impact force: panel in vertical descent incident, central North Sea waves.

Figure 19: Correlation between the planing force and maximum total impact force: panel in vertical descent incident, central North Sea waves.
Figure 20: Correlation between maximum structure force and total impact force: panel in loss of control incident, central North Sea waves.

Figure 21: Correlation between the planing force and maximum total impact force: panel in loss of control incident, central North Sea waves.
Figure 22: Correlation between maximum structure force and total impact force: panel in fly-in incident, central North Sea waves.

Figure 23: Correlation between the planing force and maximum total impact force: panel in fly-in incident, central North Sea waves.
Correlation plots: impact duration, velocities and angle against the total impact force on the sponson; vertical descent scenario, base case conditions.
Figure 24: Correlation between the impact duration and maximum total impact force: sponson in vertical descent incident, central North Sea waves.

Figure 25: Correlation between the impact velocity $u_p$ and maximum total impact force: sponson in vertical descent incident, central North Sea waves.
Figure 26: Correlation between the impact velocity $u_s$ and maximum total impact force: sponson in vertical descent incident, central North Sea waves.

Figure 27: Correlation between the impact angle $\beta$ and maximum total impact force: sponson in vertical descent incident, central North Sea waves.
Correlation plots: impact duration, velocities and angle against the total impact force on the fuselage panel; vertical descent scenario, base case conditions.
Figure 28: Correlation between the impact duration and maximum total impact force: panel in vertical descent incident, central North Sea waves.

Figure 29: Correlation between the impact velocity $u_p$ and maximum total impact force: panel in vertical descent incident, central North Sea waves.
Figure 30: Correlation between the impact velocity $u_s$ and maximum total impact force: panel in vertical descent incident, central North Sea waves.

Figure 31: Correlation between the impact angle $\zeta$ and maximum total impact force: panel in vertical descent incident, central North Sea waves.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the sponson:

1. Controlled ditching incident
Figure 32: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of calm water.

Figure 33: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of increased mean speed.
Figure 34: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of increased mean descent angle.

Figure 35: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of increased mean pitch angle.
Figure 36: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of landing beam-on to waves.

Figure 37: Exceedance distribution of the maximum total impact force: sponson in controlled ditching incident, effect of increased drag coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the sponson:

2. Vertical descent incident
Figure 38: Exceedance distribution of the maximum total impact force: sponson in vertical descent incident, effect of calm water.

Figure 39: Exceedance distribution of the maximum total impact force: sponson in vertical descent incident, effect of increased mean speed.
Figure 40: Exceedance distribution of the maximum total impact force: sponson in vertical descent incident, effect of increased speed range.

Figure 41: Exceedance distribution of the maximum total impact force: sponson in vertical descent incident, effect of increased descent angle range.
Figure 42: Exceedance distribution of the maximum total impact force: sponson in vertical descent incident, effect of increased drag coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the sponson:

3. Loss of control incident
Figure 43: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of calm water.

Figure 44: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of increased mean speed.
Figure 45: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of increased speed range.

Figure 46: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of increased mean descent angle.
Figure 47: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of increased descent angle range.

Figure 48: Exceedance distribution of the maximum total impact force: sponson in loss of control incident, effect of increased drag coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the sponson:

4. Fly-in incident
Figure 49: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of calm water.

Figure 50: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased mean speed.
Figure 51: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased speed range.

Figure 52: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased mean descent angle.
Figure 53: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased descent angle range.

Figure 54: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased mean pitch angle.
Figure 55: Exceedance distribution of the maximum total impact force: sponson in fly-in incident, effect of increased drag coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the fuselage panel:

1. Controlled ditching incident
Figure 56: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of calm water.

Figure 57: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of increased mean speed.
Figure 58: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of increased mean descent angle.

Figure 59: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of increased mean pitch angle.
Figure 60: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of increased yaw angle range.

Figure 61: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of landing beam-on to waves.
Figure 62: Exceedance distribution of the maximum total impact force: panel in controlled ditching incident, effect of increased planing force coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the fuselage panel:

2. Vertical descent incident
Figure 63: Exceedance distribution of the maximum total impact force: panel in vertical descent incident, effect of calm water.

Figure 64: Exceedance distribution of the maximum total impact force: panel in vertical descent incident, effect of increased mean speed.
Figure 65: Exceedance distribution of the maximum total impact force: panel in vertical descent incident, effect of increased descent angle range.

Figure 66: Exceedance distribution of the maximum total impact force: panel in vertical descent incident, effect of increased roll angle range.
Figure 67: Exceedance distribution of the maximum total impact force: panel in vertical descent incident, effect of increased planing force coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the fuselage panel:

3. Loss of control incident
Figure 68: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of calm water.

Figure 69: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of increased mean speed.
Figure 70: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of increased speed range.

Figure 71: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of increased mean descent angle.
Figure 72: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of increased roll angle range.

Figure 73: Exceedance distribution of the maximum total impact force: panel in loss of control incident, effect of increased planing force coefficient.
Results from Sensitivity Study

Exceedance distributions of the maximum total impact force on the fuselage panel:

4. Fly-in incident
Figure 74: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of calm water.

Figure 75: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased mean speed.
Figure 76: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased speed range.

Figure 77: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased mean descent angle.
Figure 78: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased descent angle range.

Figure 79: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased mean pitch angle.
Figure 80: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased yaw angle range.

Figure 81: Exceedance distribution of the maximum total impact force: panel in fly-in incident, effect of increased planing force coefficient.
Results from Panel Redundancy Study
Figure 82: Exceedance distribution of the maximum total impact force on fuselage panels in a controlled ditching incident; individually and together.

Figure 83: Exceedance distribution of the maximum total impact force on fuselage panels in a fly-in incident; individually and together.
Figure 84: Exceedance distribution of the maximum total impact force on fuselage panels in a loss of control incident; individually and together.

Figure 85: Exceedance distribution of the maximum total impact force on fuselage panels in a vertical descent incident; individually and together.
Helicopter Velocity Scatter Plots

Sponson and fuselage panel: base case conditions
Vertical and horizontal helicopter impact velocities

Sponson: base case

Less than design force
Greater than design force
Ditching requirements
FAA 95% survivability

Figure 86: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on sponson greater than and less than the design load. Base case conditions.
Figure 87: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on sponson less than the design load: base case conditions.
Vertical and horizontal helicopter impact velocities

Sponson: base case

Greater than design force
Ditching requirements
FAA 95% survivability
Impact severity curves

Figure 88: Scatter plot showing vertical and horizontal impact velocities of helicopter loads on sponson greater than the design load: base case conditions.
Vertical and horizontal helicopter impact velocities
Fuselage panel: base case

Figure 89: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on fuselage panel greater than and less than the design load: base case conditions.
Figure 90: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on fuselage panel less than the design load: base case conditions.
Figure 91: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on fuselage panel greater than the design load: base case conditions.
Helicopter Velocity Scatter Plots

Sponson and fuselage panel: calm water conditions
Figure 92: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on sponson greater than the design load: calm water conditions.
Figure 93: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on fuselage panel greater than the design load: calm water conditions.
Percentage of Impact Events Exceeding the Design Load within each Impact Severity Index Curve

Sponson and fuselage panel: base case and calm water conditions
Percentage of events exceeding the design load, within each impact severity index curve
Sponson: base case and calm water conditions

Figure 94: Percentage of impact events exceeding the design load within each impact severity index curve: sponson in base case & calm water conditions.

Percentage of events exceeding the design load, within each impact severity index curve
Fuselage panel: base case and calm water conditions

Figure 95: Percentage of impact events exceeding the design load within each impact severity index curve: fuselage panel in base case & calm water conditions.
Helicopter Velocity Scatter Plots

Sponson and fuselage panel: 100% increase in design loads
Figure 96: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on sponson greater than the design load: 100% increase in design load.
Figure 97: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads on fuselage panel greater than the design load: 100% increase in design load.
Percentage of Impact Events Exceeding the Design Load within each Impact Severity Index Curve

Sponson and fuselage panel: base case, and with 100% increase in the design load
Figure 98: Percentage of impact events exceeding the design load within each impact severity index curve: sponson in base case conditions, and with 100% increase in the design load.

Figure 99: Percentage of impact events exceeding the design load within each impact severity index curve: fuselage panel in base case conditions, and with 100% increase in the design load.
Helicopter Velocity Scatter Plots

Two-panel redundancy study
Vertical and horizontal helicopter impact velocities
Two fuselage panels: no redundancy

Figure 100: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads greater than the design load: two fuselage panels, no redundancy.
Figure 101: Scatter plot showing vertical and horizontal impact velocities of helicopter: loads greater than the design load: two fuselage panels, one panel redundant.
Percentage of Impact Events Exceeding the Design Load within each Impact Severity Index Curve

Two-panel redundancy study
Percentage of events exceeding the design load, within each impact severity index curve
Redundancy between two fuselage panels

Figure 102: Percentage of impact events exceeding the design load within each impact severity index curve: redundancy between two fuselage panels.
Results from *EH101* Float Redundancy Study
Figure 103: EH101 float numbering scheme.
Figure 104: Scatter plot showing vertical and horizontal impact velocities of EH101 helicopter: 4-float configuration; cases where the helicopter sank.

Non successful scenario

Ditching requirements

FAA 86% survivability

Impact severity curves
Figure 105: Scatter plot showing vertical and horizontal impact velocities of *EH101* helicopter: 5-float configuration; cases where the helicopter sank.
Figure 106: Percentage of impact events where the *EH101* helicopter sinks, within each impact severity index curve, for different float configurations.

Figure 107: Percentage of impact events where the *EH101* helicopter inverts, within each impact severity index curve, for different float configurations.
Vertical and horizontal helicopter velocities

Two front, two sponson & one cabin panels: Air space requirement

Impact severity curves

Figure 108: Scatter plot showing vertical and horizontal impact velocities of EH/101 helicopter: 5-float configuration; cases with an unsatisfactory air space.
Figure 109: Scatter plot showing vertical and horizontal impact velocities of *EH101* helicopter: 6-float configuration; cases with an unsatisfactory air space.
Figure 110: Percentage of impact events where the *EH101* helicopter provided an unsatisfactory air space, within each impact severity index curve, for different float configurations.
Appendix A: Investigation Based on the Brent Spar and Cormorant Alpha Accidents

WS Atkins Science and Technology (WSA) carried out a parallel investigation for the CAA based on three actual helicopter accident scenarios. These three accidents occurred near the Cormorant Alpha platform in 1992, at the Brent Spar platform in 1990, and near the Scilly Isles in 1983. Further information about these three accidents may be found in WSA’s literature review [1] and in the relevant Air Accidents Investigation Branch (AAIB) reports.

WSA’s investigation was ‘generic’ to the extent that it was based on a single helicopter type, the WG30, rather than the specific helicopter type involved in each of these three accidents. WSA set up a full structural model of the WG30, and then investigated a small number of ‘deterministic’ models of each accident scenario. Each deterministic scenario was based on a single set of parameters to describe the helicopter’s speed, descent angle and orientation, and the wave surface at the time of each accident. Because of the complexity of their structural and fluid models, however, WSA were only able to consider the consequences of limited variations in modelling parameters.

BMT’s investigations were intended to complement WSA’s deterministic analysis. They were based on a highly simplified impact loading model, but were intended to show in a probabilistic manner how the impact loads are likely to vary with changes in the modelling parameters and assumptions.

The models developed by BMT and WSA represented the water impact loading process in very different ways, and it was not easy to predict in advance how the results from the two models would compare. BMT therefore undertook additional calculations, based on WSA’s deterministic models of the Cormorant Alpha and Brent Spar accidents, which would enable results from the two models to be compared directly. These comparisons are described in the accompanying WSA report [1].

BMT therefore calculated water impact loads on two fuselage panels near the nose of the WG30 helicopter, based on two agreed accident scenarios. Mean values of parameters describing the helicopter and wave conditions were chosen to be identical to those used in WSA’s own deterministic analysis, and were in turn based on information contained in the two relevant accident reports [4, 5]. The standard deviation of each parameter was chosen to be representative of the uncertainty in the chosen mean value. A single sea state was modelled in each case, but realistic levels of uncertainty in the significant wave height and zero-crossing period in each sea state were represented. Mean values of each parameter, and the uncertainty in each parameter value, were agreed with WSA before the study commenced [35, 36].

The procedures used in this investigation were identical to those used during BMT’s base case and sensitivity studies (see Sections 5 and 6), and were based on the formulation described in Section 4. Results from BMT’s Monte Carlo simulation were compared with results obtained by running the program in a ‘deterministic’ manner, using mean values of each parameter which were identical with those used during WSA’s analysis.
Panel Models

Brent Spar

The helicopter involved in the Brent Spar accident suffered structural damage in a number of different areas [1]. WSA’s investigations indicated severe water impact loading on the starboard side of the nose. The panels defined in Figure 111 and Figure 112 were therefore agreed to be of particular interest [36]. The attitude of the helicopter in these diagrams is shown at the instant of impact onto the water surface, with the same heel and trim angles as the helicopter involved in the Brent Spar accident.

The calculations were based on a simplified model of the starboard panels identified in Figure 112. They were modelled as two separate rectangular panels: a ‘base panel’ facing downwards, and a ‘side panel’ facing to starboard. Impact loads on these two panels were calculated as if they were in isolation. Panel dimensions and orientations were based on information supplied by WSA [36], and are described in Table A1-1. The length and breadth of each rectangular panel were chosen to give the same length and area as the equivalent group of WSA panels.

The orientation of the panel was described by three inclination angles, representing successive clockwise rotations of an initially vertical panel facing to starboard, about axes pointing forwards, to starboard, and downwards respectively. These three angles are shown in Table A1-1.

| Table A1-1: Panel parameters considered during the Brent Spar investigation. |
|-------------------------------------------------|----------------|----------------|
| Inclination about roll axis                      | 41°            | 74°            |
| Inclination about pitch axis                     | 0°             | 0°             |
| Inclination relative to forward direction        | -20°           | 0°             |
| Panel length                                     | 0.82 m         | 0.82 m         |
| Panel width                                      | 0.18 m         | 0.16 m         |

Cormorant Alpha

The helicopter involved in the Cormorant Alpha accident also suffered structural damage on the starboard side of the nose [1]. It was therefore agreed [37] that BMT’s calculations should be based on the same fuselage panels that had been considered during the Brent Spar investigation. Panel dimensions and orientations were based on information supplied by WSA [37], and are described in Table A1-2.
### Table A1-2: Panel parameters considered during the Cormorant Alpha investigation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Side panel</th>
<th>Base panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination about roll axis</td>
<td>24°</td>
<td>73.5°</td>
</tr>
<tr>
<td>Inclination about pitch axis</td>
<td>0°</td>
<td>8.6°</td>
</tr>
<tr>
<td>Inclination relative to forward direction</td>
<td>-23.8°</td>
<td>-10.0°</td>
</tr>
<tr>
<td>Panel length</td>
<td>0.82 m</td>
<td>0.82 m</td>
</tr>
<tr>
<td>Panel width</td>
<td>0.18 m</td>
<td>0.16 m</td>
</tr>
</tbody>
</table>

### Impact Parameters

#### A2.1 Brent Spar

Impact parameters representing the *Brent Spar* scenario were also agreed with WSA, and are summarised in Table A2-1. The impact speed represents the resultant speed of the helicopter in its direction of travel at the instant of impact, and the mean direction of fall was vertically downwards. Two impact speed scenarios were considered: a 'full-speed' scenario, representing a helicopter falling vertically under gravity off the deck of a representative offshore platform 25m high, and a 'half-speed' scenario representing a lower drop height.

WSA’s fax [36] listed the co-ordinates of each panel relative to earth-based axes at the instant of impact. The panel angles used in BMT’s simulations therefore already took account of the helicopter’s orientation, and the mean roll, pitch and yaw angles of the helicopter itself were set equal to zero.

WSA [36] stated that the uncertainty in the vertical impact speed was ±2 m/s in the full-speed case and ±1 m/s in the half-speed case, and the uncertainty in the horizontal impact speed was ±2 m/s in both cases. The uncertainty in the horizontal velocity, relative to the mean vertical velocity, was treated as an uncertainty in the descent angle. WSA stated that the uncertainties in the angles of orientation of the panels were ±1.5°, and these were treated as uncertainties in the roll, pitch and yaw angles of the helicopter itself. As agreed with WSA, the ‘uncertainty’ was considered to be a maximum value, and was assumed to represent three standard deviations of a normal distribution.

The mean value and standard deviation of the helicopter's heading angle relative to waves were chosen to be consistent with BMT's earlier simulations of vertical drop incidents, and represent a fairly broad spread of angles. The range of wave heading angles chosen has no particular significance, however, because the results proved to be insensitive to wave conditions.
The sea conditions at the time of the *Brent Spar* accident were stated to be ‘calm’. This description has been interpreted as a sea state with a significant wave height of 1.0m or less. Sea states were sampled from a wave scatter table constructed as follows. The significant wave height was assumed to be between 0.0m and 1.0m, at 0.2m intervals, all such heights having equal probability. The distribution of wave periods was assumed to be identical to that used during BMT’s main sensitivity study (see Section 6.1 of [2]), for wave heights between 0.0m and 1.0m, and was based on all-year, all-directions ‘PC-Global Wave Statistics’ data for the Central North Sea area.

### Table A2-1: Impact parameters based on the *Brent Spar* accident scenario.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact speed</td>
<td>22.0 m/s full-speed</td>
<td>0.7 m/s full-speed</td>
</tr>
<tr>
<td></td>
<td>11.0 m/s half-speed</td>
<td>0.35 m/s half-speed</td>
</tr>
<tr>
<td>Descent angle</td>
<td>90.0° (vertical descent)</td>
<td>2.0° full-speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0° half-speed</td>
</tr>
<tr>
<td>Helicopter roll, pitch</td>
<td>0.0°</td>
<td>0.5° in all cases</td>
</tr>
<tr>
<td>and yaw angles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heading angle to waves</td>
<td>60.0°</td>
<td>60.0°</td>
</tr>
</tbody>
</table>

A2.2 **Cormorant Alpha**

Impact parameters representing the *Cormorant Alpha* scenario were also agreed with WSA, and are summarised in Table A2-2. The helicopter's assumed mean heading and wave direction at the instant of impact are illustrated in Figure 117. These parameters are based on conditions defined in references [38] and [39].

WSA’s fax [37] quoted the co-ordinates of each panel relative to earth-based axes at the instant of impact. Once again the panel angles used in BMT's simulations already took account of the helicopter's orientation, and the mean roll, pitch and yaw angles of the helicopter itself were set equal to zero.

WSA had defined the helicopter and sea state conditions at the time of the *Cormorant Alpha* accident [37], stating that the uncertainty in the helicopter's resultant speed on impact was ±5 m/s, and the uncertainty in its descent angle was ±1.5 degrees. The uncertainties in the roll and pitch angles were stated to be ±1.5 degrees. The helicopter's yaw angle at the time of the actual incident was not known. It was agreed, therefore, that the mean yaw angle should be set to zero, and a fairly large uncertainty in the yaw angle (±15 degrees) should be assumed. Once again the ‘uncertainty’ was considered to be a maximum value, and was assumed to represent three standard deviations of a normal distribution.
<table>
<thead>
<tr>
<th>Table A2-2: Impact parameters based on the Cormorant Alpha accident scenario.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact speed</td>
</tr>
<tr>
<td>Descent angle</td>
</tr>
<tr>
<td>Helicopter roll angle</td>
</tr>
<tr>
<td>Helicopter pitch angle</td>
</tr>
<tr>
<td>Helicopter yaw angle</td>
</tr>
<tr>
<td>Heading angle to waves</td>
</tr>
</tbody>
</table>

Conditions at the time of the Cormorant Alpha accident were stated [38] to be: a significant wave height of 7 to 8m, an average wave period of 8 to 10 seconds, with a wave direction of 340°, and a helicopter heading of 100°.

As in earlier investigations [39], it was assumed that the stated wave direction was that from which the waves were travelling, and that the so-called ‘average’ wave period was the zero-crossing period $T_z$. These conditions were therefore represented by a synthesised scatter table of significant wave heights, $H_s$, and zero-crossing periods, $T_z$, centred on the mean condition $H_s = 7.5m$, $T_z = 9.0s$, and with a variation of about ±0.5m in $H_s$ and ±1.0s in $T_z$.

The wave scatter table assumed during these calculations is shown in Table A2-3. This distribution was based on an uncorrelated bi-variate normal distribution with standard deviations equal to 0.5m in $H_s$ and 1.0s in $T_z$. 
### Table A2-3: Assumed scatter table representing the uncertainty in wave conditions at the time of the Cormorant Alpha accident.

<table>
<thead>
<tr>
<th>$H_s$ (m)</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8.5</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8.0</td>
<td>0</td>
<td>3</td>
<td>15</td>
<td>24</td>
<td>15</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>7.5</td>
<td>0</td>
<td>5</td>
<td>24</td>
<td>40</td>
<td>24</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>7.0</td>
<td>0</td>
<td>3</td>
<td>15</td>
<td>24</td>
<td>15</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6.5</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$T_z$ (s)</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### Results from the Brent Spar Investigation

The main results from the *Brent Spar* investigation are shown in Figures 113 to 116. These four figures show exceedance probability distributions for the maximum impact load on the side and base panels in full-speed and half-speed impacts. Three sets of results are shown on each figure:

- The solid curve shows the range of loads occurring when all parameters were subject to the levels of uncertainty shown in the above tables.

- The dashed curve shows the variability associated with the wave environment alone, due to variations in the significant wave height and zero-crossing period, in the heading of the helicopter relative to the waves, and in the height and local slope of the individual wave at the instant of impact. The helicopter speed, descent angle and attitude were fixed in this case at their mean values.

- The vertical bar represents the fully deterministic scenario, with completely calm water, and all impact parameters set at their mean values.

The shapes of the curves are very similar for both panels at both impact speeds, with a fairly broad spread of values when all parameters were allowed to vary.

The impact loads occurring during a half-speed incident are a quarter of those occurring during the corresponding full-speed incident. This result is consistent with the theoretical formulation, which predicts that the impact load will vary with the square of the impact speed.

The amount of variability was much reduced when only the wave parameters were allowed to vary, confirming an earlier conclusion that the impact loads occurring in a vertical descent incident are insensitive to wave conditions.

The results obtained using the deterministic model are summarised in Table A3-1. The forces on the base panel are over three times the magnitude of those on the side panel. This result is not surprising, because the base panel was inclined at only 16°.
to the horizontal. Even higher loads are possible if the panel is closer to the horizontal on impact.

<table>
<thead>
<tr>
<th>Side panel</th>
<th>Base panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-speed impact</td>
<td>176 kN</td>
</tr>
<tr>
<td>Half-speed impact</td>
<td>44 kN</td>
</tr>
</tbody>
</table>

Table A3-1: The maximum impact force predicted in each deterministic Brent Spar impact scenario.

Results from the Cormorant Alpha Investigation

Figures 118 and 119 show exceedance distributions of the maximum total impact force on the base panel and side panel respectively, based on the Cormorant Alpha accident scenario described above. Five sets of results are shown on each figure:

- The solid curve shows the range of loads occurring when all parameters were subject to the levels of uncertainty shown in the above tables.

- The dashed curve shows the variability associated with the surface slope and velocity at the point of impact when all other parameters (including the sea state itself) were fixed at their mean values.

- The chain-dashed curve shows the variability associated with the helicopter speed, descent angle and attitude alone, and represent impacts onto calm water.

- The two vertical bars represent results obtained using alternative fully deterministic scenarios, which are described in Section A4.1.

The solid lines demonstrate the wide range of impact loads that can occur when the calculations represent uncertainties in all the parameters describing the helicopter and the environment. These calculations indicate that there is a 5% probability of exceeding 350 kN on the base panel, and 89 kN on the side panel.

The dashed lines on these two figures show that there were still substantial variations in the impact loads when the helicopter's speed, descent angle, attitude and heading were all set at their mean values, and the significant wave height \( H_s = 7.5 \) m and zero up-crossing wave period \( T_c = 9 \) s were also fixed. Even though the sea state was fixed, the wave surface represented by this sea state was irregular, and the helicopter could make contact at any point on this surface. The dashed curves in Figures 118 and 119 show the range of impact loads that occurred in this scenario, due entirely to variations in the local water surface slope and surface velocity at different points of contact.

Both figures show a fairly broad spread of impact loads associated with variations in the local water surface slope and velocity. There are also noticeable differences between the distributions obtained using the original Cormorant Alpha sea state data and assuming ‘calm water’. These results appear at first sight to be at variance with corresponding results from the main sensitivity study (see Section 6.2 in the main part...
of this report and Figure 68), where wave conditions were found to have no noticeable effect on the impact load distribution corresponding to a loss of control incident. The key difference is that the sensitivity study was intended to be generic, covering a range of possible loss of control incidents, occurring randomly throughout the year. The majority of these simulated incidents occurred in fairly calm sea conditions. The Cormorant Alpha scenario was based on one particular incident, which occurred during rough sea conditions. The high sea state at the time of the Cormorant Alpha accident therefore gave the wave parameters more significance than they had during the generic study.

The sea state, surface slope and velocity have a particularly marked effect on base panel loads, as shown in Figure 118. The load distribution obtained by varying the surface slope and velocity alone is close to that obtained when all parameters are allowed to vary. Furthermore the ‘calm water’ load distribution has markedly less spread than when the simulation was based on sea states representative of the Cormorant Alpha accident. Sea state was more significant in this respect than variations in the helicopter's speed, descent angle, attitude and heading. This result is again at variance with those obtained from the main sensitivity study (see Section 6.2 in the main part of this report and Figure 68), which apply to loads on a side-facing panel, and are not necessarily valid for loads on a base panel.

A4.1 The Deterministic Cormorant Alpha Scenario

The dashed lines in Figures 118 and 119 show that impact forces on both the base panel and side panel are sensitive to variations in the water surface slope and velocity at the point of impact. The results from these simulations therefore had to be processed further in order to determine the maximum impact force associated with a deterministic impact scenario, where the wave surface slope and velocity are fixed at the instant of impact.

The contour plots in Figures 120 and 121 show how the maximum total impact forces on the base panel and side panel vary with the water surface angle \( \beta_w \) and the normal water surface velocity \( u_n \). These contour plots are based on results from Monte Carlo simulations with fixed mean helicopter and sea state parameters. As expected, the force generally increases when the water surface rises (i.e. as the surface velocity becomes more negative), and when it is inclined towards the helicopter (a negative surface angle). The contour plot for the base panel shows a large peak centred around a water surface angle of about -18 degrees, this being the angle at which the water surface is parallel to the panel itself.

BMT had previously recommended [39] that a wave slope angle of 10 degrees, and a wave phase speed between 12 and 16 m/s should be assumed in WSA's deterministic model. The damage report suggested that the helicopter involved in the Cormorant Alpha accident had come down onto the rear flank of a wave travelling in approximately the same direction. The deterministic model therefore represents a wave surface, moving at an angle of 60° to the helicopter's own heading (see Figure 117), inclined towards it, and receding at the instant of impact.

Assuming that the water surface moves horizontally with the mean wave phase speed (14 m/s), the velocity of the water surface normal to itself is \( 14 \sin 10° = 2.4 \) m/s. The deterministic scenario should therefore represent the following: a surface slope angle equal to -10°, inclined towards the helicopter as it approaches, and a normal water surface velocity (downwards) equal to +2.4 m/s.
This particular deterministic scenario is represented by the symbol ⬤ in Figures 120 and 121. The maximum total impact force on the base panel in this scenario is 160 kN, and the corresponding force on the side panel is 45 kN. These two (‘deterministic, receding’) values are shown as solid vertical bars in Figures 118 and 119.

The assumed phase speed of the wave surface is comparable in magnitude with the speed of the helicopter on impact, but its value is very uncertain. The deterministic calculation procedure predicts a much higher impact load if it is based on a regular wave with the same surface slope, but a shorter period, and therefore a lower wave phase speed. The symbol ○ in Figures 120 and 121 represents the scenario where the water surface is assumed to be stationary at the point of impact. The maximum total impact forces on the base panel and side panel are then increased to 250 kN and 59 kN respectively. These alternative (‘deterministic, stationary’) estimates are shown as light vertical bars on Figures 118 and 119. Substantially lower deterministic estimates of the impact load are therefore obtained when the water surface is assumed to be receding away from the helicopter at the point of impact, compared with the loads obtained assuming a stationary surface.

There are significant differences between the probabilities of exceeding these alternative deterministic estimates, when all the uncertainties in the helicopter and sea conditions are taken into account. The probability of exceeding the deterministic load on the base panel with a ‘receding’ water surface is over 20%, but this probability is reduced to only 9% if the water surface is assumed to be stationary at the point of impact. There are much larger probabilities of exceeding the deterministic loads on the side panel: 50% and 25% respectively. Whereas both deterministic estimates for the base panel may be regarded as reasonably conservative, this is not true of corresponding estimates for the side panel. More conservative estimates are obtained if the water surface is assumed to be stationary at the point of impact than if it is assumed to be receding away from the helicopter.

The results obtained using the deterministic model are summarised in Table A4-1. The force on the base panel is over six times the magnitude of the corresponding value for the side panel. This result is not surprising, because the base panel was inclined at only 8° relative to the water surface on impact. Significantly higher loads may occur if the panel is more nearly parallel to the water surface on impact.

<table>
<thead>
<tr>
<th>Table A4-1: The maximum impact force predicted in each deterministic Cormorant Alpha impact scenario.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Receding water surface ($u_w = 2.4 \text{ m/s}$)</td>
</tr>
<tr>
<td>Stationary water surface ($u_w = 0.0 \text{ m/s}$)</td>
</tr>
</tbody>
</table>
Results from the Study based on the
*Brent Spar* Accident Scenario
Figure 111: Forward part of WSA's finite element model, highlighting panels identified for investigation.

Figure 112: Enlargement of panels identified for investigation.
Figure 113: Exceedance distribution of the maximum total impact force: side panel in *Brent Spar* full-speed accident scenario.

Figure 114: Exceedance distribution of the maximum total impact force: side panel in *Brent Spar* half-speed accident scenario.
Figure 115: Exceedance distribution of the maximum total impact force: base panel in *Brent Spar* full-speed accident scenario.

Figure 116: Exceedance distribution of the maximum total impact force: base panel in *Brent Spar* half-speed accident scenario.
Results from the Study based on the Cormorant Alpha Accident Scenario
Figure 117: Mean wave heading and helicopter heading directions assumed during the *Cormorant Alpha* investigation.
Figure 118: Exceedance distribution of the maximum total impact force: base panel in *Cormorant Alpha* accident scenario.

Figure 119: Exceedance distribution of the maximum total impact force: side panel in *Cormorant Alpha* accident scenario.
Figure 120: Contour plot of maximum total impact force against water surface angle and velocity, with other parameters fixed: *Cormorant Alpha* base panel.

Figure 121: Contour plot of maximum total impact force against water surface angle and velocity, with other parameters fixed: *Cormorant Alpha* side panel.