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DEVICES TO PREVENT HELICOPTER TOTAL INVERSION FOLLOWING A DITCHING

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DEVICES TO PREVENT HELICOPTER TOTAL INVERSION FOLLOWING A DITCHING

BMT Fluid Mechanics Limited, Document No. 44117 Report 3

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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.

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1 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 lead 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.

2 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.

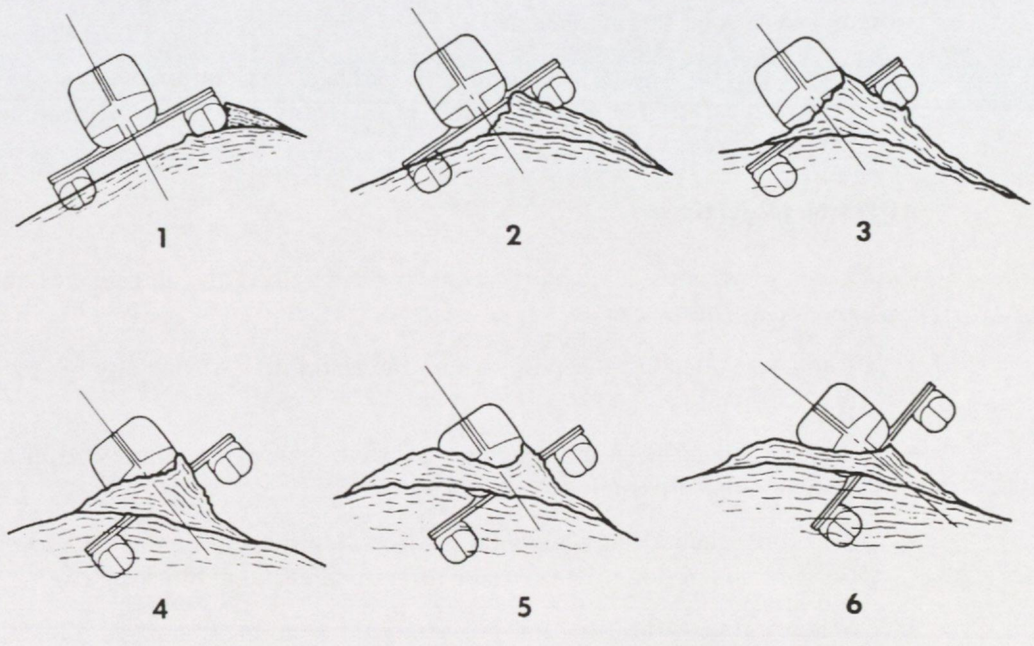

Figure 1 – The nature of capsize of a helicopter by a breaking wave [2].

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 escape[1].

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:

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

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*

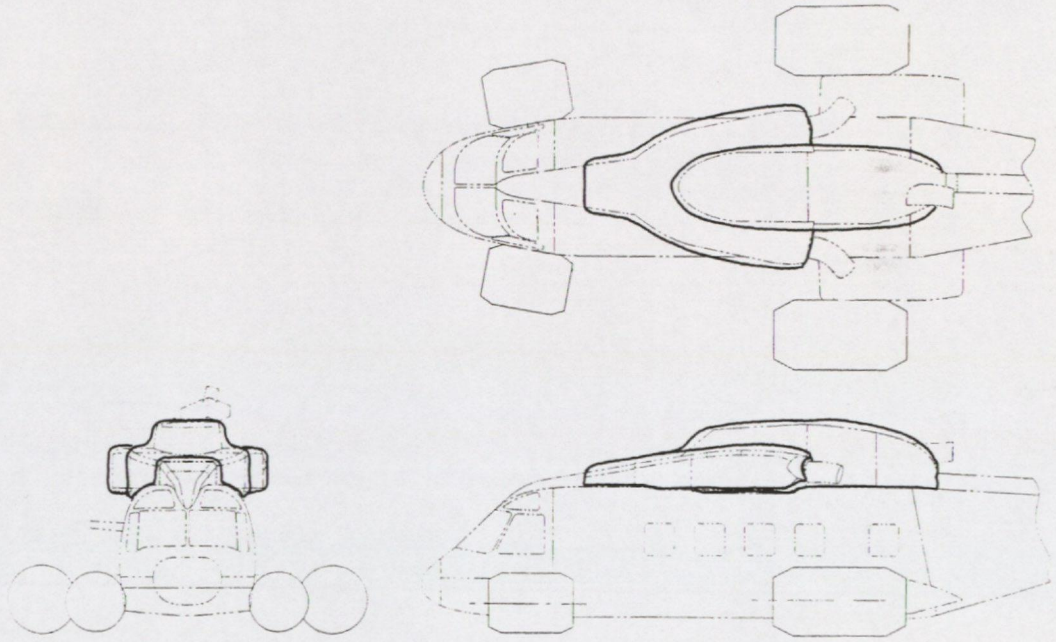

Figure 2 – Buoyant foam-filled engine cowling panels.

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 m^2 and so, in order to obtain an additional 6 m^3, 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*

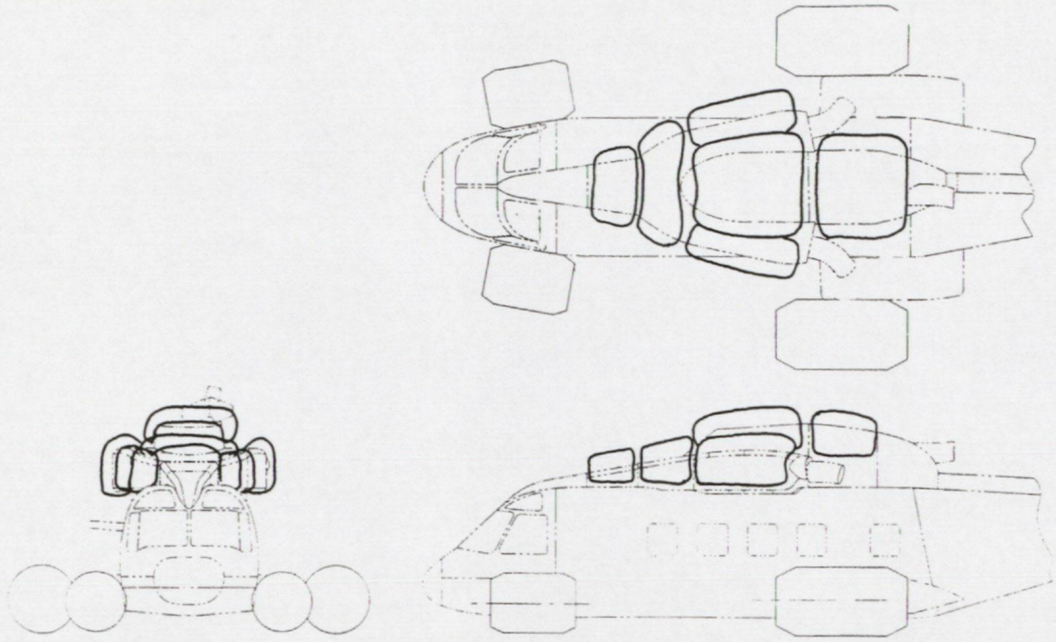

Figure 3 – Engine cowling panels with integral buoyancy bags.

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

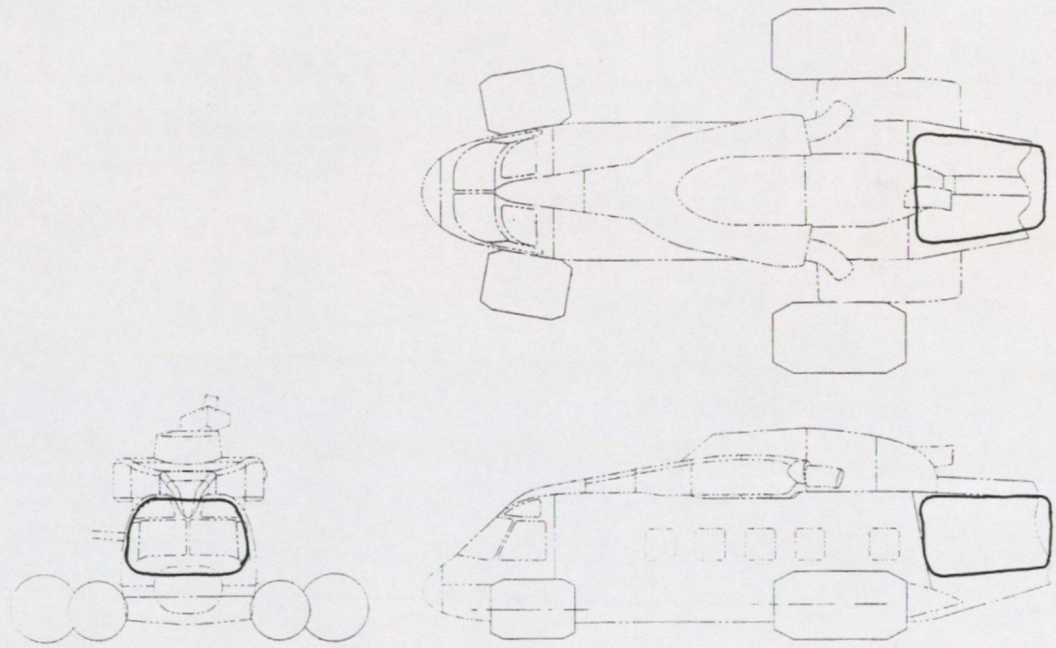

Figure 4 – Buoyancy bags inside rear fuselage.

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 capsize.

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*

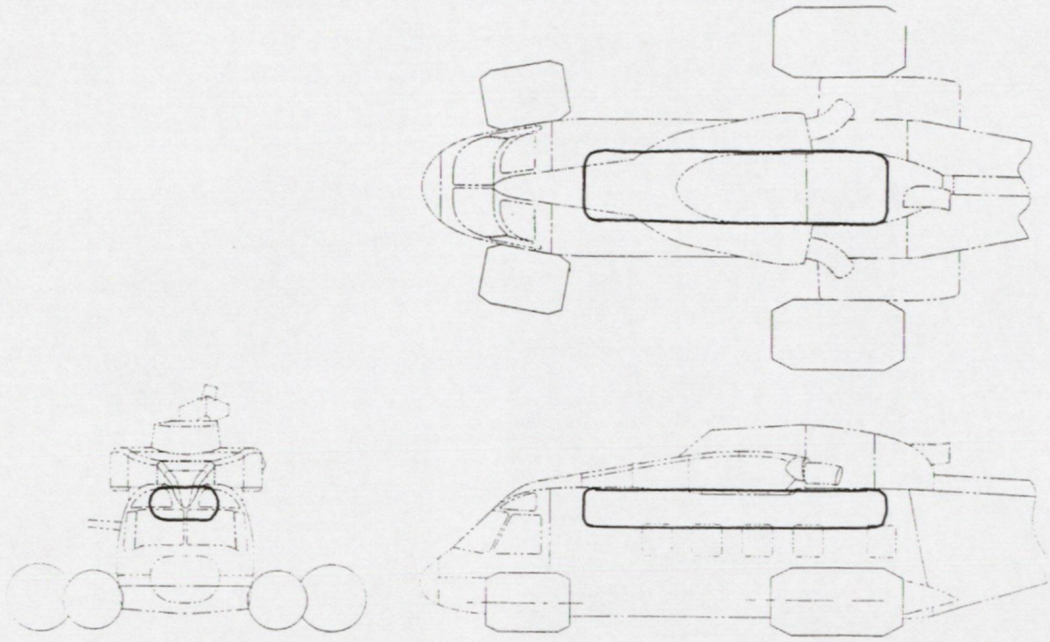

Figure 5 – Buoyancy inside passenger cabin roof.

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

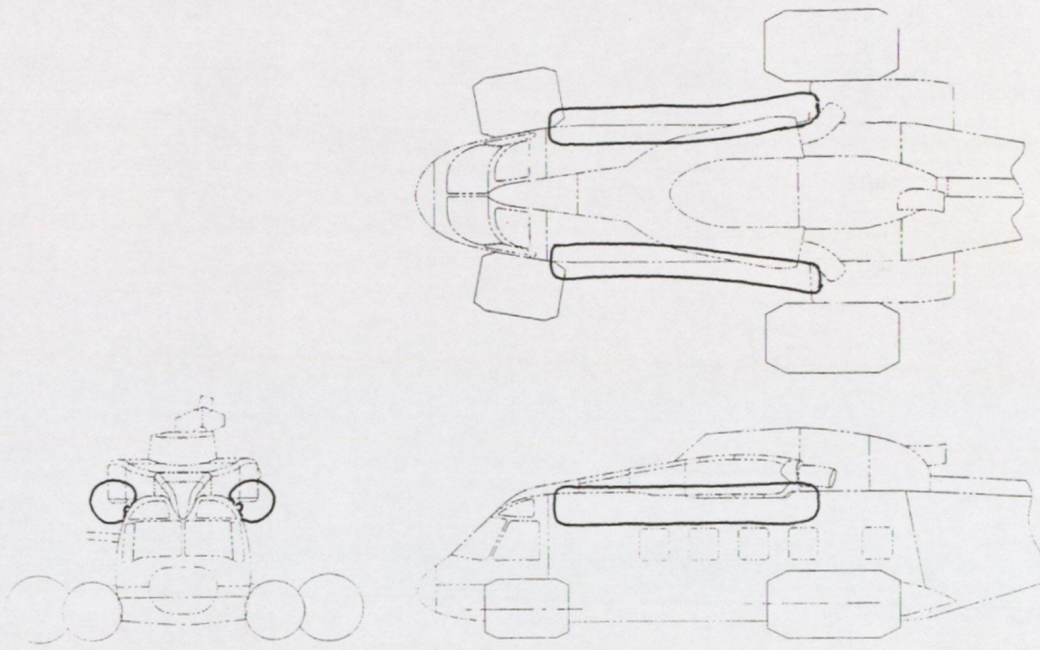

Figure 6 – Long buoyancy bags along upper cabin wall.

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

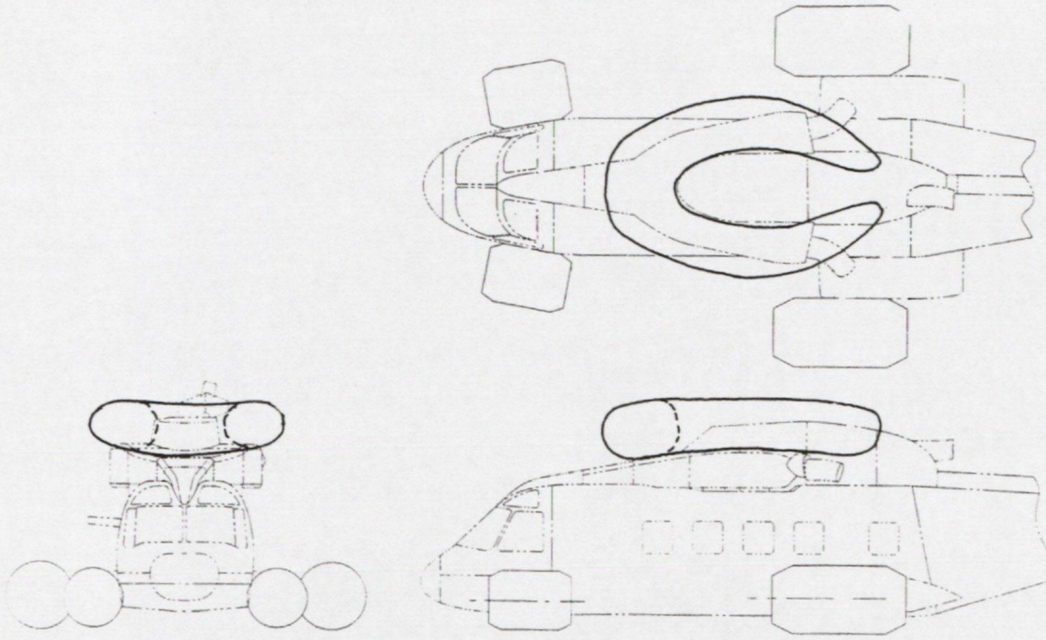

Figure 7 – Flotation collar under rotor head.

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*

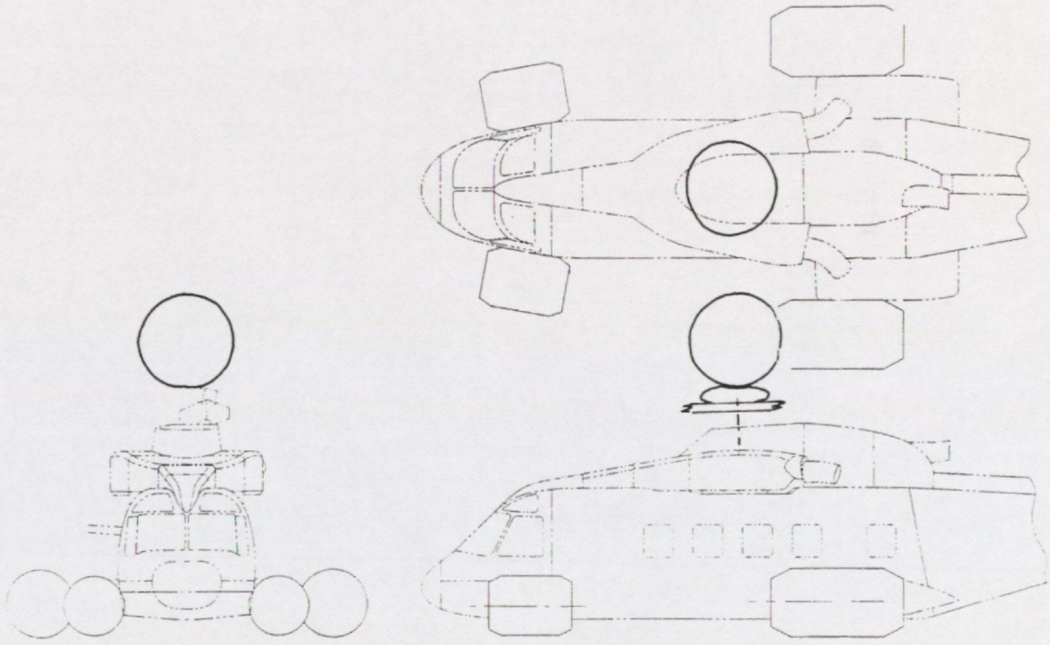

Figure 8 – Flotation on rotor head.

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 is 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.

3.2.8 *Tethered inflatable flotation units*

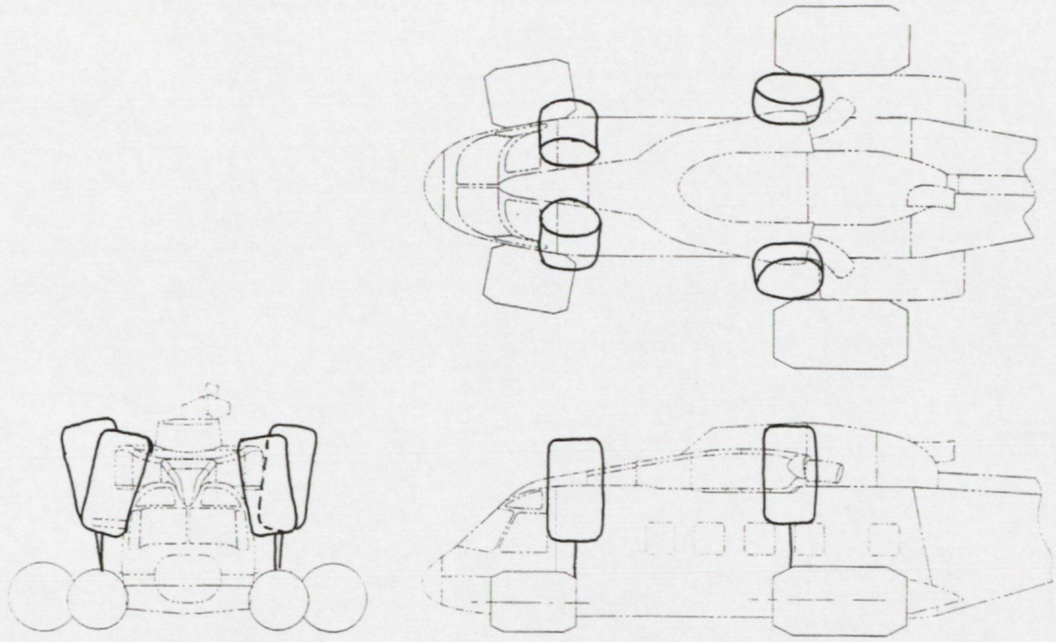

Figure 9 – Tethered inflatable flotation units.

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.

3.2.9 Increased passenger seat buoyancy

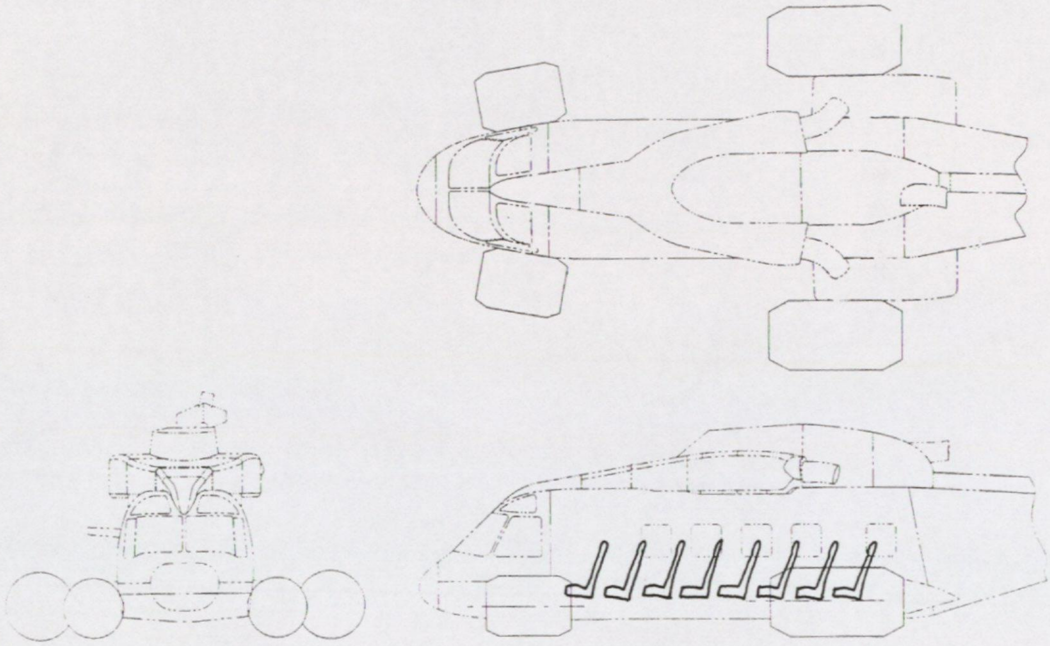

Figure 10 – Increased passenger seat buoyancy.

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.

3.2.10 *Dynamic chemical foam in engine spaces*

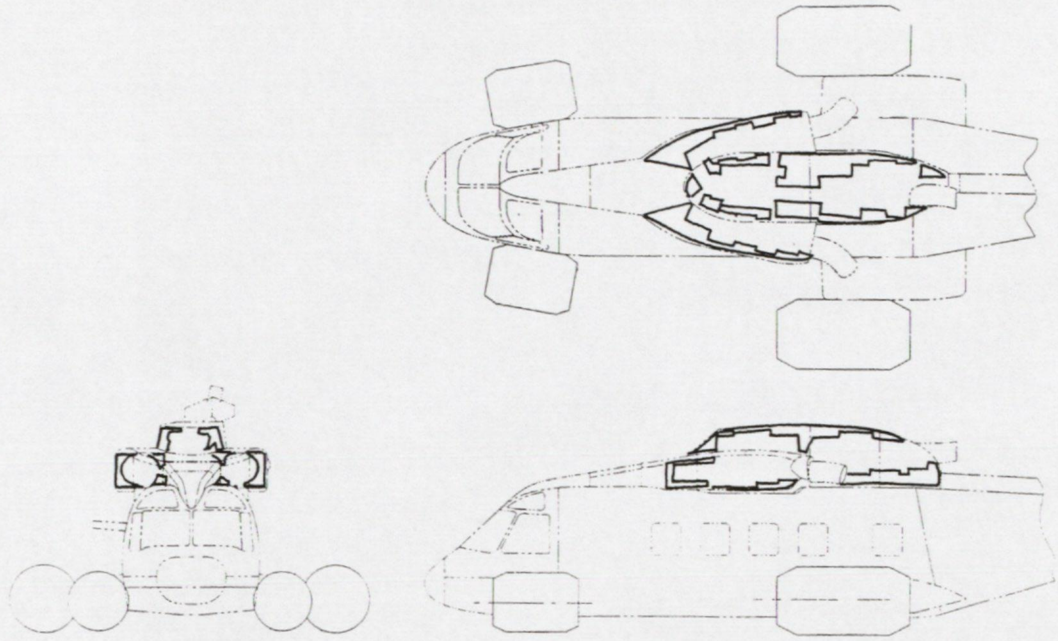

Figure 11 – Dynamic chemical foam in engine spaces.

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;

No.	Device
1.	Foam filled cowlings.
5.	Cabin wall floats.
8.	Tethered flotation units.

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;

No.	Device
3.	Rear fuselage buoyancy.
9.	Buoyant seating.
10.	Foam-filled engine spaces.

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:

No.	Device
1.	Foam filled cowlings.
5.	Cabin wall floats.
8.	Tethered flotation units.

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.

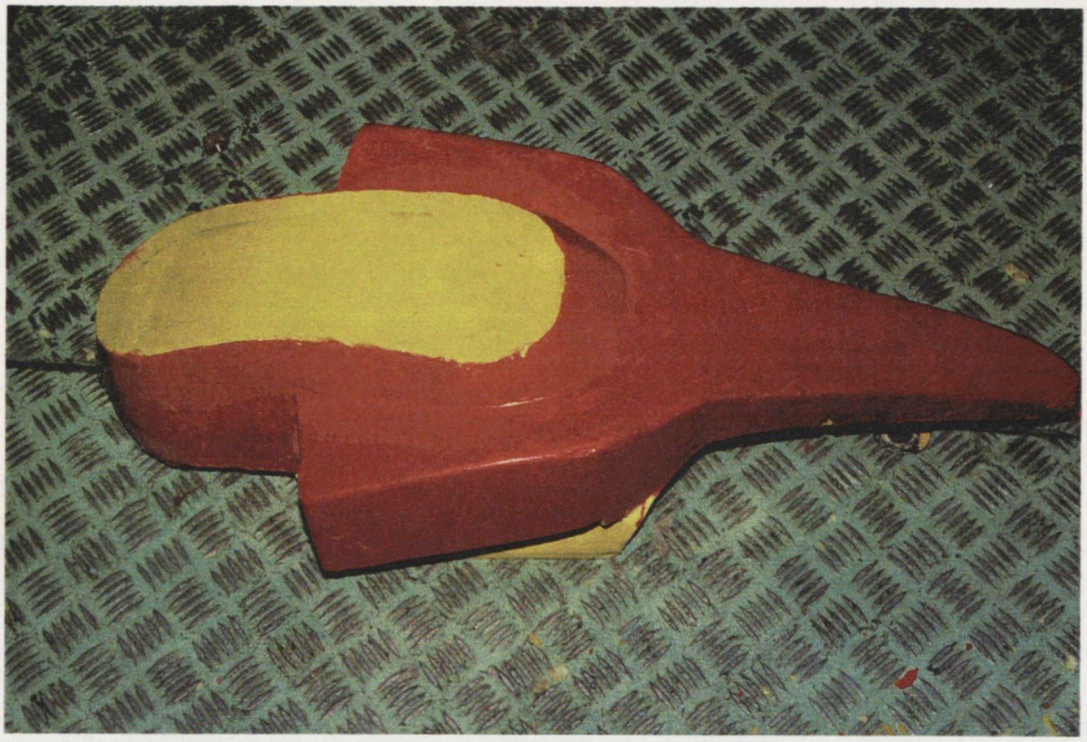

Figure 12 – Buoyant Engine Cowling Panels (5m^3 version)

Figure 13 – Long buoyant flotation units (Set 1 in the foreground)

4.5.4 *Tethered Floating Units*

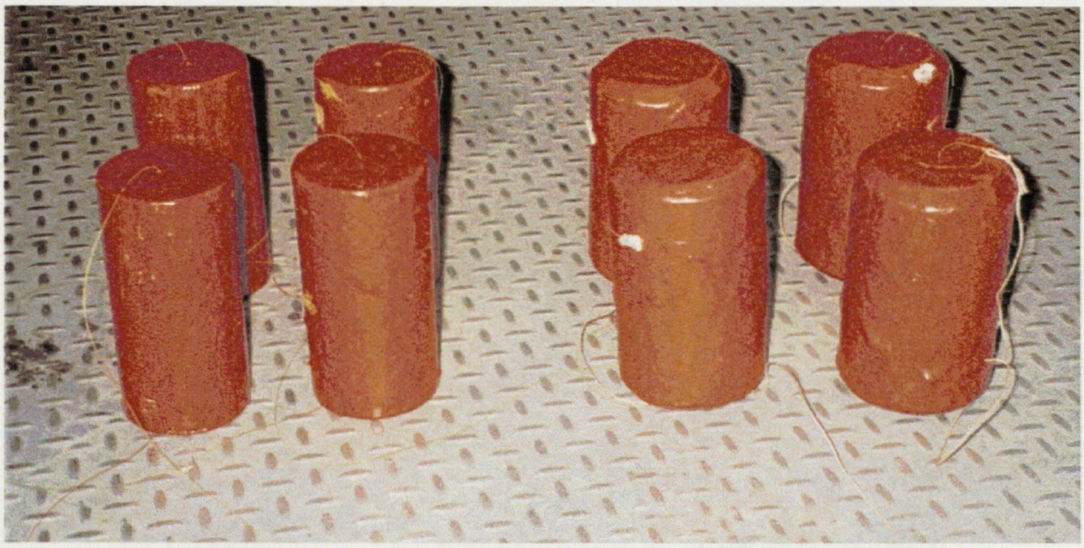

Figure 14 – Tethered Buoyant Units (Set 1 right, Set 2 left)

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 8.3m^3, and a second set with a volume totalling 5.6m^3.

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 capsize 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 capsize 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.

Figure 15 – Standard helicopter capsized in calm water.

Figure 37 of Appendix D shows the roll rightng 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 capsize, and provides the starting point for considering the effectiveness of the novel flotation units.

5.2.2 *Performance in Waves*

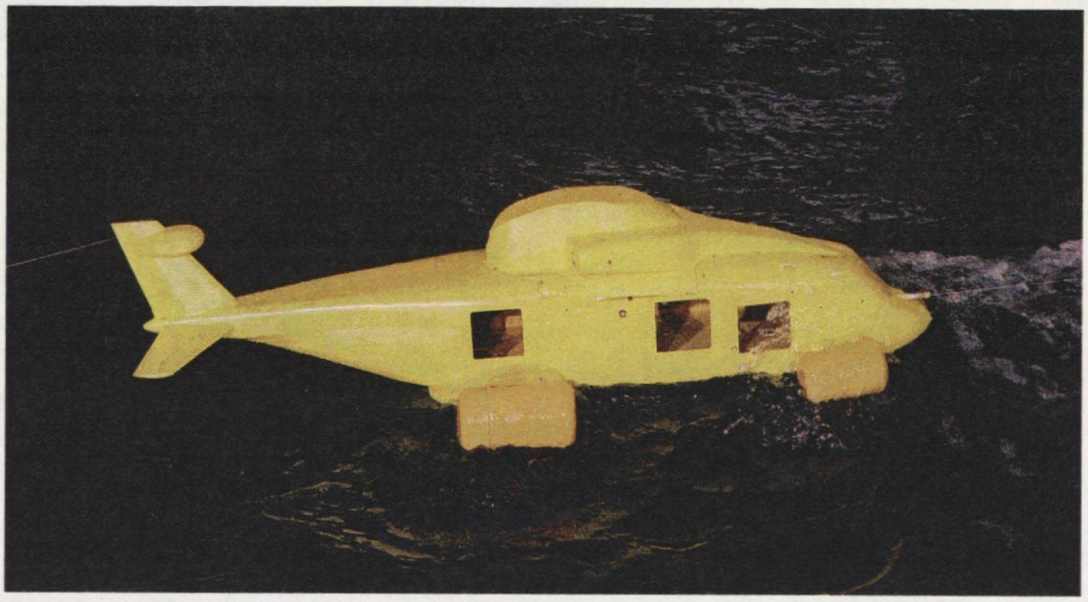

Figure 16 – Standard helicopter in waves.

The standard test helicopter capsized in large breaking waves in a sea-state having a JONSWAP wave spectrum, significant wave height H_s = 4.3m, and peak period T_p = 6.3s. 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 12,839kg) was chosen for the remainder of the study.

The JONSWAP wave spectrum with H_s = 4.3m and T_p = 6.3s 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 $7.9m^3$, whilst Set 2 was significantly smaller with a total buoyancy of $4.9m^3$. The Set 1 units are shown installed on the model in Figure 17.

Figure 17 – Long flotation units (Set 1).

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.

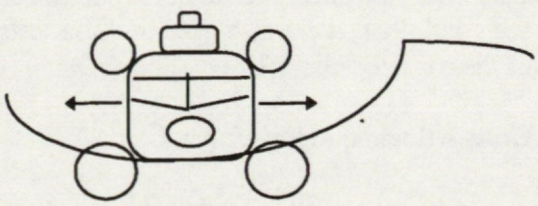

Figure 18 – Prior to capsize, escape on both sides of aircraft.

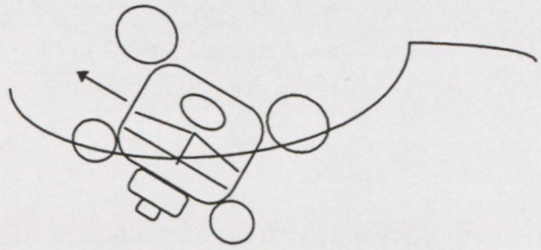

Figure 19 – After 1st rotation, escape from port side of aircraft.

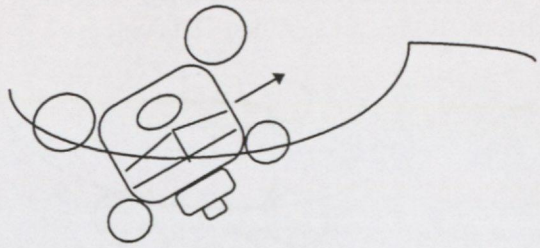

Figure 20 – After 2nd rotation, escape from starboard side of aircraft.

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.

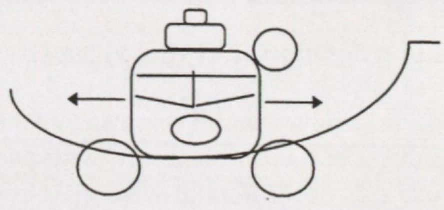

Figure 21 – One long buoyancy unit on port side, prior to capsize.

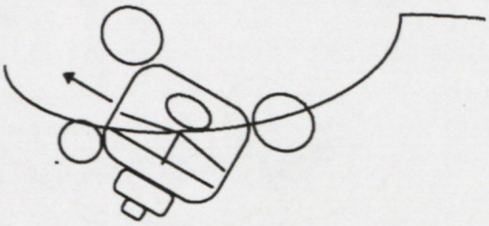

Figure 22 – One long buoyancy unit on port side, capsized (in a single rotation).

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.

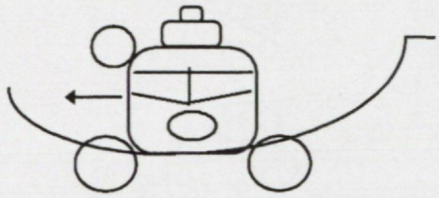

Figure 23 – One long buoyancy unit on starboard side, prior to capsize.

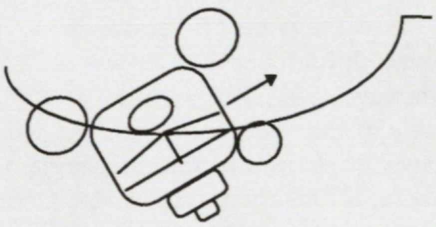

Figure 24 – One long buoyancy unit on starboard side after capsize (in one rotation).

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.

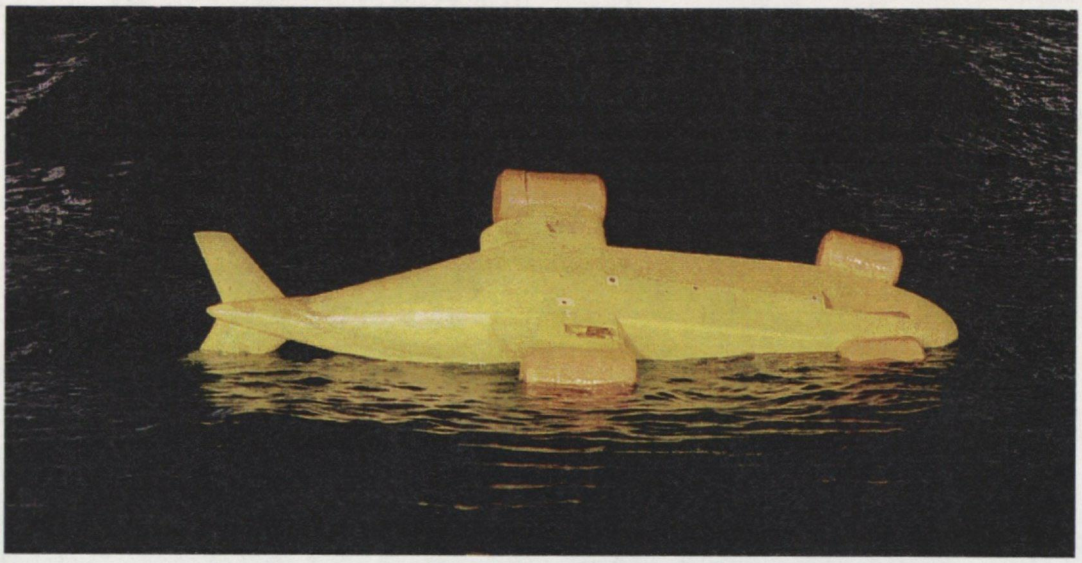

Figure 26 – Single Set 1 long flotation unit capsized, "dry" side away from camera.

5.4 Buoyant Foam Cowling Panels

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.

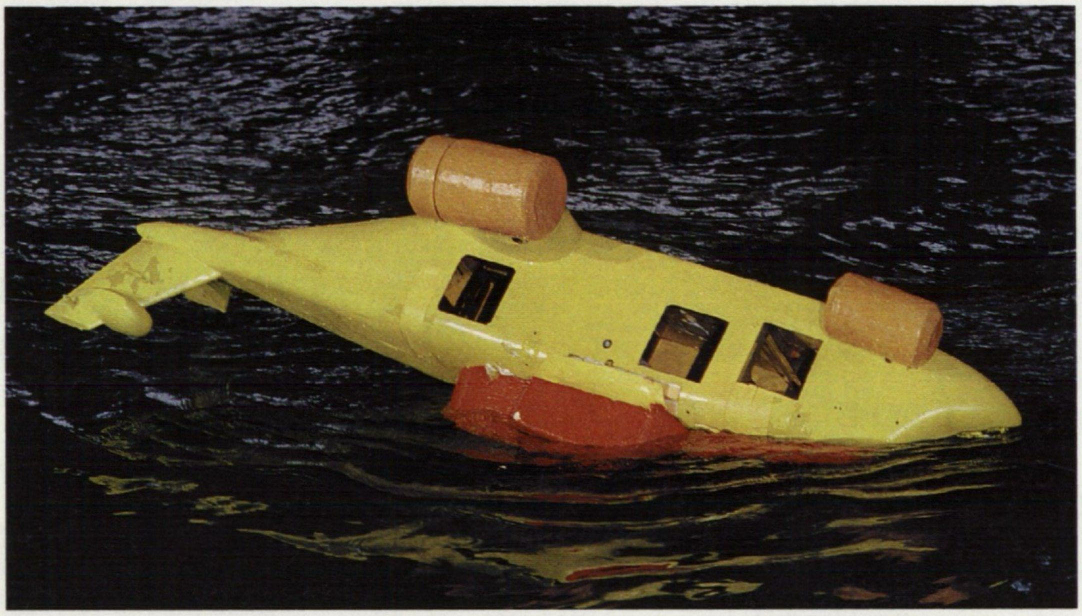

Figure 28 – Foam filled buoyant cowling panels capsized in waves.

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 capsize 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.

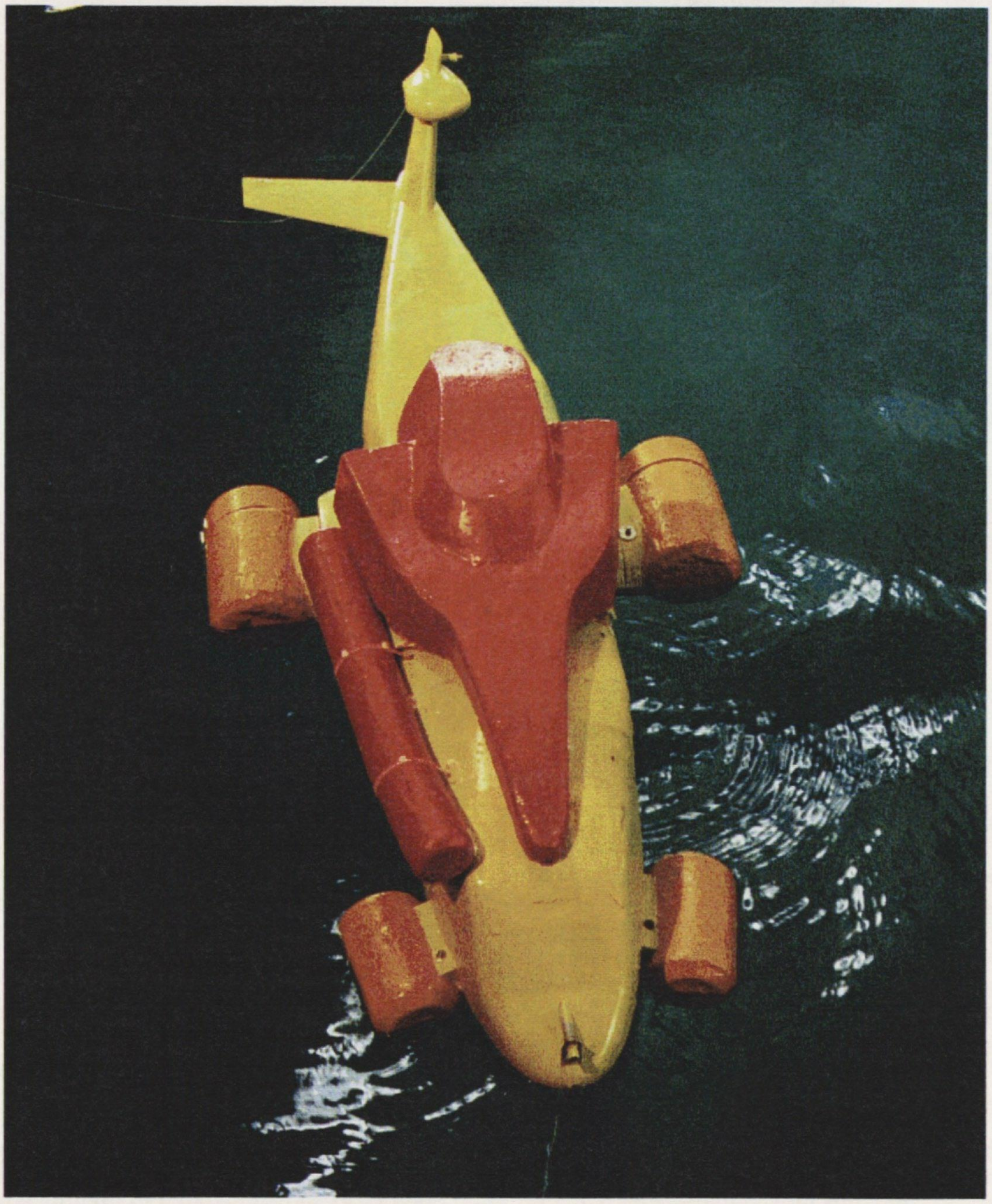

Figure 29 - Buoyant cowling and single long unit combination.

A single long bag of the smaller Set 2 was installed on the starboard side of the helicopter in combination with the 6m^3 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.

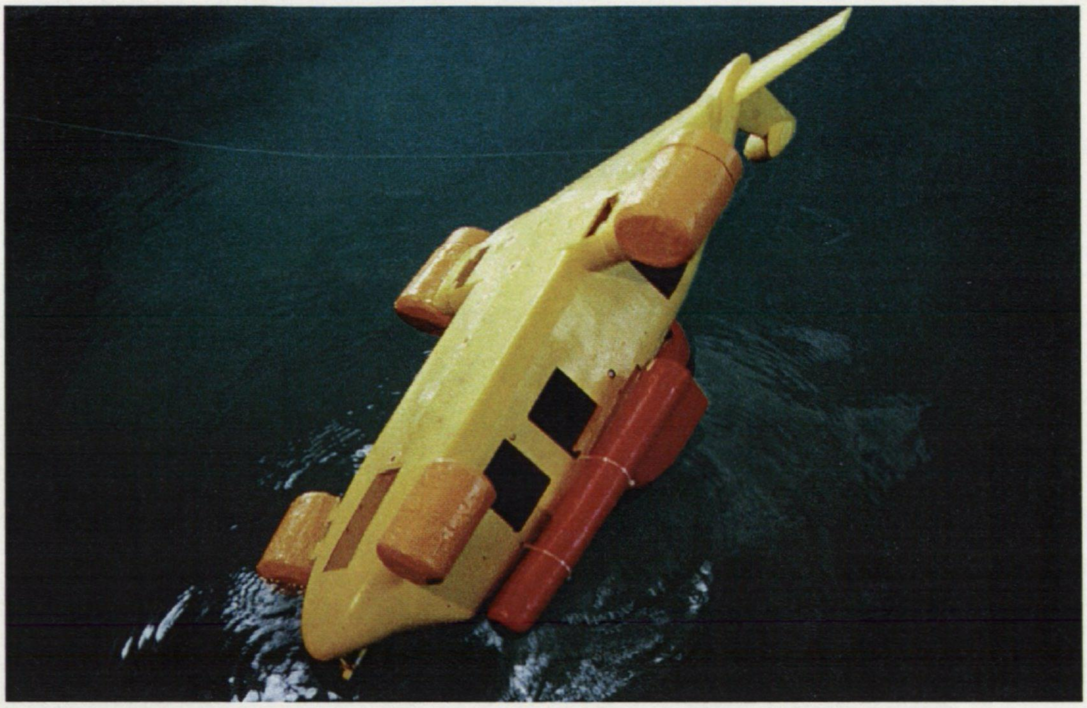

Figure 30 – Cowling (6m3) and long unit (Set 2) combination capsized.

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 6m^3 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 2.1m^3 for each unit (total of 8.3m^3 for the four units in the set). Set 2 was significantly smaller at 1.4m^3 each (5.6m^3 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.

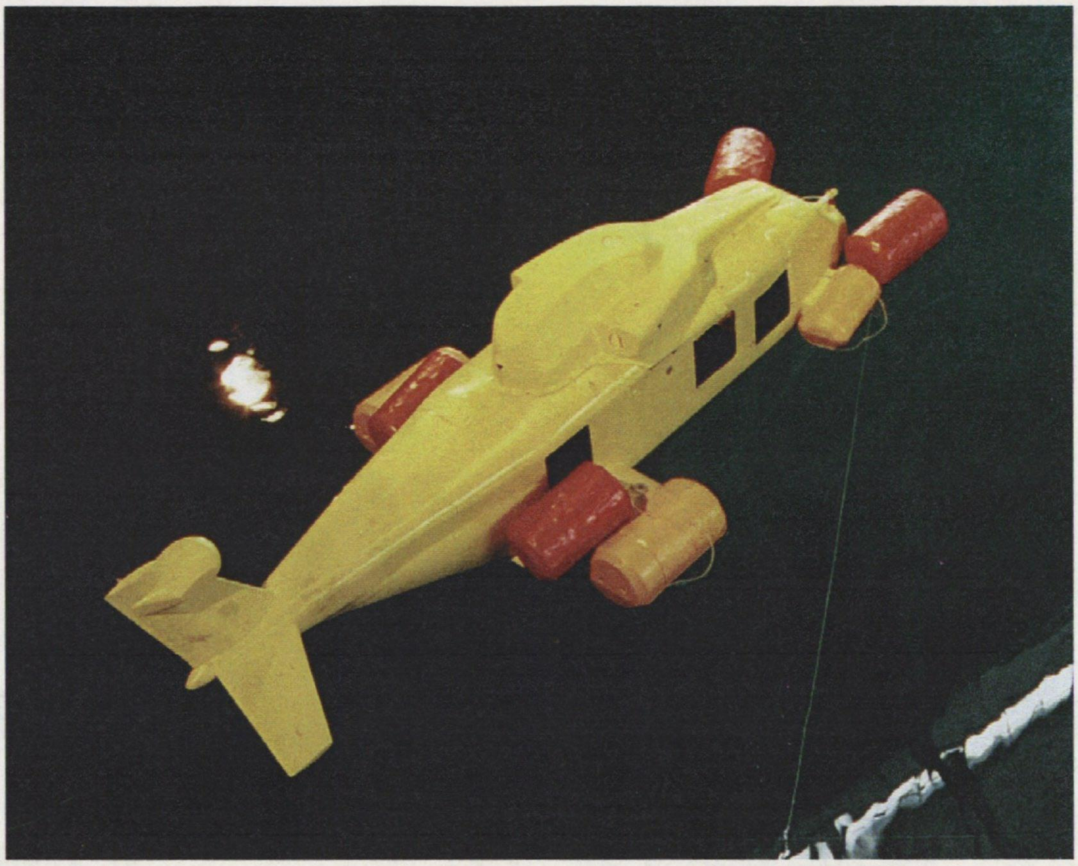

Figure 31 – Free tethered units in calm water.

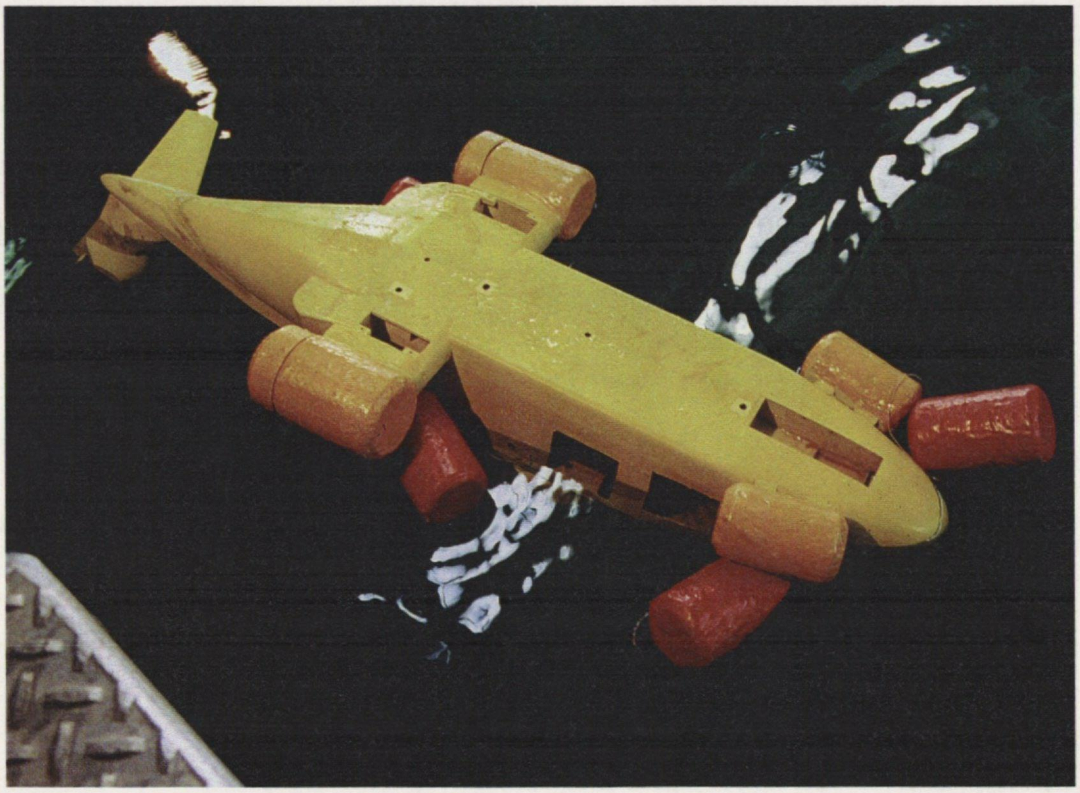

Figure 32 – Free tethered units capsized in calm water.

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 ($8.3m^3$) 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 ($5.6m^3$), were not tested.

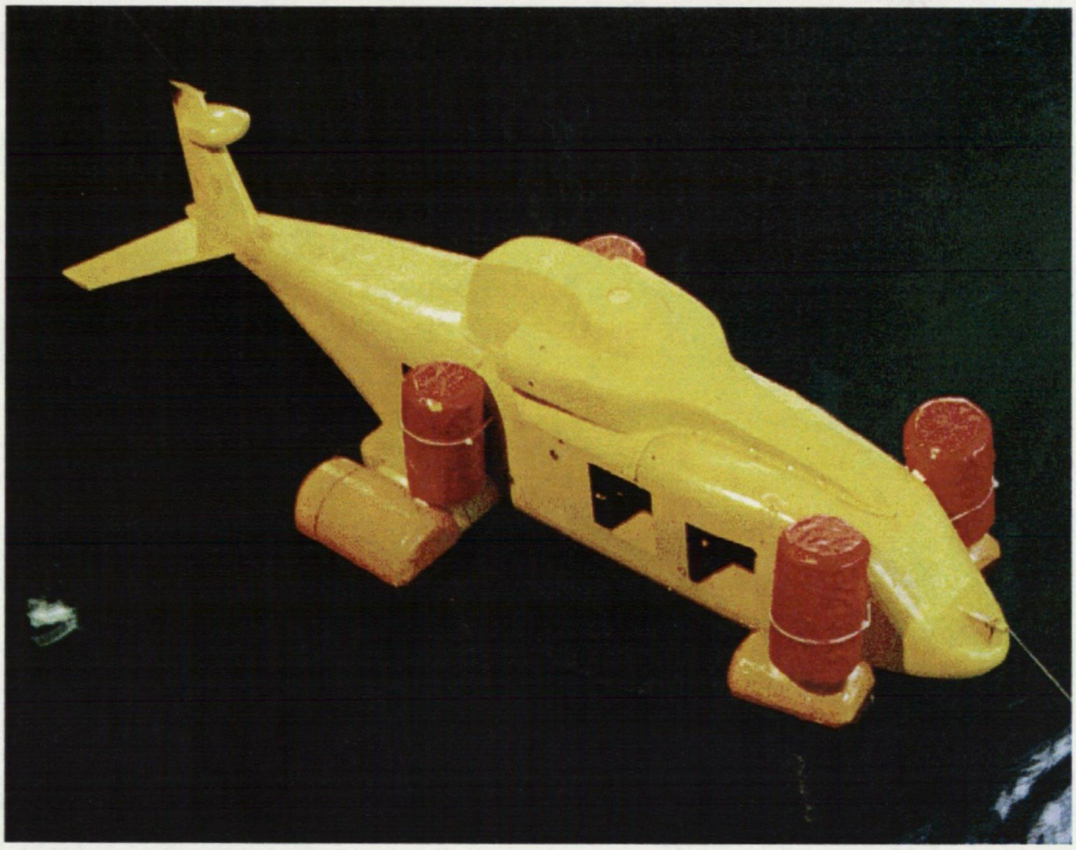

Figure 33 – Secured tethered units.

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.

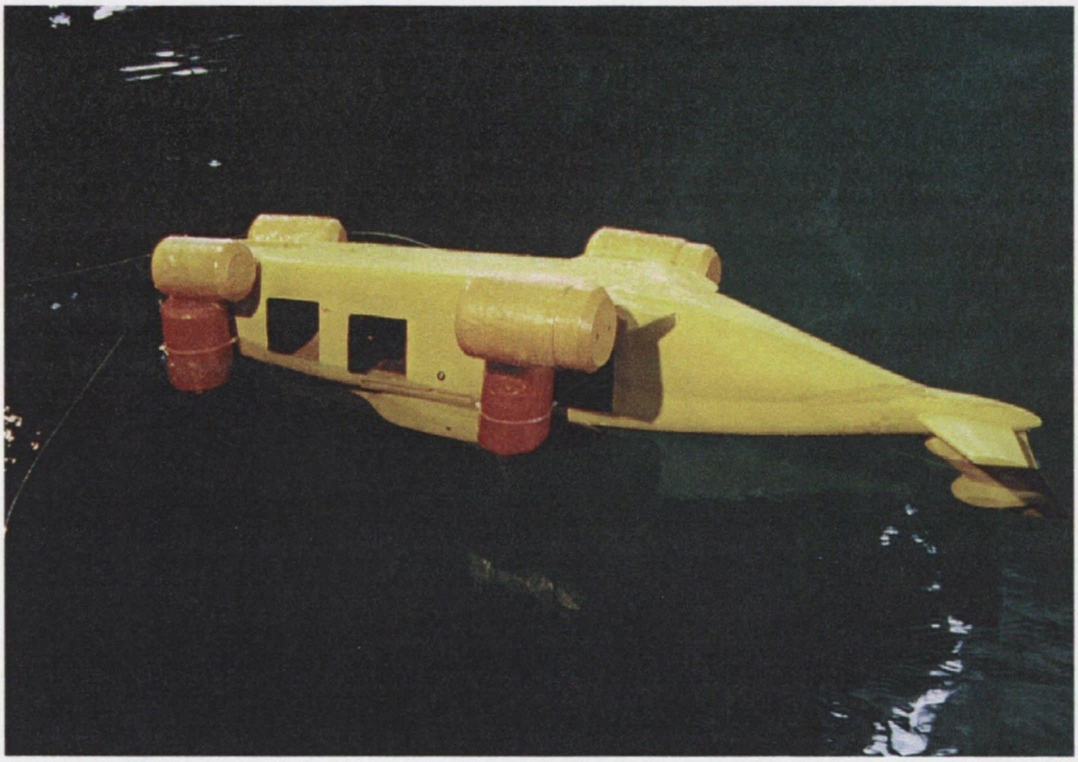

Figure 34 – Secured tethered units capsized.

5.7 Results Summary

The results described previously are summarised in Table 1.

Table 1 – Results Summary

Conditions:	Calm Water Attitude	Observed Wave Response	Ranking
Individual Systems			
Buoyant Cowling Panels ($6m^3$)	Excellent – doors and windows on one side of the aircraft well clear of water surface	Excellent	Best of the three systems
Buoyant Cowling Panels ($5m^3$)	Good – doors and windows on one side of the aircraft clear of water surface	Good	
Long Units Set 1 ($7.9m^3$)	Good – doors and windows on one side of the aircraft clear of water surface	Occasional waves over the doors and windows	Next best
Long Units Set 2 ($4.9m^3$)	Poor, Windows and doors on one side only just clear of water	Only half the doors and windows clear	
Long Units Single set 1	As double units but just slightly lower in the water	Similar behaviour to double units	
Tethered Units Set 1 ($8.3m^3$) free	Effectiveness is poor	Ineffective	Worst of the three systems
Tethered Units Set 1 ($8.3m^3$) secured	Good – doors and windows on both sides clear of surface	Ineffective, doors and windows mainly covered by water	
Tethered Units Set 2 ($5.6m^3$)	Not Tested	Not Tested	-
Combination			
Buoyant Cowling Panels ($6m^3$) plus single long bag (from Set 2)	Excellent – doors and windows on one side of the aircraft well clear of water surface	As for the $6m^3$ cowling, but with the advantage of no second capsize rotation.	-

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 $6m^3$ to $5m^3$ 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 $7.9m^3$ (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 $4.9\ m^3$ (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 capsize 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 capsize, shows clearly the initial capsize 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 $6m^3$ buoyant engine cowling panels. This had the key benefit of combining the effectiveness of the buoyant cowling with the removal of the second capsize 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 capsize 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.

6 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 $6m^3$ to $5m^3$ 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 $7.9m^3$ (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 $4.9\ m^3$ (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 trying 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 $6m^3$ buoyant cowling panel, 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.

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.

7 REFERENCES

[1] *Review of helicopter ditching performance,* BMT Offshore Ltd., Report on Project 44011/00 for the Civil Aviation Authority. Report 1 Release 2, July 1993.

[2] Kidwell J C, Crago W A, *Model testing to establish ditching and flotation stability characteristics of helicopters*, American Helicopter Society, 26th Annual Forum, Washington DC, June 1970.

[3] *Model Flotation Tests on the EH101 Helicopter (Civil Version)*, Report EEL/ED/414 Issue A

[4] *Helicopter Model Tests – Devices to Prevent Total Inversion*, HHTC Model Test Report Assignment T5ANR04J, October 1996.

[5] Olbers, D.J., Richter, K., Sell, W. and Walden, H., 1973, *Measurement of wind wave growth and swell decay during the 'Joint North Sea Wave Project' (JONSWAP).* Deutsches Hydrographisches Zeitschrift, Series A No.12.

Appendix A
Panel Meeting Background Briefing

HELICOPTER 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

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

[2] BHC Draft Report no. X/O/3282, 'Study of float positioning', November 1985.

[3] CAA-SRG Internal Report, 'Helicopter ditching survival aspects', ref. 9/31/R50-11C-3, September 1989.

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, capsize, 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 $3m^3$), 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

C.1. BMT marks

SJR's marks:

Device No.	Description	Effectiveness	Practicality	Safety	TOTAL POINTS	Rank
		Marks (out of 10)				
		1.50	1.00	1.00		
1	Foam-filled cowlings	6	5	10	24.0	2
2	Cowl integral float units	6	3	5	17.0	9
3	Rear fuselage buoyancy unit	1	8	10	19.5	7
4	Cabin ceiling float	4	8	8	22.0	4
5	Cabin wall floats	4	7	8	21.0	6
6	Collar under rotor head	6	5	5	19.0	8
7	Rotor flotation unit	10	3	6	24.0	2
8	Tethered flotation units	6	8	8	25.0	1
9	Buoyant seating	1	10	10	21.5	5
10	Foam-fill engine space	6	4	4	17.0	9

RGS's marks:

Device No.	Description	Effectiveness	Practicality	Safety	TOTAL POINTS	Rank
		Marks (out of 10)				
1	Foam-filled cowlings	8	7	10	29.0	1
2	Cowl integral float units	10	5	5	25.0	4
3	Rear fuselage buoyancy unit	3	10	10	24.5	8
4	Cabin ceiling float	5	10	8	25.5	3
5	Cabin wall floats	8	10	5	27.0	2
6	Collar under rotor head	10	5	5	25.0	4
7	Rotor flotation unit	10	3	5	23.0	9
8	Tethered flotation units	8	5	8	25.0	4
9	Buoyant seating	0	10	10	20.0	10
10	Foam-fill engine space	10	5	5	25.0	4

IWD's marks:

Device No.	Description	Effectiveness	Practicality	Safety	TOTAL POINTS	Rank
		Marks (out of 10)				
1	Foam-filled cowlings	8	3	7	22.0	5
2	Cowl integral float units	8	3	7	22.0	5
3	Rear fuselage buoyancy unit	1	2	1	4.5	10
4	Cabin ceiling float	7	6	6	22.5	4
5	Cabin wall floats	6	6	6	21.0	8
6	Collar under rotor head	9	4	9	26.5	2
7	Rotor flotation unit	10	4	10	29.0	1
8	Tethered flotation units	8	3	8	23.0	3
9	Buoyant seating	4	8	5	19.0	9
10	Foam-fill engine space	8	3	7	22.0	5

C.2. Average BMT marks

Device No.	Description	Effectiveness	Practicality	Safety	TOTAL POINTS	Rank	Ave. Rank
		Marks (out of 30)					
1	Foam-filled cowlings	22	15	27	75.0	2	3
2	Cowl integral float units	24	11	17	64.0	7	6
3	Rear fuselage buoyancy unit	5	20	21	48.5	10	8
4	Cabin ceiling float	16	24	22	70.0	5	4
5	Cabin wall floats	18	23	19	69.0	6	5
6	Collar under rotor head	25	14	19	70.5	4	5
7	Rotor flotation unit	30	10	21	76.0	1	4
8	Tethered flotation units	22	16	24	73.0	3	3
9	Buoyant seating	5	28	25	60.5	9	8
10	Foam-fill engine space	24	12	16	64.0	7	6

C.3. GKN-WHL Marks

AB's marks:

Device No.	Description	Effectiveness 1.50	Marks (out of 10) Practicality 1.00	Safety 1.00	TOTAL POINTS	Rank
1	Foam-filled cowlings	8	6	8	26.0	1
2	Cowl integral float units	9	3	3	19.5	7
3	Rear fuselage buoyancy unit	3	8	8	20.5	5
4	Cabin ceiling float	5	7	6	20.5	5
5	Cabin wall floats	8	7	6	25.0	3
6	Collar under rotor head	8	2	2	16.0	9
7	Rotor flotation unit	9	1	1	15.5	10
8	Tethered flotation units	7	8	7	25.5	2
9	Buoyant seating	4	8	9	23.0	4
10	Foam-fill engine space	7	5	1	16.5	8

MJL's marks:

Device No.	Description	Effectiveness	Marks (out of 10) Practicality	Safety	TOTAL POINTS	Rank
1	Foam-filled cowlings	10	5	10	30.0	3
2	Cowl integral float units	10	3	8	26.0	7
3	Rear fuselage buoyancy unit	7	9	10	29.5	4
4	Cabin ceiling float	10	7	6	28.0	6
5	Cabin wall floats	10	10	10	35.0	1
6	Collar under rotor head	10	7	7	29.0	5
7	Rotor flotation unit	10	3	4	22.0	8
8	Tethered flotation units	10	8	9	32.0	2
9	Buoyant seating	4	7	7	20.0	9
10	Foam-fill engine space	3	4	6	14.5	10

SC's marks:

Device No.	Description	Effectiveness	Marks (out of 10) Practicality	Safety	TOTAL POINTS	Rank
1	Foam-filled cowlings	7	7	8	25.5	2
2	Cowl integral float units	8	5	5	22.0	4
3	Rear fuselage buoyancy unit	4	7	8	21.0	5
4	Cabin ceiling float	5	6	4	17.5	10
5	Cabin wall floats	9	8	8	29.5	1
6	Collar under rotor head	7	4	4	18.5	8
7	Rotor flotation unit	8	3	5	20.0	6
8	Tethered flotation units	8	6	6	24.0	3
9	Buoyant seating	3	8	6	18.5	8
10	Foam-fill engine space	8	5	3	20.0	6

C.4. Average GKN-WHL marks

Device No.	Description	Effectiveness	Marks (out of 30) Practicality	Safety	TOTAL POINTS	Rank	Ave. Rank
1	Foam-filled cowlings	25	18	26	81.5	2	2
2	Cowl integral float units	27	11	16	67.5	5	6
3	Rear fuselage buoyancy unit	14	24	26	71.0	4	5
4	Cabin ceiling float	20	20	16	66.0	6	7
5	Cabin wall floats	27	25	24	89.5	1	2
6	Collar under rotor head	25	13	13	63.5	7	7
7	Rotor flotation unit	27	7	10	57.5	9	8
8	Tethered flotation units	25	22	22	81.5	2	2
9	Buoyant seating	11	23	22	61.5	8	7
10	Foam-fill engine space	18	14	10	51.0	10	8

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

Device No.	Description	Marks (out of 60) Effectiveness	Practicality	Safety	TOTAL POINTS	Rank	Ave. Rank
1	Foam-filled cowlings	47	33	53	156.5	2	2
2	Cowl integral float units	51	22	33	131.5	7	6
3	Rear fuselage buoyancy unit	19	44	47	119.5	9	7
4	Cabin ceiling float	36	44	38	136.0	4	5
5	Cabin wall floats	45	48	43	158.5	1	4
6	Collar under rotor head	50	27	32	134.0	5	6
7	Rotor flotation unit	57	17	31	133.5	6	6
8	Tethered flotation units	47	38	46	154.5	3	3
9	Buoyant seating	16	51	47	122.0	8	8
10	Foam-fill engine space	42	26	26	115.0	10	7

Alternative Overall Ranking Scheme
Number of ranked 1st, 2nds and 3rds
Score 3 for a first, 2 for a 2nd, 1 for a third

		No. 1sts	No. 2nds	No 3rds		Rank
		3	2	1		
1	Foam-filled cowlings	2	2	1	11	1
2	Cowl integral float units				0	
3	Rear fuselage buoyancy unit				0	
4	Cabin ceiling float				0	
5	Cabin wall floats	2	1	1	9	2
6	Collar under rotor head		1		2	5
7	Rotor flotation unit	1	1		5	4
8	Tethered flotation units	1	2	2	9	2
9	Buoyant seating				0	
10	Foam-fill engine spaces				0	

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

Unit	Prototype Length (m)	Model Length (m)	Prototype Diam. (m)	Model Diam. (m)	Prototype Volume (m^3)	Model Volume (m^3)
Forward	1.83	0.183	1.07	0.107	1.64(each)	0.00164
Main	2.38	0.238	1.42	0.142	3.77(each)	0.00377

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

Device	No Off	Prototype Length (m)	Model Length (m)	Prototype Diam. (m)	Model Diam. (m)	Prototype Volume (m^3, each)	Model Volume (m^3, each)	% over 6 m^3
Long Units(Set 1)	2	6.20	0.620	0.90	0.090	3.94	0.00394	31.5
Long Units(Set 2)	2	5.55	0.555	0.75	0.075	2.45	0.00245	-18.3
Tethered Units(Set 1)	4	2.00	0.200	1.20	0.120	2.08 **	0.00226	38.7
Tethered Units(Set 2)	4	2.00	0.200	1.00	0.100	1.39 **	0.00157	-7.3
Buoyant Cowling	1	Thickness (m)		0.200	0.020	6.20	0.00620	3.3
Reduced Buoyant Cowling	1	Thickness (m)		0.200	0.020	5.10	0.00510	-15.0

** 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

Full Load Condition				
	Required		Achieved	
Parameter	**Prototype**	**Model**	**Model**	**Prototype**
Displacement (kg)	14290	13.94	13.94	14290
XCG (m)	8.385	0.839	0.839	8.390
YCG (m)	-0.0076	-0.001	0.0	0.0
ZCG (m)	2.675	0.268	0.268	2.680
k_{xx} (Roll) (m)	1.503	0.150	0.153	1.530
k_{yy} (Pitch) (m)	3.271	0.327	0.329	3.290

Half Fuel Condition				
	Required		Achieved	
Parameter	**Prototype**	**Model**	**Model**	**Prototype**
Displacement (kg)	12839	12.53	12.53	12839
XCG (m)	8.295	0.830	0.830	8.300
YCG (m)	-0.0085	-0.001	0.0	0.0
ZCG (m)	2.843	0.284	0.282	2.820
k_{xx} (Roll) (m)	1.501	0.150	0.150	1.500
k_{yy} (Pitch) (m)	3.350	0.335	0.302 ***	3.020

*** 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 co-ordinates of this point, defined from the same origin as the helicopter centre of gravity are as follows:

Origin of Acceleration Measurements (full scale distance in metres)

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 Hs = 2.0 m, To = 5.8 s WAVE CONDITION B						
MOTION STANDARD DEVIATIONS						
RUN	HELICOPTER CONDITION	ROLL	HEAVE	HEAVE	SWAY	SWAY
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
703	Set 1 bags on both sides	6.22	1.04	5.74	0.27	0.84
704	Set 1 bag, port side, upwave	4.82	0.94	5.09	0.17	0.45
709	Set 1 bag, port side, downwave	7.25	0.84	4.44	0.33	1.03
801	Buoyant Cowling	5.32	1.11	6.29	0.32	1.01
1006	" " (reduced Volume)	5.11	1.07	6.13	0.31	0.87

BEAM SEAS Hs = 2.9 m, To = 6.04 s WAVE CONDITION E						
MOTION STANDARD DEVIATIONS						
RUN	HELICOPTER CONDITION	ROLL	HEAVE	HEAVE	SWAY	SWAY
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
702	Set 1 bags on both sides	8.03	1.30	8.36	0.32	1.01
705	Set 1 bag, port side, upwave	6.56	1.21	7.61	0.23	0.66
708	Set 1 bag, port side, downwave	9.24	1.08	6.54	0.44	1.62
802	Buoyant Cowling	7.06	1.38	8.91	0.43	1.53
1005	" " (reduced Volume)	6.86	1.36	8.85	0.43	1.36

BEAM SEAS Hs = 4.3 m, To = 6.32 s WAVE CONDITION F						
MOTION STANDARD DEVIATIONS						
RUN	HELICOPTER CONDITION	ROLL	HEAVE	HEAVE	SWAY	SWAY
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
701	Set 1 bags on both sides	9.64	1.46	10.96	0.55	2.11
706	Set 1 bag, port side, upwave	8.11	1.37	9.51	0.32	1.06
707	Set 1 bag, port side, downwave	10.18	1.25	9.32	0.53	2.38
803	Buoyant Cowling	8.77	1.51	11.26	0.55	2.64
1004	" " (reduced Volume)	8.50	1.49	11.49	0.50	1.97

Table 5 – Motion Data Statistics – Head Seas

HEAD SEAS Hs = 2.0 m, To = 5.8 s WAVE CONDITION B						
	MOTION STANDARD DEVIATIONS					
RUN	HELICOPTER CONDITION	PITCH	HEAVE	HEAVE	SURGE	SURGE
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
904	Set 1 bags on both sides	3.72	0.64	3.19	0.21	0.56
908	Set 1 bag, port side	3.64	0.62	3.10	0.23	0.65
1001	Buoyant Cowling (reduced Vol.)	4.18	0.79	4.06	0.20	0.50

HEAD SEAS Hs = 2.9 m, To = 6.04 s WAVE CONDITION E						
	MOTION STANDARD DEVIATIONS					
RUN	HELICOPTER CONDITION	PITCH	HEAVE	HEAVE	SURGE	SURGE
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
903	Set 1 bags on both sides	5.35	0.87	5.01	0.29	0.92
907	Set 1 bag, port side	5.12	0.84	4.92	0.33	1.11
1002	Buoyant Cowling (reduced Vol.)	5.89	1.01	5.96	0.29	0.88

HEAD SEAS Hs = 4.3 m, To = 6.32 s WAVE CONDITION F						
	MOTION STANDARD DEVIATIONS					
RUN	HELICOPTER CONDITION	PITCH	HEAVE	HEAVE	SURGE	SURGE
NUMBER			ACCEL.	SMM	ACCEL.	SMM
		(deg)	(m/s^2)		(m/s^2)	
905	Set 1 bags on both sides	7.03	1.10	7.88	0.35	1.26
906	Set 1 bag, port side	6.65	1.06	7.54	0.40	1.53
1003	Buoyant Cowling (reduced Vol.)	7.54	1.19	8.37	0.35	1.17

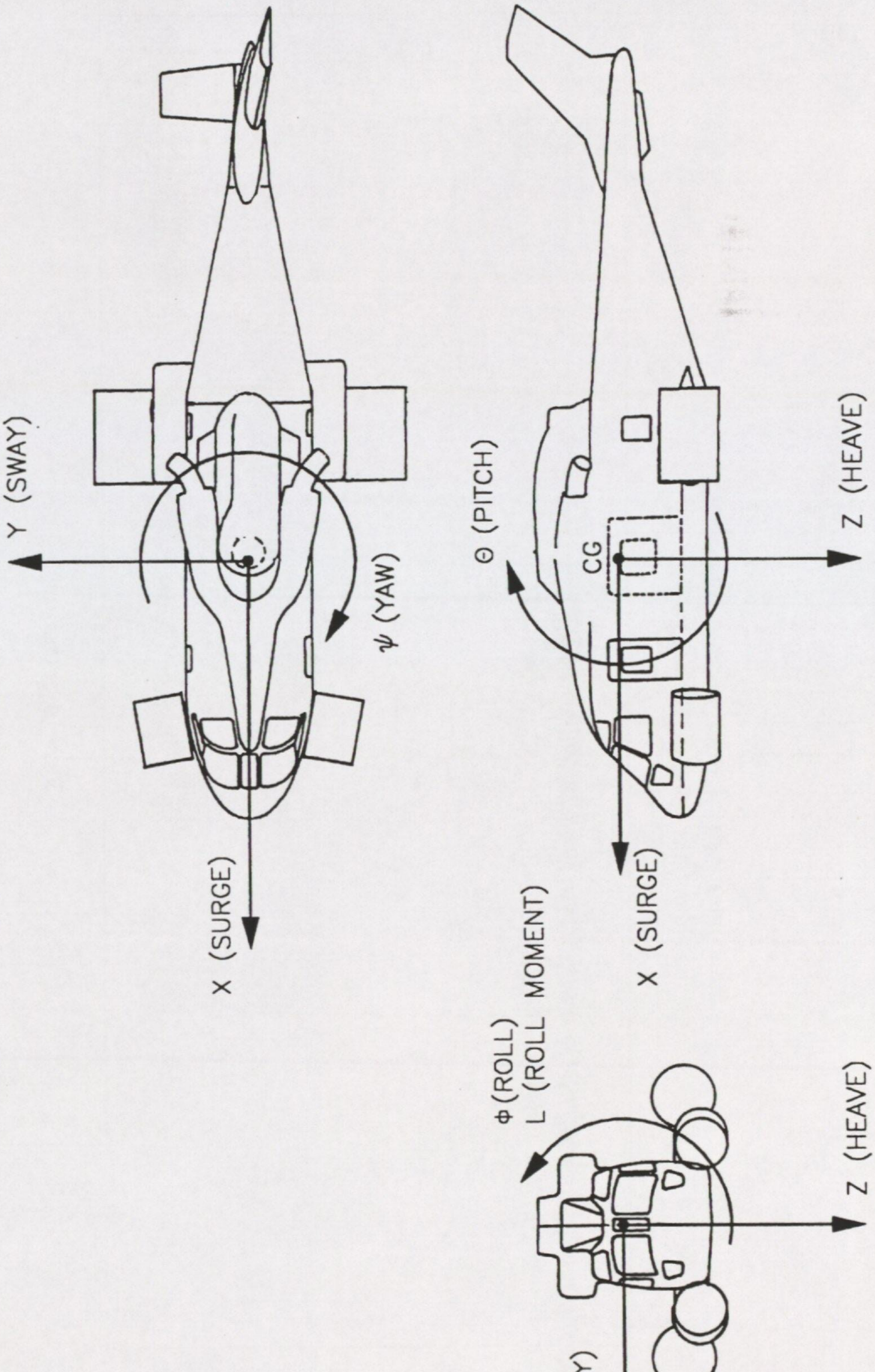

Figure 35 – Helicopter motions sign convention.

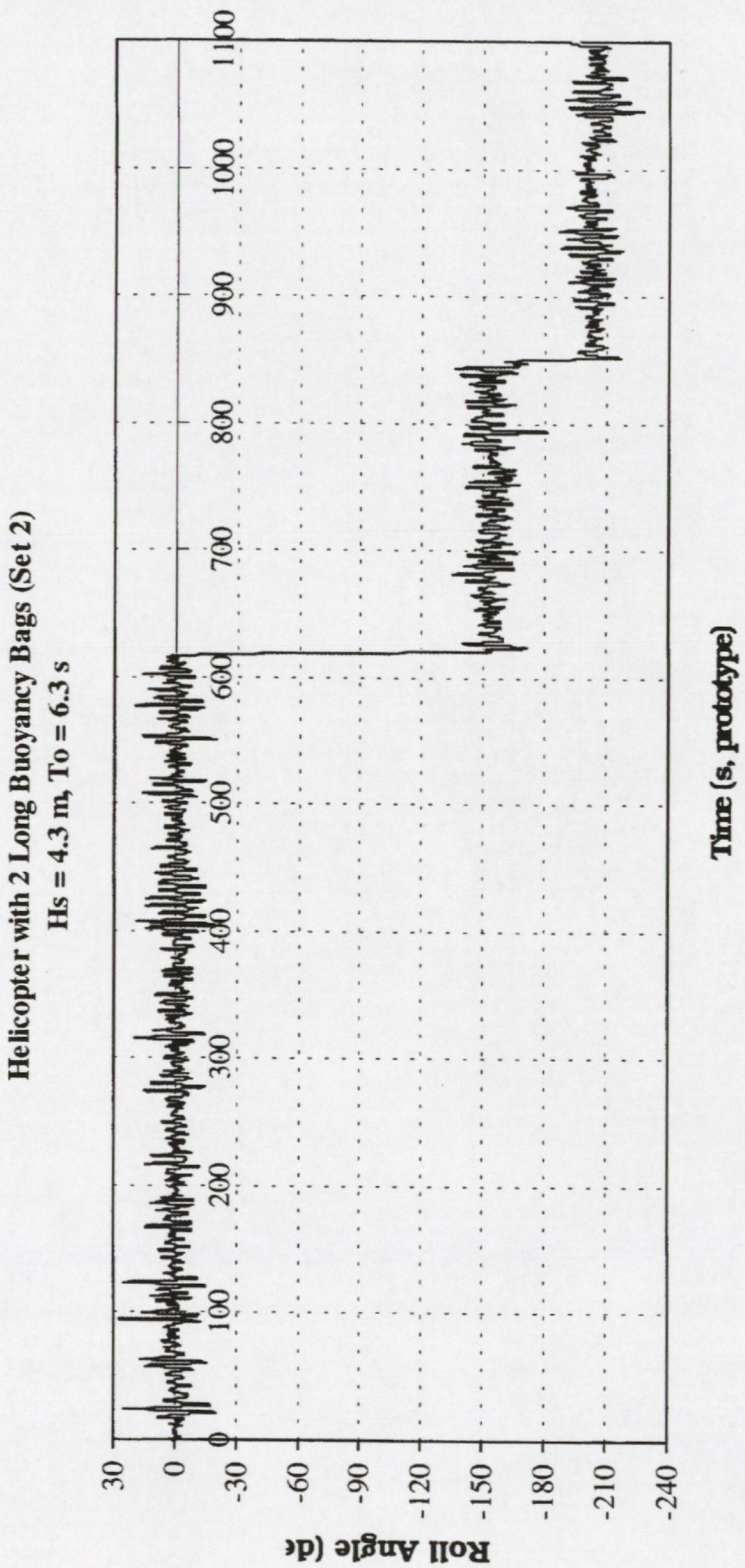

Figure 36 – Typical capsize time history (showing two rotations).

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.

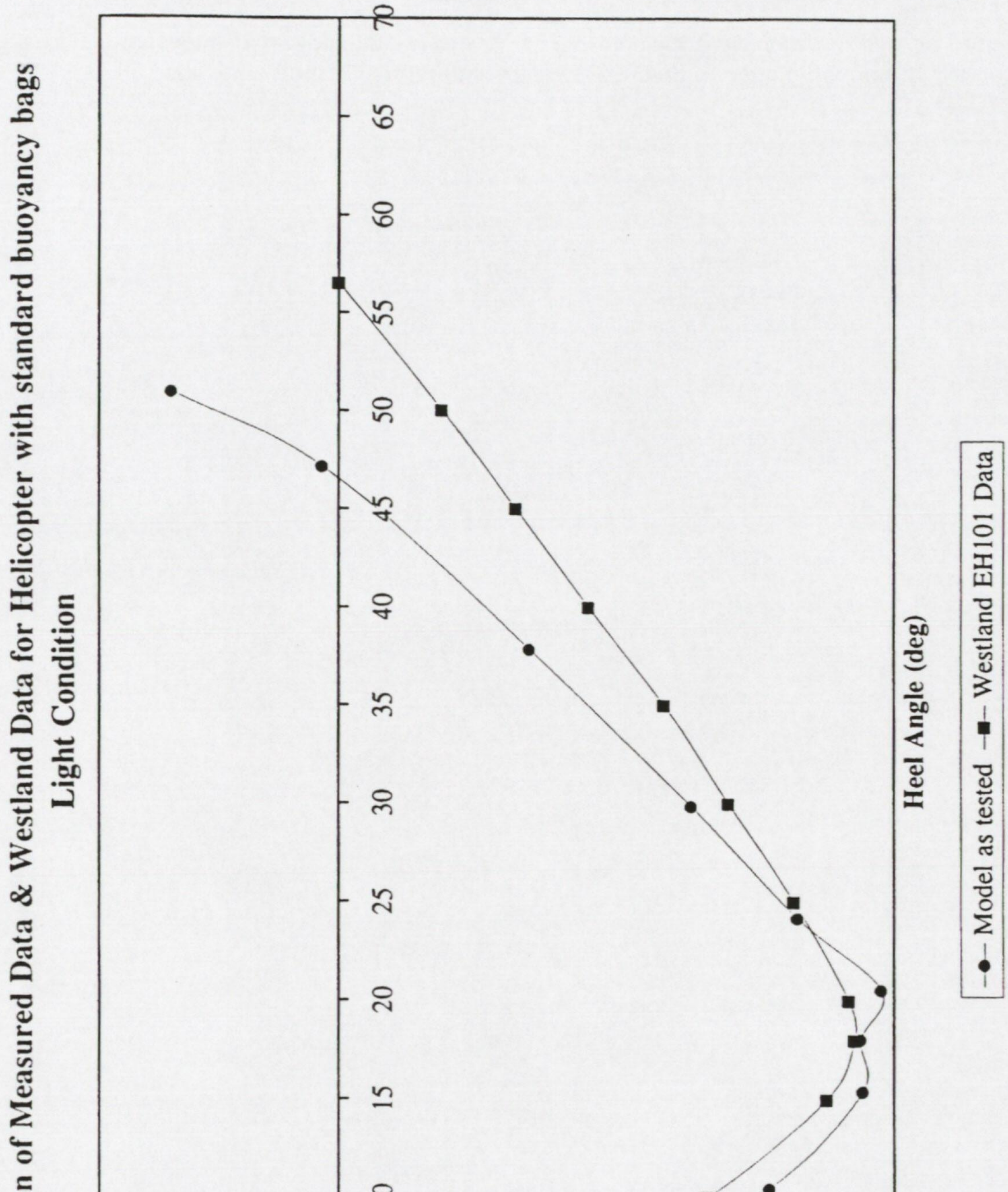

Figure 37 – Roll righting moment – Standard helicopter.

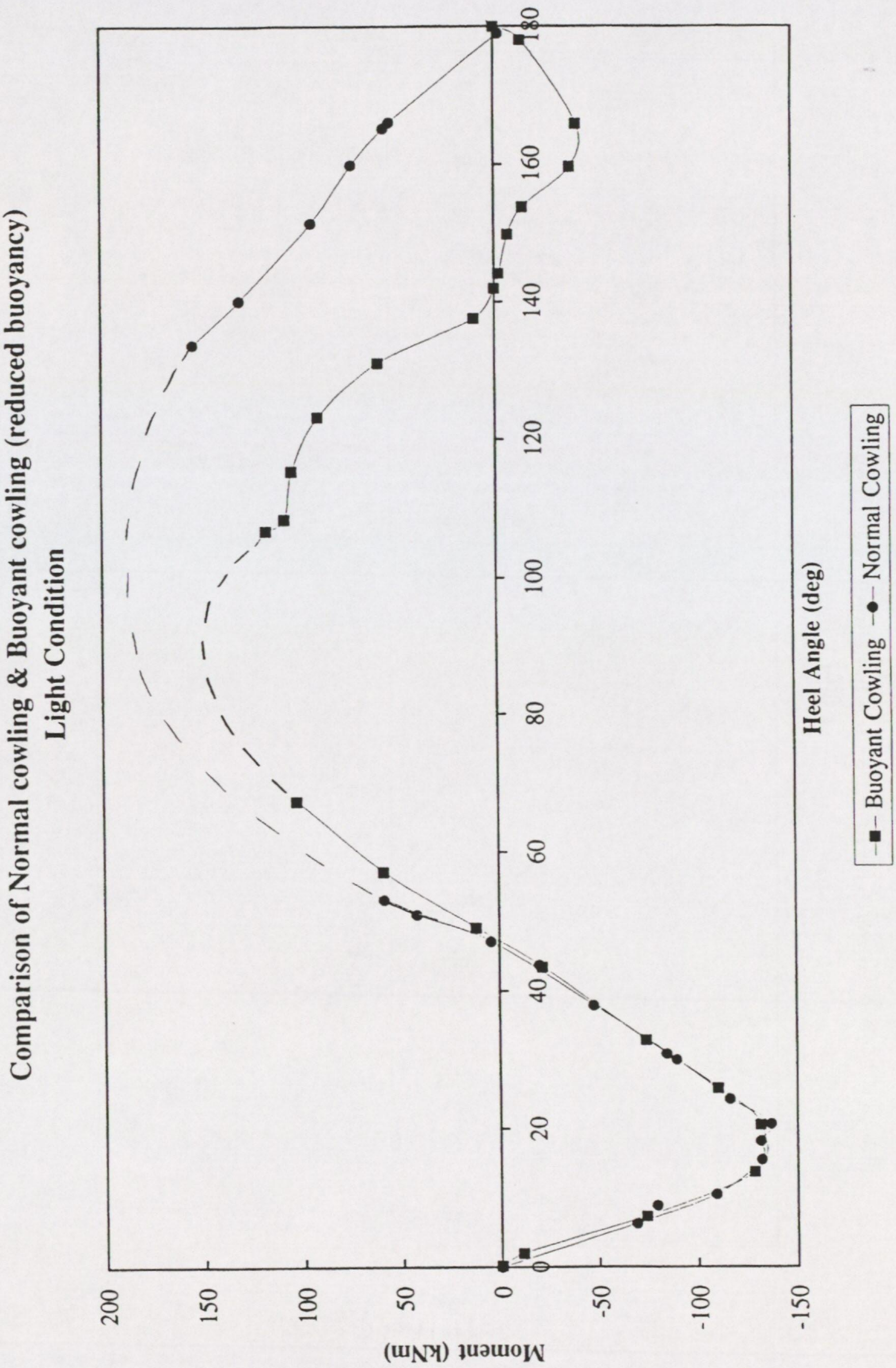

Figure 38 – Roll righting moment – Comparing buoyant cowling with standard helicopter.

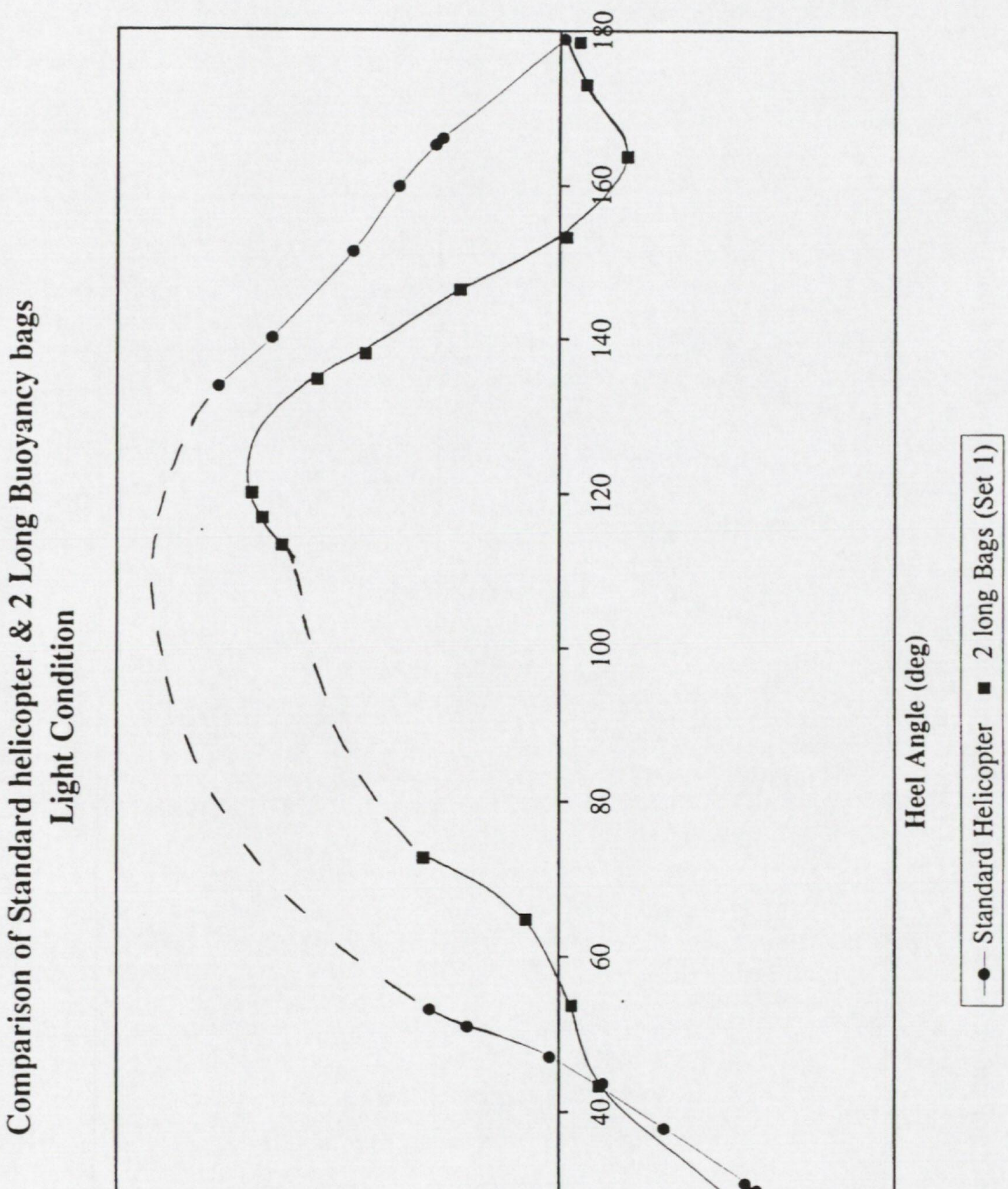

Figure 39 – Roll righting moment – Comparing 2 long buoyancy bags with standard helicopter.

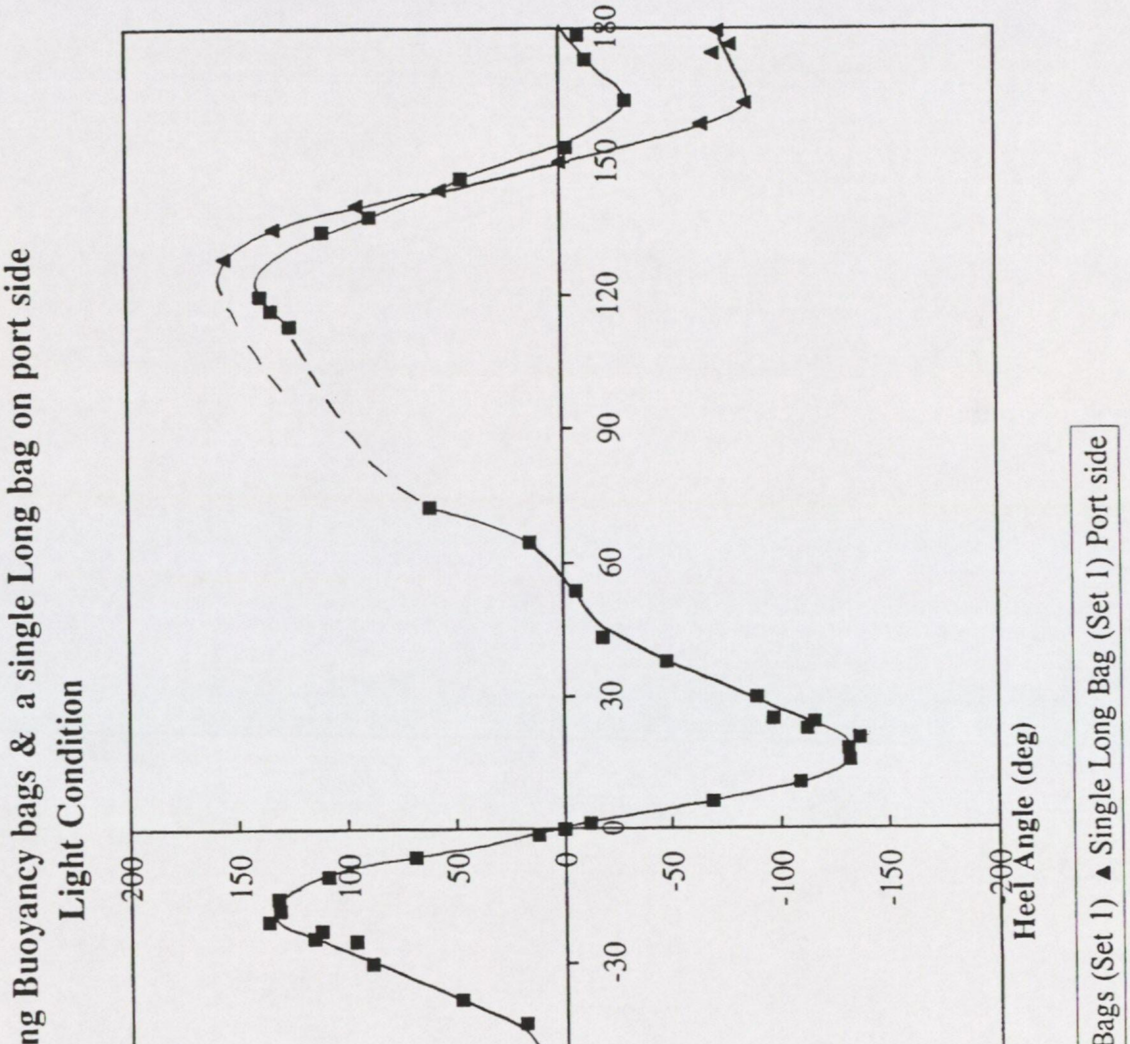

Figure 40 – Roll righting moment – Comparing single long buoyancy bag with standard helicopter.