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Summary Report on Helicopter Ditching and Crashworthiness Research

Part A General

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Executive Summary

This report summarises the results of research activities undertaken over a period of about twelve years, aimed at improving the safety of offshore helicopter operations, and initiated by the UK Civil Aviation Authority (CAA) in response to recommendations made in the 1984 HARP and 1995 RHOSS reports. A number of associated but hitherto unpublished papers and research reports are attached as appendices to this report.

Review studies found ambiguities in the requirements for helicopter ditching, and raised questions about how the sea states specified in the requirements should be interpreted, and whether model tests should be performed in regular or irregular waves. There was evidence that helicopters capsize in breaking waves only, and that the occurrence of breaking waves in regular wave tests depends mainly on the characteristics of the test tank. Tests in irregular waves are considered to be more realistic and meaningful, and are to be preferred.

These review studies also questioned whether more stringent ditching criteria might be appropriate in sea areas where conditions are more severe. There are substantial differences in capsize risk between helicopters designed to sea state 4 and sea state 6 ditching criteria, between helicopter operations in the Northern and Southern North Sea, and between summer and winter operations.

An early experimental study had shown the benefits of float scoops for preventing helicopter capsize after ditching. An improvement in sea-keeping performance of one sea state was consistently obtained for a very modest increase in cost and weight.

In recognition of the mismatch between the practical upper limit of helicopter sea-keeping performance and prevailing wave climates, additional emergency flotation systems were subsequently devised to prevent total inversion following capsize. The aim of this scheme is to mitigate the consequences of capsize by ensuring that an air pocket is retained within the cabin, reducing the time pressure to escape, and that some of the escape routes remain above the water level facilitating egress. Three such systems were model-tested in a wave tank. The most effective device proved to be buoyant engine cowling panels, and the second most effective was cabin wall floats. Having a cabin wall float on one side of the helicopter proved to be almost as effective as units on both sides, and prevented the occurrence of a double rotation after capsize. Both devices (buoyant engine cowling panels and cabin wall floats) were considered worthy of further development. Passenger egress trials using a helicopter underwater escape trainer confirmed the benefits of side-flotation for improving chances of escape and survival after capsize.

Investigations were also undertaken into possible ways to improve the crashworthiness of emergency flotation systems (EFS). Three survivable water impacts were studied using finite element modelling techniques to establish the nature of the loads experienced. A number of EFS modifications were recommended to improve performance following a severe impact. These modifications were considered to be cost-effective, and some are already incorporated into modern EFS design. Automatic arming and activation of emergency flotation systems were judged to be the most cost effective.

An associated study considered variability in water impact loads on typical flotation components over a wide range of possible survivable crash scenarios and sea conditions. The most important outcome from this study was in highlighting the major benefits of flotation redundancy, particularly having additional flotation units installed at a location less vulnerable to water impact, high on the cabin walls. Similar floats had been proposed to prevent total helicopter inversion following capsize.

A study on emergency breathing systems (EBS) showed that such systems could help to overcome cold shock and extend underwater survival times. At the end of this study, however, CAA reviewed its policy on EBS and concluded that there was no compelling case to either mandate or ban the use of EBS.

Follow-up reports by a JAA and a JAA/ FAA working group supported the above findings, and recommended changes to the sea conditions to be used in EFS and ditching equipment certification, adoption of an irregular wave model testing standard, no change to existing structural ditching requirements, automatic activation and arming of flotation systems, guidance on the benefits of fitting scoops, adoption of best current practice in EFS design for crashworthiness, and further studies on the merits of EBS. The working groups supported further development of the side-floating helicopter concept, for which the next step is a helicopter type-specific design study.

1 Introduction

This report summarises and consolidates the results from a number of research activities, initiated by the UK Civil Aviation Authority (CAA) over a period of about twelve years in response to recommendations made in the 1984 HARP [1][1] and 1995 RHOSS [2] Reports. The objective of this research was to improve the safety of offshore helicopter operations and, in particular, to improve survival and escape prospects for those on board a helicopter that ditches or crashes onto water. These research activities included investigations into means of improving the sea-keeping performance of ditched helicopters, mitigating the consequences of capsize, and means of improving the crashworthiness of emergency flotation systems.

A secondary purpose of this report is to provide a vehicle for the publication of a number of related minor studies and other unpublished work, setting them in the proper context.

1.1 Background

Helicopters are an essential part of offshore oil and gas industry operations. A recent review [3, 4] noted that 90,000 hours and about 200,000 sectors are flown each year on the UK Continental Shelf (UKCS). Since 1976 there have been 12 fatal helicopter accidents associated with UKCS offshore operations, which have claimed a total of 118 lives. The UKCS offshore helicopter fleet experienced no accidents in the last year (2003) for which statistics were available, and the last fatal accident occurred in 2002 resulting in 11 fatalities. Previously [3] there had not been a fatal offshore accident since 1992. In 2003 the five-year moving average total accident rate was 1.77 per 100,000 flying hours, and the fatal accident rate was 0.25 per 100,000 flying hours. In view of the fact that these operations are performed over long distances and in an often-hostile environment, this is considered to be a good safety record.

1.2 The HARP Report

A major review of helicopter certification standards was commissioned in 1982 at the request of the Chairman of the CAA, to consider whether current technology could be employed to design helicopters to meet enhanced standards of airworthiness. A joint CAA/ Industry group, known as the Helicopter Airworthiness Review Panel (HARP), was given the following primary terms of reference:

1. "To review the existing airworthiness requirements for public transport helicopters, taking into account associated operational practice."
2. "To recommend in principle such changes as are considered necessary and practicable to ensure that the safety standards of these aircraft match more closely those of comparable fixed wing aircraft."

The HARP findings were published by the CAA in 1984 in what is commonly referred to as the HARP Report [1]. Of the fifteen recommendations contained in the report, two related to crashworthiness and two related to ditching. The Panel's recommendations on ditching and crashworthiness led directly to the programme of research described in this report.

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[1] The reference list may be found in Section 9 on page 42.

The HARP Report stated that ditching was of particular concern to the British helicopter industry because of the long distances flown over water, and recommended that resolution of the stability problems of ditched helicopters should be urgently addressed. Moreover, the Report stated that:

> "The frequency of forced landings (and hence in over-water operations of ditchings) is such that a high probability of survival of all occupants is essential. To achieve this, the helicopter must have adequate buoyancy, stability, practicable means of escape and effective life-raft equipment.
>
> Buoyancy needs to be assured in order to provide the pilot with ditching as an acceptable option, and there are strong arguments in favour of deployment of flotation bags before contact with the water. … The need for stability is emphasised by the very limited practicability of escape from a capsized helicopter. The conditions on which the stability of the helicopter should be demonstrated must take account of realistic wind speeds accompanying severe sea states. Special consideration needs to be given to conditions in the very inhospitable areas such as the Northern North Sea."

1.3 The RHOSS Report

A Review of Helicopter Offshore Safety and Survival (RHOSS) was commissioned by the CAA in response to recommendations made by the accident investigators after a fatal helicopter accident near the Cormorant Alpha platform in the North Sea in March 1992. The joint CAA/ Industry group reported its findings in the so-called RHOSS Report, published in 1995 [2].

The RHOSS Report distinguished between a 'ditching', described as a controlled descent (with some measure of warning) into a 'non-hostile' sea, and a 'crash', which encompassed all uncontrolled or inadvertent impacts with the water, controlled descents into a hostile sea, and a helicopter falling off a helideck. Accident statistics indicated that there was no significant difference between the rate of occurrence of survivable impacts on water and ditchings. It would not be reasonable, therefore, to optimise safety measures entirely in favour of one at the expense of the other. The report noted that important safety requirements, such as flotation equipment and life-raft activation, had been framed around the ditching scenario, but more needed to be done to improve the prospects of survival after a crash.

The RHOSS Report supported the then ongoing research into helicopter crashworthiness, flotation and stability, and the automation of emergency flotation equipment activation. It stressed the need to improve provision for flotation after a severe water impact, including the possibility of installing extra flotation devices specifically to cater for a crash. Improved flotation would make a major contribution to prospects for safe escape. The report noted that the CAA would only be justified in requiring additional safety measures, however, when these are expected to produce overall benefits at a reasonable cost.

The RHOSS Report dismissed as impractical the prohibition of offshore flights in weather unsuitable for ditching. The report nonetheless stressed that it would not be defensible to allow flights to proceed in conditions such that, if an accident were to occur, survivors did not have a realistic expectation of being rescued. It was therefore necessary to develop a procedure by which offshore managers could assess the relationship between the time required to rescue survivors of a crash and the time that they could be expected to survive in the sea in the prevailing conditions. The RHOSS Report concluded by noting that, following the Cormorant Alpha experience, a more realistic attitude now prevailed concerning use of helicopters for other than essential purposes in marginal weather conditions.

1.4 Scope and Structure of This Report

The CAA's on-going research activities in helicopter ditching and water impact followed directly from the recommendations of the HARP and RHOSS Reports, and form the basis for the present report. Figure 1 illustrates the chronological relationship between these research activities and the HARP (box 1) and RHOSS (box 4) reports, and refers to CAA papers in which results from this research are presented, together with a number of hitherto unpublished papers and reports, which are included as Appendices to this report.

The research detailed in Figure 1 is covered in the report as follows:

- Box 2 – Sections 2 and 3.2 (float scoops).
- Box 3 – Section 4.
- Box 5 – Section 3.3
- Box 6 – Section 4.
- Box 7 – Section 5.
- Box 8 – Section 6.2.

All of the CAA's ditching and water impact research has been presented to, and reviewed by, two international regulatory bodies: the JAA HOSS and the FAA/JAA WIDDCWG. These activities are covered in Section 6.1.

Overall top-level conclusions of all the research performed are presented in Section 7 of this report, and lists of abbreviations and references are given in Sections 8 and 9 respectively.

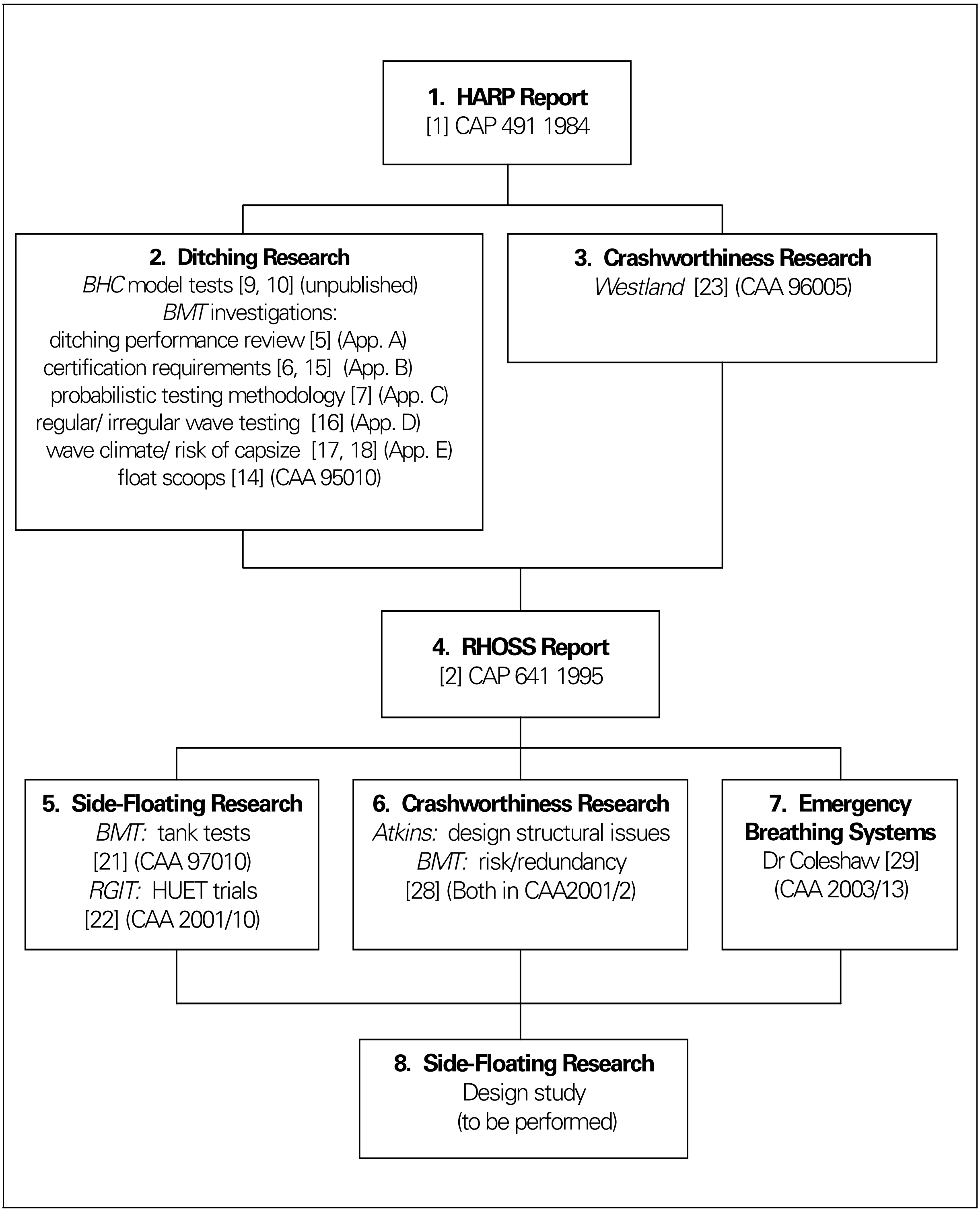

Figure 1 Chronological relationship between safety research activities.

2 Ditching Performance and Requirements

2.1 Introduction

All European and US helicopters currently used in support of offshore oil and gas exploration and production have been certificated in accordance with the requirements of JAR/FAR 27 or 29. Contained within these codes are requirements

27/29.801 pertaining to 'ditching', which is defined to be an emergency landing on water, deliberately executed, with the intent of abandoning the helicopter as soon as practical. The helicopter is assumed to be intact prior to water entry, with all controls and essential systems, except engines, functioning properly.

Whilst compliance with requirement 27 or 29.801 is optional for the manufacturer, operational rules prescribe a number of requirements applicable when the helicopter is being operated over water. These rules specify equipment intended to enhance occupant survivability in the event of a forced landing on the surface of the water. Those helicopters being operated under FAR Part 135 are required to be equipped with floats when operating over water. Those helicopters operating under JAR OPS 3 are required to be similarly equipped, except those operating in Performance Class 1 (Category A engine failure accountability), which are permitted to operate up to 10 minutes flying time from land without floats. Such equipment is intended to keep the helicopter upright on the surface long enough for the occupants to escape. The FAR and JAR also require life-rafts, life-jackets and survival equipment to be carried in order to enhance survivability until rescue arrives.

2.2 Helicopter Ditching Review

In 1992 the CAA commissioned BMT to review a number of documents relating to helicopter ditching, including the then-current UK Emergency Alighting on Water helicopter design requirements specified in British Civil Airworthiness Requirements (BCAR) Paper no. G779, dated 7 October 1985. The objectives of these review studies, reported in [5, 6, 7], were:

- To carry out a critical review of certain documents relating to ditching performance and requirements, to draw conclusions and prepare an overview document suitable for publication by the CAA.
- To perform a critical review of BCAR Paper no. G779 relating to helicopter ditching, to recommend how the BCAR requirements might be improved and whether there were better ways to assess a helicopter's water-borne stability.
- To review helicopter ditching performance over the previous 20 years, and to assess the practicality of imposing a new probability-based methodology for North Sea helicopter operations.

2.2.1 Helicopter Ditching Performance Review (1993)

The first of these BMT reports [5] was prepared in 1993 to meet the first of the above objectives, and is reproduced in Appendix A.

An earlier internal CAA report [8] had stated that the objective of ditching certification is to ensure that the helicopter remains upright for sufficient time for the occupants to escape (5 minutes). This means that there should be an acceptably low probability of meeting a wave that is large enough or steep enough to capsize the helicopter in this short time interval. BMT's report [5] noted that the probability of experiencing a capsize depends on two key factors:

- The height and period (or slope) of the wave required to capsize the helicopter.
- The probability of experiencing such a wave, or larger, during the exposure period.

The report went on to review the current understanding of these two factors as evidenced by five reports [8, 9, 10, 11, 12], then drew attention to gaps in current understanding and made recommendations about the direction of future research. The report concluded that there were more important gaps in current understanding of the first factor than of the second.

Results from model tests performed by the British Hovercraft Corporation (BHC) on a range of different helicopter types were examined. These tests had been performed in both regular and irregular waves. The results showed that the helicopter types tested generally had little difficulty in complying with the (then-current) BCAR regular wave steepness criterion, but all had capsized in irregular waves less severe than the implied BCAR sea state 6 limit.

Little attempt had been made in previous test reports to interpret the capsize boundary in terms of the helicopter's physical properties or static stability. Some weak relationships were identified during BMT's review study. Thus, for example, Figure 2 shows that heavier helicopter types and loading conditions tended to be more stable. The same was also true of helicopters with broader beams (see Figure 3) and certain higher static stability parameters. There was little confidence, however, that these weak relationships could be used to design modifications to the helicopter that would result in improved stability in waves. It was nonetheless clear that capsize of the model helicopter was very sensitive to precise details of the model and waves, possibly explaining some of the difficulty experienced when attempting to correlate the results.

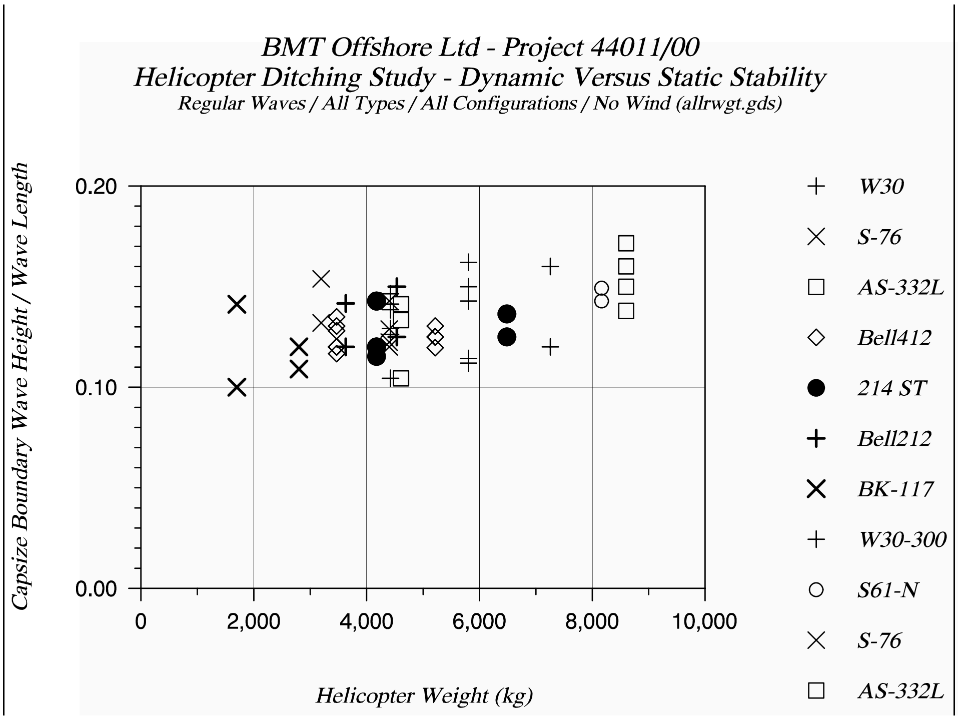

Figure 2 Influence of helicopter weight on regular wave stability boundary.

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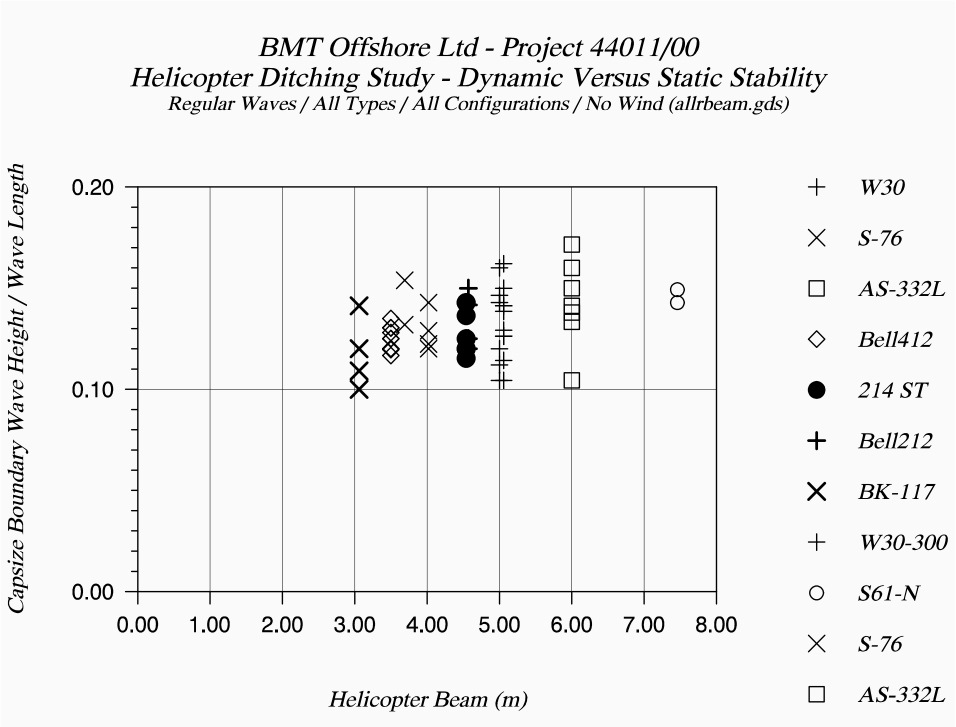

Figure 3 Influence of helicopter beam on regular wave stability boundary.

Interpreting results from tests in irregular waves proved to be especially difficult. Results were sometimes presented in terms of sea state numbers, rather than the less ambiguous significant wave height and period parameters. Poor wave spectrum shapes and unrealistic combinations of wave height and period (i.e. steepness) were also found.

Capsize was essentially caused by breaking waves, and it was considered unlikely that an undamaged helicopter would capsize in non-breaking waves. The mechanism of helicopter capsize was considered to be similar to that experienced by small vessels, including sailing yachts, in severe weather. The capsize process has been described as a 'knock-down', and key stages are illustrated in Figure 4 using a Bell Jet Ranger helicopter as an example.

At stage 1 the beam-on helicopter experiences the steepening front face of the wave. The floats make the helicopter statically quite stiff in roll, so that the helicopter tries to remain aligned with the wave slope and therefore heels away from the approaching crest (stages 2 and 3). When the up-wave float is near the wave crest, the breaking wave projects a high-velocity horizontal water jet at the up-wave float (or, in the case of larger hull-floating helicopters, at the side of the fuselage). The impact of water momentum in the breaking part of the wave, combined with a tendency for the down-wave float to 'dig in' to the water causes a number of things to happen. A sudden powerful overturning moment (stages 4 to 6) is generated between the point of water impact and the 'dug-in' float. The total immersion of the down-wave float, and the fact that the up-wave float is by now completely out of the water, means that the restoring roll moment (tending to maintain the hull aligned with the water surface) is now reducing. If the overturning energy imparted by the breaking wave exceeds the capacity of the reduced roll restoring moment, then capsize will occur.

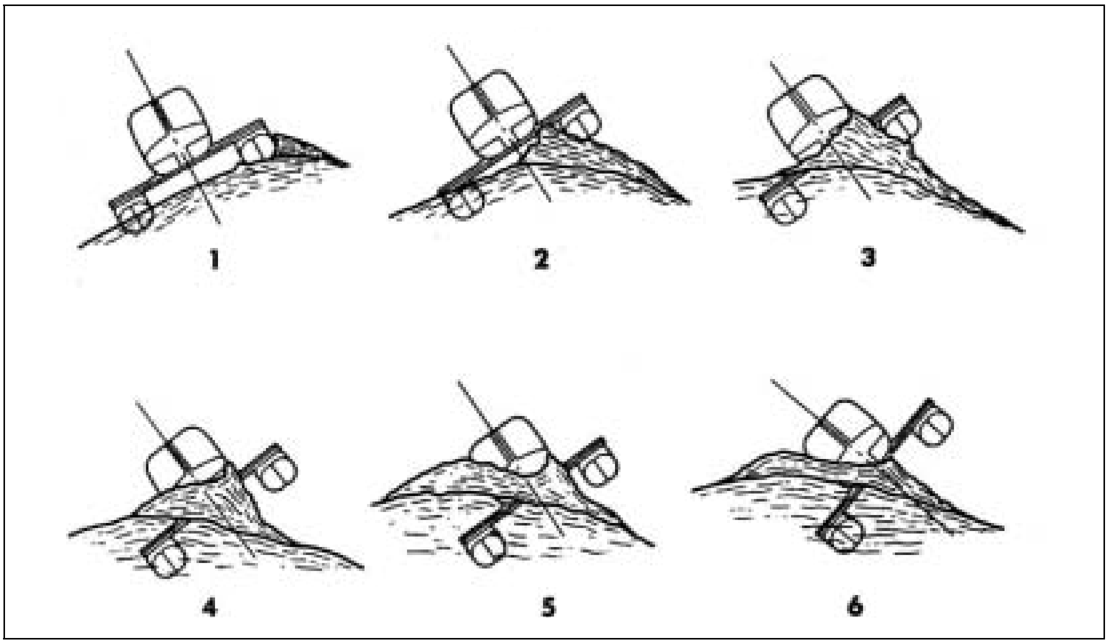

Figure 4 Helicopter capsize by a breaking wave, from [13].

Physical considerations suggested that the following helicopter properties are likely to be beneficial: a high roll inertia, a large range of static stability, a large angle of peak righting moment, a low lateral resistance to movement through the water, and a low above-water profile.

A device, such as a sea anchor, that maintains the helicopter's nose towards the waves, was seen as potentially beneficial to survival. Subsequent discussions revealed practical difficulties in deploying sea anchors, however, and Appendix D of [5] documents a capsize that occurred too quickly for a sea anchor to be deployed. The use of sea anchors to reduce the occurrence of capsize was therefore not pursued.

There was clear evidence that float scoops could provide a worthwhile improvement to the helicopter's resistance to capsize, but it was not clear whether the benefit came primarily from improvements to the helicopter's static stability curve, or improvements to its dynamic (inertia and damping) properties. The merits of float scoops were investigated further in CAA Paper 95010 [14], key findings from which are summarised in Section 3.2 of this report.

Results from tests on helicopter models with raised flotation, making it float at a lower level in the water (known as the 'wet floor' approach), had been inconclusive [9]. The effect on the helicopter's static stability varied markedly depending on the aircraft's weight and type. The effect on resistance to capsize in waves was also very variable. It seemed likely that the location of the floats would have to be chosen very carefully to obtain any beneficial effect.

An Institute of Oceanographic Sciences (IOS) study [12] had demonstrated a method for estimating the probability of occurrence of a capsizing wave in a given time interval. This work indicated that there was approximately a 5% probability of capsize in a 10-minute period. This result seemed to be inconsistent with ditching experience and with results from model tests in irregular waves, both of which suggested that the probability was closer to 30%. It was suggested that the wave height capsize criterion assumed by IOS may have been at fault. By contrast the CAA had suggested [8] that the target probability of capsize following a ditching should be just 1%.

It was noted that the attachment of floats to the engine cowlings could prevent permanent total inversion of the helicopter, and permit it to float in a stable side-floating attitude following capsize. The concept of using additional flotation units to prevent total inversion was investigated in a subsequent study, described in CAA Paper 97010 [21] (see Section 3.3).

The report made a number of specific recommendations, many of which were followed up in subsequent CAA work. These recommendations included:

- Future model tests on helicopters in waves should concentrate on behaviour in long sequences of irregular waves, so that the probability of capsize can be properly estimated.
- Means should be sought to reduce the risk of capsize which, ditching evidence and model tests suggest, is considerably higher than the CAA target.
- Computer simulation models should be developed further to represent floating helicopters subjected to regular, irregular and breaking waves, and access to existing model test data should be sought in order to validate theoretical predictions.
- The float scoop concept appeared to provide significant benefit, and should be developed further.
- Lowering the level of the helicopter in the water (the 'wet floor' concept) required further detailed investigation before determining whether (and how) floats should be raised on any individual helicopter type.
- Attention should be given to measures (such as engine cowling mounted floats) that would prevent permanent inversion following capsize.
- Consideration should be given to extending the IOS probabilistic analysis, and capsize probability analyses should be performed using long-term, good-quality North Sea data sets.

2.2.2 Helicopter Ditching Requirements Review (1993-1995)

Report [6] reviewed the UK Emergency Alighting on Water helicopter design requirements specified in British Civil Airworthiness Requirements (BCAR) Paper no. G779, dated 7 October 1985. The main objectives of this study were to recommend how the requirements might be improved, and whether there were better ways to assess a helicopter's water-borne stability. This report was prepared in 1993 at a time when all helicopters operating in the UK North Sea were certificated according to BCAR. This report is reproduced in Appendix B1.

The BCAR requirements were superseded by JAR/FAR airworthiness requirements 27 and 29, and BMT undertook a further review [15] in 1995 of the differences between the BCAR and JAR requirements for ditching certification. This report is reproduced in Appendix B2. Both review studies reached similar conclusions, and are therefore discussed together.

Both the BCAR and JAR requirements contained ambiguities in terms of the performance expected in regular and irregular wave model tests. These requirements appeared to have been interpreted in the past to mean that the helicopter may comply with one or other criterion, but not necessarily with both. Both sets of requirements also contained ambiguities in their definitions of wave steepness.

All of the existing helicopter types considered in the earlier BMT review [5] seemed to comply with the regular wave steepness criterion, but none seemed to comply with the BCAR implied irregular wave, sea state 6 criterion. Many capsized in sea state 4, and the remainder in sea state 5. It was deduced that the regular wave steepness criterion was being applied in isolation, and that results from any irregular wave tests were being ignored.

It was noted, however, that JAR requirements referred to 'reasonably probable water conditions', which seemed to be interpreted as 'not less than sea state 4'. The BCAR requirement therefore seemed to be more onerous, and invited the possibility that more severe conditions than sea state 6 should be considered in particular geographical areas. These ambiguities were considered to be undesirable, and clarification of the requirements was recommended.

Results from helicopter model capsize tests in regular waves were considered likely to be misleading, and should be discouraged. An undamaged helicopter will normally only capsize in breaking waves. The steepness at which regular waves break in a wave test basin depends primarily on the purity of the wavemaker motion, the distance travelled by the waves, and the presence of spurious waves in the basin. Results from model tests in breaking 'regular' waves are therefore likely to depend more on the wave basin's properties than on characteristics of the helicopter. An irregular wave criterion was considered to offer a more realistic measure of the likely actual performance of a helicopter ditched in the sea.

The first report [6] also discussed the merits of defining a maximum probability of capsize in a given operational area as an alternative to defining capsize performance in specified sea states. This possibility was investigated in a follow-up CAA study [7] (see Section 2.2.3). Various deficiencies and differences between the BCAR and JAR requirements were also noted in [15].

The two review reports [6, 15] recommended that:

- Current practice, of defining wave conditions using sea state numbers, should be dropped in favour of a more precise definition in terms of significant wave height, wave period and spectrum shape.
- The designer should be required to select a sea state with an appropriately low probability of exceedance in the intended area of operation.
- Sea state steepness [1] should be more rigorously defined, possibly linking this requirement to one based on actual wave conditions in the area of operation using probabilities of exceedance.
- The criteria should focus on irregular wave model testing, defined in terms of significant wave height, wave period and spectrum shape, together with a definition of the way in which the severity of test conditions should be selected, and a minimum standard for model testing.
- Use of regular wave model tests, based on a specific wave steepness criterion, should be discouraged because capsize normally occurs only in breaking waves, and the results from regular wave tests are likely to depend primarily on the wave basin's properties rather than those of the helicopter.
- If damage to the flotation system is considered to be a reasonably probable occurrence, it will be necessary to define sea state requirements for evaluating helicopter stability with damaged flotation. There are various possible ways in which to do this. The sea states used to evaluate damaged flotation might be the same as are used when the flotation is intact, or the same as when the hull and airframe are damaged.

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[1] The steepness of an irregular sea state is often defined in terms of its significant steepness, $S_s = 2\pi H_s / gT_z^2$, where *g* is the acceleration due to gravity, Hs is the significant wave height and *Tz* is the mean zero up-crossing wave period.

2.2.3 Ditching Performance and Probabilistic Methodology (1993)

Report [7] was prepared in 1993 as a result of the recommendations of [6]. It summarised the findings from the two earlier BMT reports [5, 6], and assessed the practicality of imposing a new probability-based methodology for helicopter ditching certification. This report is reproduced in Appendix C of this report.

Report [7] considered that the CAA helicopter certification requirements (BCAR) relating to ditching were ambiguous and deficient in certain respects, most notably in the way in which limiting wave conditions were defined. It proposed that the requirements could be improved by requiring capsize performance to be demonstrated in irregular waves rather than regular waves. Irregular wave tests, whilst presenting some significant model testing difficulties, offer a more realistic approach than using regular waves which can potentially produce misleading results. The report also recommended that consideration should be given to the development of a model testing standard.

A simple analysis of civil and military helicopter ditching occurrences had indicated that the risk to the individual offshore worker of suffering a fatality due to helicopter capsize following a controlled ditching was probably less than 3×10^{-5} per year (or about once every 30,000 man years). However, the report recommended that means should be sought to reduce the risk of capsize following ditching because this risk seemed to be significantly higher than the CAA's stated target of 1% [8].

The report suggested a move away from a prescriptive wave condition requirement. 'Risk of capsize' targets might be defined instead. The designer would be required to demonstrate that these targets are achieved by the helicopter within a defined area of operation. Existing probabilistic work on capsize should be extended to cope with varying probabilities of capsize with wave height, and then used in conjunction with long-term North Sea wave data sets to derive probabilities of capsize.

2.3 Regular and Irregular Wave Testing (1996)

Earlier reviews [6, 15] had noted ambiguities in the then-current BCAR and JAR certification requirements for model tests to assess helicopter stability after ditching, especially in the performance expected in regular and irregular waves. None of the existing helicopters considered in the earlier reviews seemed to have passed the BCAR irregular sea state criterion, but all seemed to have passed the regular wave steepness criterion. It was also noted that the JAR irregular sea state criterion was less stringent (sea state 4) than the BCAR criterion (sea state 6).

BMT subsequently [16] compared the costs of performing two alternative series of model tests. One test programme was considered to be typical of that required to certificate a helicopter according to existing regular wave requirements, and the second to meet modified irregular wave requirements. This report is reproduced in Appendix D.

Two scopes of work were presented and costs were summarised. The advantages and disadvantages of each approach were discussed, together with data analysis requirements. Both test programmes included tests to define and demonstrate static stability characteristics.

The conventional test programme included a number of irregular wave tests as well as a systematic series of regular wave tests. This test programme was regarded as typical of those currently performed for certification. The irregular wave test programme consisted entirely of irregular wave tests (no role was seen for regular wave tests), and was based on demonstrating an 80% probability of remaining upright in sea state 4. The model would be tested in four conditions: fully and lightly loaded, with the centre of gravity well forward and aft.

Similar costs were found in both cases, although it was noted that costs would depend on the particular capabilities of, and procedures followed by, a given wave test basin. Of considerable greater significance was the relative reliability and statistical significance of the results obtained by the two methods. On these grounds the irregular-wave procedure was considered to be far superior, providing a far more realistic measure of the actual performance of a helicopter ditched in the sea.

2.4 Helicopter Capsize Risks in UK Sea Areas (1997)

Earlier review studies [5, 6, 7] questioned whether more stringent criteria might be appropriate in particular geographical areas where sea conditions are more severe, and the risks of capsize correspondingly higher. A further BMT study [17] therefore investigated the occurrence of different sea states on six different routes in the North Sea and West of Shetland, together with the associated helicopter capsize risks. It was shown that, on average in the North Sea, a helicopter making a controlled landing on the water and fitted with an emergency flotation system compliant with the guidance might expect to be capsized by waves on about 30% of occasions. A further report [18] investigated sea conditions in which a helicopter had ditched, but not capsized, near the Brae Alpha platform in January 1995. These two reports are reproduced together in Appendix E.

2.4.1 Wave Climate Study

The first of these two reports [17] noted that research studies performed for the CAA had considered sea states in which capsize of a ditched helicopter might occur, and in the ability of helicopter emergency flotation systems to survive an impact with the sea and thus keep the damaged helicopter afloat. The risks associated with these occurrences would clearly depend on the severity of the sea state at the time of the incident, and the likelihood of any given sea state would depend in turn on the nature of the local wave climate. This wave climate varies considerably between different sea areas.

Six typical helicopter routes used to serve the oil and gas industry in the southern, central and northern areas of the North Sea and West of Shetland were selected for the wave climate study. The data was interpreted in terms of the probability of exceeding particular sea states specified in the helicopter airworthiness certification requirements. As noted in review reports [6, 15], these requirements were defined in terms of survival in sea states varying between 4 and 6.

The report drew attention to the large difference in capsize risk between helicopters capable of withstanding sea states 4 and 6. Averaged over a whole year, sea state 4 is exceeded for 36% of the time in the northern North Sea, and so a helicopter certified to sea state 4 ditching requirements may be considered to have approximately 1 in 3 probability of capsize in this sea area. If, however, the helicopter is capable of meeting the more onerous sea state 6 ditching requirement, there would be only a 2% (or 1 in 50) probability of capsize. This result dramatically demonstrates the large difference in risk implied by different certification requirements. In this same sea area the probability of exceeding sea state 4 varied from 65% in winter to only 7% in summer, again implying a large difference in risk. As expected, the risk also varied substantially between different sea areas, sea state 4 being exceeded for only 14% of the time in the southern North Sea.

The study did not compare risks of capsize for individual helicopter types. It was noted, however, that the data could be used in further studies on particular helicopter types to assess the risk of capsize following a ditching, and to assess the severity of wave impacts resulting from helicopter crashes onto the sea.

2.4.2 G-TIGK Ditching

The second report [18] investigated circumstances in which a Super Puma helicopter (G-TIGK) had ditched in the North Sea near the Brae Alpha platform on 19th January 1995. Sea conditions at the time of ditching were rough (sea state 5), but the emergency flotation system worked well, and the helicopter did not capsize. The crew and passengers were able to escape to the life-rafts without injury. The helicopter eventually sank a few hours later when the flotation was damaged as a vessel attempted to get alongside for salvage purposes.

Information on weather conditions at the time of ditching was gathered to help set the apparently good performance of the emergency flotation system into context with research work on helicopter ditching. Although detailed measurements were not available, data from the UK Meteorological Office's wave forecast model were examined, and significant wave steepness values[1] were estimated over the period of the incident. All the available evidence indicated that wave conditions were not more severe than sea state 5 at any time between ditching and sinking. Conditions were nonetheless deteriorating, and were nearer the top end of sea state 5 by the time the helicopter sank.

Although small spilling breakers ('whitecaps') could be seen in a photograph taken at the time, and the significant wave steepness increased from 1/21 to 1/17 towards the end of the period of the incident, these sea states were considered to be not particularly steep. Breaking waves were therefore considered to be of insufficient magnitude to cause capsize. The photograph also appeared to show the helicopter heading into the wind and waves. If this was true throughout, then this would also have been a major factor reducing the likelihood of capsize.

3 Helicopter Ditching and Capsize Research

3.1 Introduction

Emergency flotation systems (EFS) have been mandated on UK offshore helicopters since the 1970s for extended flights over water. It is difficult if not impossible, however, to design practical flotation systems that will keep a helicopter afloat and stable in the more severe sea conditions prevalent in the northern North Sea during winter months.

The CAA initiated a major programme of research into helicopter ditching and capsize in response to the HARP Report's [1] recommendation that the stability problems of ditched helicopters should be urgently pursued, and the RHOSS Report [2] strongly supported the CAA's then on-going research into helicopter crashworthiness, flotation and stability.

Sections 3.2 and 3.3 review the history of this research programme, and summarise the main phases of the work and key findings. Section 3.3.6 concludes with an outline of work yet to be performed.

3.1.1 The Wet Floor Approach

Model tests conducted by the British Hovercraft Corporation (BHC) in the mid 1980s investigated two possible ways to improve a helicopter's static stability and capsize performance. One of these involved raising the floats.

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[1] The significant steepness of an irregular sea state is, $S_s = 2\pi H_s / gT_z{}^2$ where *g* is the acceleration due to gravity, *Hs* is the significant wave height and *Tz* is the mean zero up-crossing wave period.

Raising the floats makes the helicopter sit at a lower level in the water [9], and usually leads to flooding of the passenger cabin. This is known as the 'wet floor' approach, and contrasts with the 'dry floor' approach which was mandated under then-current BCAR ditching requirements. BCAR stated that the sill of any exit used for emergency evacuation should be above the calm water flotation line of the helicopter when floating on water following an emergency landing.

Results from the BHC 'wet floor' model tests were inconclusive [5], and the effects on both the helicopter's static stability and its capsize performance in waves were very variable, depending on the aircraft's weight, type and the test conditions. It seemed likely that the location of the floats would have to be chosen very carefully to obtain any beneficial effect. Reference [5] summarised key findings from these tests, and recommended numerical simulation studies to obtain a better understanding of the way in which the helicopter's static stability properties influence the capsize boundary.

A review of relative merits [19] concluded that there would be practical difficulties and uncertainties in adopting the 'wet floor' approach. These difficulties included the short time necessary to attain the flooded state, how to flood the cabin in a controlled manner, the positioning of floats to avoid blocking doors and escape hatches, difficulties with deploying life-rafts from a flooded cabin, the variable results obtained from the BHC model tests, the increased risk of rotor strike (on a wave) and consequent capsize, psychological factors and possibly increased risks of hypothermia to unprotected passengers. Reference [19] concluded that the additional risks to unprotected personnel and the inconclusive nature of the test results precluded the adoption of the 'wet floor' approach in preference to the 'dry floor' approach for conventional airline-type operations. The report nonetheless concluded that the advantage of improved stability in severe conditions might justify use of the 'wet floor' approach in operations over severe sea areas where personnel wear protective clothing and are trained in escape procedures from a flooded helicopter.

In view of the concerns expressed in reference [19] and the inconclusive nature of results from the BHC model tests, the 'wet floor' approach was not pursued.

3.2 Float Scoops (1995)

The second way of improving helicopter stability investigated by BHC was that of adding water scoops to the emergency flotation. These scoops would be similar to those routinely used on inflatable life-rafts to improve stability. Model tests at BHC [10] showed that float scoops provided significant and generally consistent benefits, increasing the helicopter's capsize threshold by about one sea state for all but one of the nine helicopter types tested.

The CAA therefore commissioned BMT to undertake a follow-up study [14], with the assistance of Westland Helicopters Limited, to consolidate the state-of-art as regards float scoops and, specifically, to estimate the cost implications of fitting scoops to a typical large transport helicopter.

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

Estimates of the dynamic forces experienced by the floats, with and without scoops, indicated that the magnitude of these forces depends crucially on the zero-crossing period of the sea state selected for analysis and, depending on the selection of this period, might lead to forces larger or smaller than the simple static load assumptions currently used in the helicopter design process. In the cases studied, the addition of the scoops to the floats increased the forces by between 12% and 17%.

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

The capsize boundaries for helicopter types currently operating in the North Sea region lie in the sea state range 4 to 5. Fitting float scoops to existing helicopter types would raise their capsize boundaries by approximately one sea state, significantly reducing the risk of capsize following a ditching (see Section 2.4.1). The final report on this study was published in CAA Paper 95010 [14].

Figure 5 to Figure 7 illustrate the benefits obtained by fitting float scoops onto a Sikorsky S-76 type helicopter. Figure 5 shows the proposed locations of scoops on the helicopter floats. Figure 6 shows the increase in the helicopter's static roll righting moment which resulted from the addition of scoops, and Figure 7 shows the corresponding increase in the regular wave height at which capsize occurred.

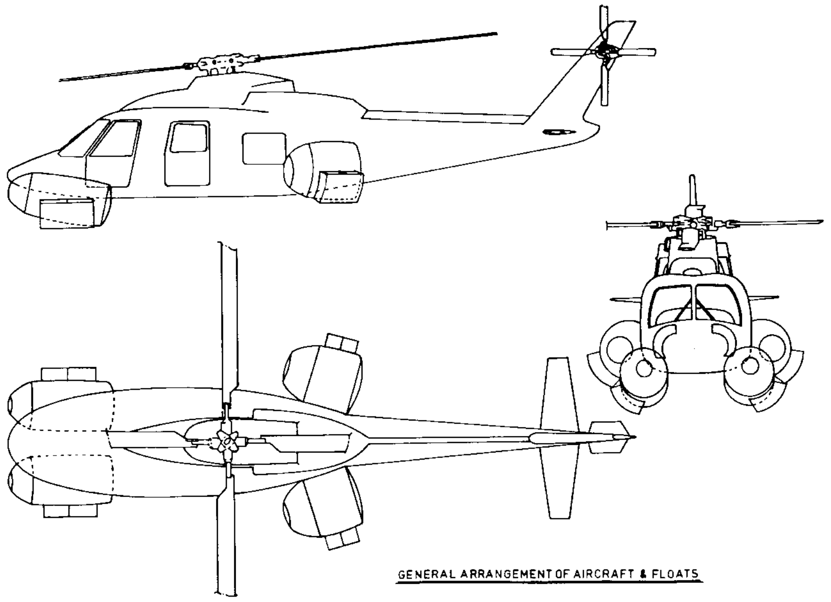

Figure 5 General arrangement drawings of a Sikorsky S-76 type helicopter, showing proposed float scoop locations.

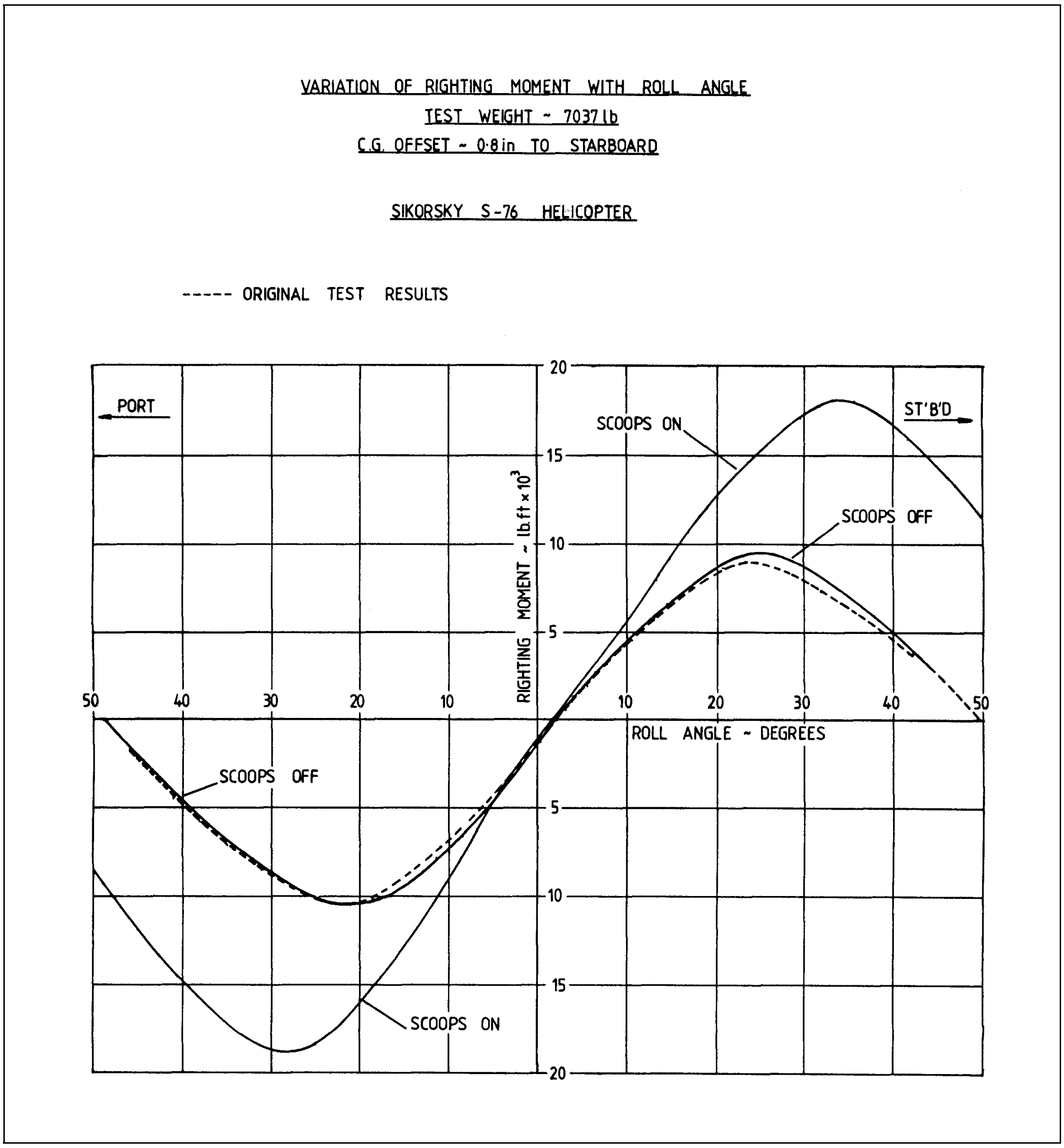

Figure 6 Static stability (righting moment) curves for a Sikorsky S-76 type helicopter, showing increased stability due to float scoops.

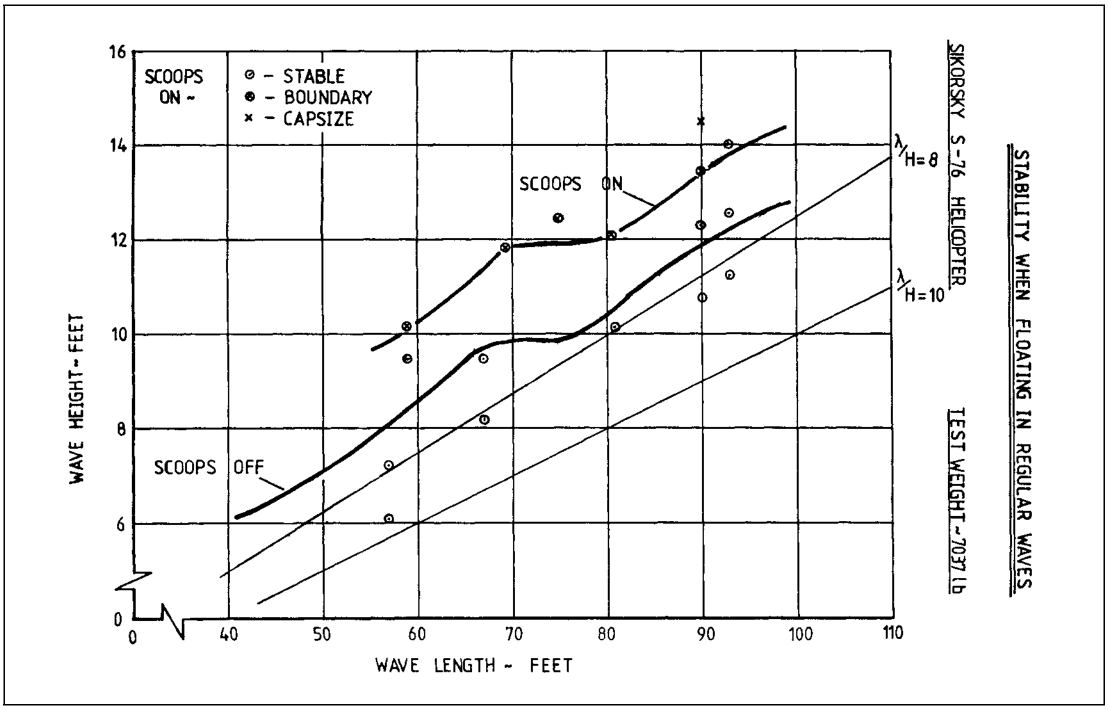

Figure 7 Increase in regular wave height at which capsize occurred when float scoops were added to a Sikorsky S-76 type helicopter.

3.3 Means to Prevent Total Inversion (1997)

3.3.1 Introduction

Even with float scoops fitted, the probability of capsize is still relatively high in areas such as the northern North Sea in winter. In addition, capsize could still occur in moderate seas for reasons other than insufficient stability. Since further improvements to the helicopter's sea-keeping performance were considered to be impractical, means to mitigate the consequences of capsize were sought. To this end, the CAA commissioned BMT to investigate means to prevent the capsized helicopter from turning to a completely inverted attitude. Results from the CAA's programme of research into means to prevent total helicopter inversion after ditching have been published in CAA Papers 97010 and 2001/10 [21, 22] and in a conference paper [20]. Key findings from this research are summarised below.

3.3.2 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. Helicopters certified for operation over the sea are fitted with various items of additional flotation equipment (normally in the form of inflatable buoyancy bags) in order to fulfil the certification requirements. However, helicopters inevitably have a high centre of gravity due to the weight of engines and main rotor gearbox located on the cabin roof. It is therefore unlikely that they can ever be made sufficiently seaworthy to remain upright and stable in severe sea conditions.

Past experience has shown that ditched helicopters are likely to capsize in moderate to severe sea states. When helicopters do capsize, they invariably turn completely upside down (as shown in Figure 8), leading to complete flooding of the cabin and immersion of all doors and windows. When this happens the occupants must escape very quickly because of their limited breath-holding capability (see Section 5), but escape is very difficult because all escape routes are submerged. Occupants who do not escape from the cabin within a matter of seconds are likely to drown.

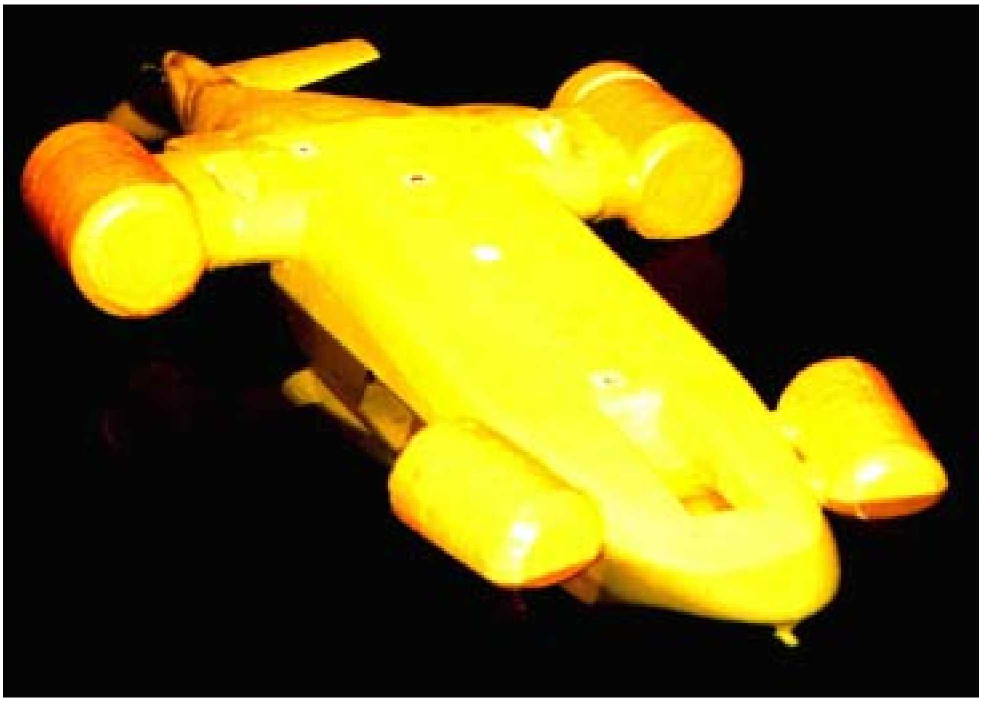

Figure 8 Model helicopter completely inverted following capsize.

A study of wave climate data along six representative North Sea helicopter routes [17] showed that there is a significant risk of ditching in seas greater than sea state 4 in the northern North Sea during winter months. Other circumstances, such as damaged or malfunctioning flotation equipment, rotor strike, or imperfect alighting onto the sea (e.g. due to loss of yaw control after tail rotor failure), may also lead to capsize in more moderate seas.

One potential solution is to locate additional flotation devices high on the fuselage in the vicinity of the main rotor gearbox and engines, so as to prevent total inversion of the helicopter following capsize. This scheme serves to retain an air space within the cabin, thereby removing the time pressure for escape and ensuring that some of the doors and windows remain above water level facilitating egress. A brief model test was performed by the British Hovercraft Corporation in 1985 on a Sikorsky S-76 type helicopter to test this idea, but the results of the test were not considered to be completely successful and no further work was pursued at that time. A subsequent review of helicopter ditching research [5] proposed further investigations into this concept, and the CAA commissioned a major programme of research [21] aimed at identifying ways to mitigate the consequences of capsize following a helicopter ditching.

Although the study was performed using drawings, specifications and models of the EH101 helicopter provided by Westland Helicopters Limited (WHL), it was not intended to be specific to any particular helicopter type, and the results are applicable to any medium or large transport helicopter.

The initial work took the form of a desk study followed by hydrodynamic model tests in waves. The desk study was performed by a team of specialists drawn from BMT and WHL, and a total of ten ideas resulted. Three of these concepts were short-listed for model testing in order to determine their effectiveness in preventing total inversion following capsize, and two of them were found to be practical and effective.

3.3.3 Devices Initially Considered

Discussions between helicopter design and hydrodynamic and stability specialists from WHL and BMT took place during the first phase of the work, and ten possible novel flotation devices were identified:

(1) Buoyant foam-filled engine cowling panels.

(2) Engine cowling panels with integral inflatable buoyancy bags.

(3) Buoyancy bags inside the rear fuselage.

(4) Buoyancy inside the passenger cabin roof.

(5) External cabin wall floats.

(6) A flotation collar under the rotor head.

(7) Flotation attached to the top of the rotor head.

(8) Tethered inflatable flotation units.

(9) Increased passenger seat buoyancy.

(10) Dynamic chemical foam in engine spaces.

The specialists assessed the merits and disadvantages of each device, and ranked them to determine which were the most attractive for further study based on the following three qualities:

- Effectiveness - how effective is the device likely to be in preventing total inversion following 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 to the operation of the helicopter?

Three devices, shown diagrammatically in Figure 9 to Figure 11, emerged from this initial selection process as being worthy of further investigation:

(1) Buoyant foam-filled engine cowling panels.

(5) External cabin wall floats.

(8) Tethered inflatable flotation units.

Increasing the total number and distribution of flotation units on the helicopter provides additional spin-off benefits by increasing the overall level of redundancy and hence crashworthiness of the emergency flotation system. Two of these devices were considered to be significantly less vulnerable to damage in a crash onto water than existing conventional emergency flotation units because they would be located at a high level, well above the likely water impact zone. The benefits of having these additional flotation units in the event of a crash onto water are discussed in Section 4.

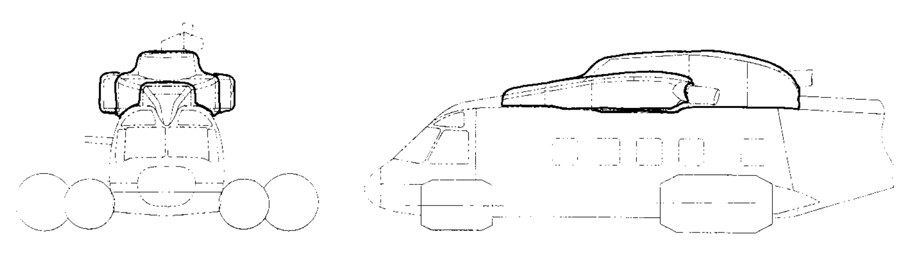

Figure 9 Buoyant foam-filled engine cowling panels.

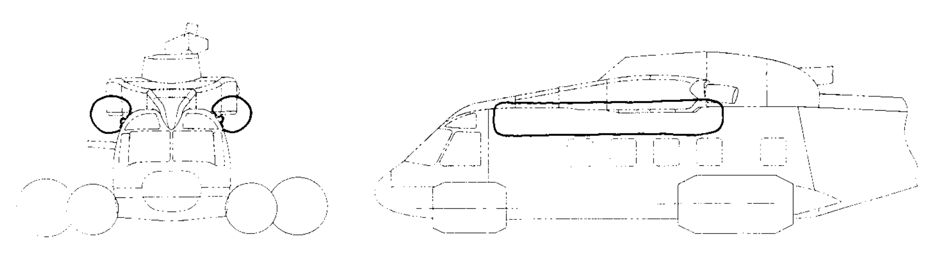

Figure 10 External cabin wall floats.

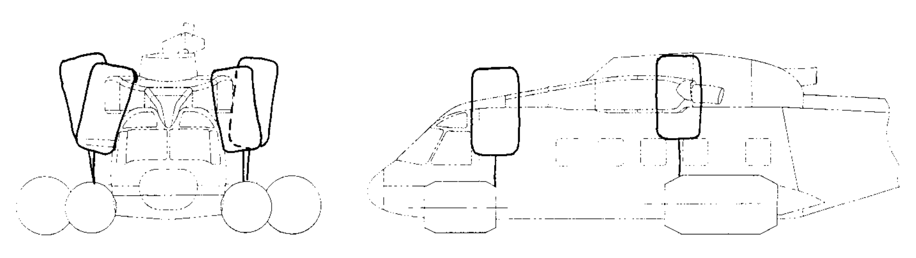

Figure 11 Tethered inflatable flotation units.

3.3.4 Model Tests

The effectiveness of each of these three devices was assessed in a second phase of the study, by means of model tests in a wave tank. A detailed description of the model tests and results may be found in reference [21].

Mainly qualitative assessments were made of the effectiveness of the novel devices with the helicopter capsized in calm water and waves. Their effectiveness was judged in terms of the extent to which doors and windows were held clear of the water surface following capsize, and were free from severe wave impact. Quantitative measurements of static stability were also made on the standard helicopter, and on selected novel devices, by means of static roll righting moment tests.

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 likely to capsize. In order to maintain a beam-on heading during the model tests, the helicopter model was held by two light lines, one attached to the nose and the other to the tail. These lines kept the model aligned generally beam-on to the waves, providing a more stringent test of the effectiveness of the additional buoyancy devices, whilst minimising interference with the free-floating behaviour of the model. Table 1 summarises the main model test findings.

Table 1 Model Test Findings

Conditions	Calm Water Attitude	Observed Wave Response	Ranking
Individual Systems			
Buoyant Cowling Panels 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 Buoyant Cowling Panels (5m^3)	Good - doors and windows on one side of the aircraft clear of water surface	Good	
Cabin Wall Floats Cabin Wall Floats 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
Cabin Wall Floats Cabin Wall Floats Set 2 (4.9m^3)	Poor, Windows and doors on one side only just clear of water	Only half the doors and windows clear	
Cabin Wall Floats Single Set 1	As double units but just slightly lower in the water	Similar behaviour to double units	
Tethered Units Tethered Units Set 1 (8.3m^3) free	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	
Combination			
Buoyant Cowling Panels (6m^3) plus single cabin wall float (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.	-

Buoyant engine cowling panels (see Figure 12 and Figure 13) proved to be the most effective device for preventing total inversion. They kept the doors and windows well clear of the water except for the occasional large wave. Cabin wall floats (see Figure 14) proved to be the second most effective device.

Tethered buoyant units proved to be the least effective of the three devices tested. The tethering arrangement proved to be ineffective, and they had to be attached directly to the fuselage to prevent movement and maintain their position in order to provide any benefit. 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.

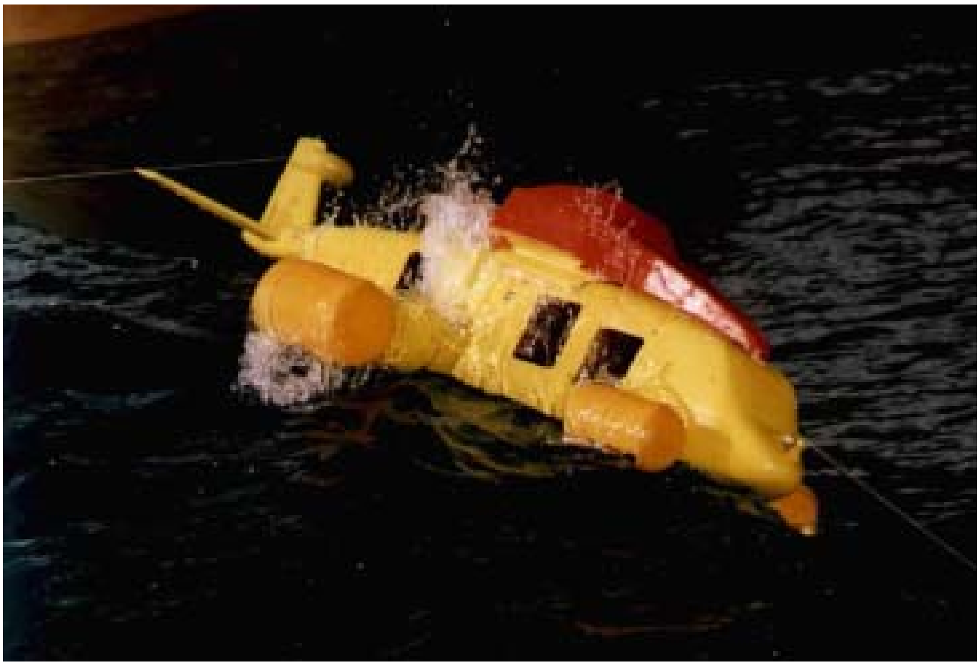

Figure 12 Model fitted with foam-filled cowling panels in waves.

Figure 13 Model fitted with foam-filled cowling panels following capsize.

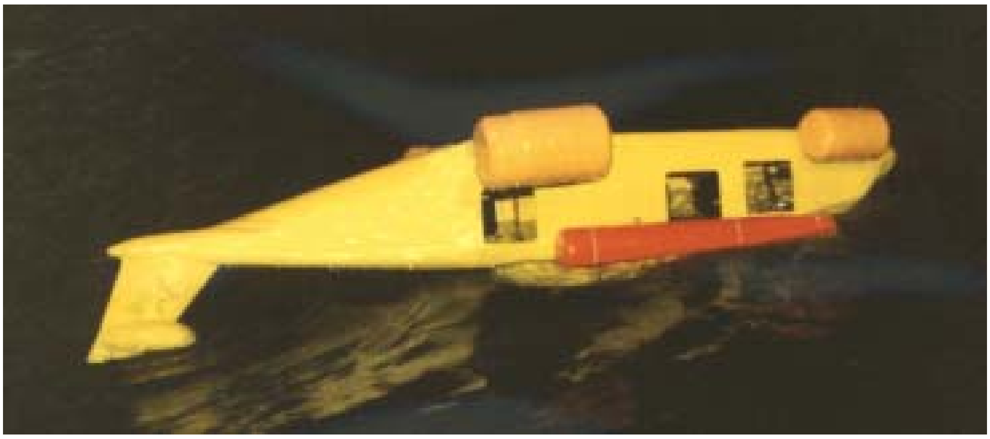

Figure 14 Model fitted with cabin wall floats following capsize.

These tests showed that the capsized helicopter with buoyant engine cowling panels and cabin wall floats had two stable floating attitudes. In calm water these two attitudes provided equal stability. In waves, however, 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 now 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.

This last finding revealed that results from an earlier BHC model test had previously been misinterpreted by the CAA [8], who had dismissed the use of cowling floats in the belief that the helicopter would continue to 'tumble' in waves. A re-reading of the original BHC report showed that only two rotations had occurred, and this finding was confirmed by the work described in reference [21].

A single cabin wall float mounted on one side of the helicopter was also 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 float version. A single cabin wall float was also tested in combination with the 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 cabin wall float.

In addition to the above tests to assess the effectiveness of the buoyancy devices, tests were carried out on the capsized model to obtain motion data that could be used to inform any subsequent studies of passenger egress. Statistics of helicopter motions and accelerations in head and beam sea conditions (for significant wave heights Hs = 2.0m, 2.9m and 4.3m) may be found in reference [21].

Overall it was concluded that additional emergency flotation of this type can be effective in providing a stable capsized attitude, with doors and windows above the water level facilitating escape. Furthermore, increasing the total quantity and distribution of flotation units on the helicopter has potential for providing redundancy and improving the overall crashworthiness of the emergency flotation system (see Section 4).

On the basis of these results it was concluded that foam-filled engine cowling panels and external cabin wall floats were worthy of further development, and further investigations were recommended. In particular, an investigation of the practical problems posed by passenger escape from a side-floating helicopter and a helicopter type-specific design study were recommended.

3.3.5 **Human Factors Study**

Following the demonstration of the practicality and effectiveness of auxiliary flotation and on the recommendation of [21], the CAA instigated a human factors study [22] at RGIT Limited to develop an appropriate technique and associated training procedures for egress from side-floating helicopters, and determine the overall benefits/ disbenefits of the scheme by comparison with egress from a fully inverted helicopter. The study used naïve subjects who were first trained, and then evaluated during simulated escapes from fully inverted and side-floating cabins in RGIT's training pool. This study confirmed the expected benefits of the side-floating arrangement.

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

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

Carefully controlled feasibility trials were performed in which all possible means of escape from the side-floating helicopter simulator were explored. A risk assessment was carried out and escape procedures were developed. Thirty naïve subjects were then recruited to evaluate escape from the side-floating helicopter simulator following capsize through an angle of either 150° or 210°, and to compare it with escape from a fully inverted helicopter simulator following a 180° capsize. Psychological and physiological measurements were taken at various intervals during the trials to measure the subjects' performance and levels of anxiety. Subjects also rated their perception of the difficulty associated with each escape. Each trial was filmed in order to measure escape times and assess ease of escape. The different escape procedures were compared in order to assess their relative advantages and disadvantages.

The majority of subjects preferred escape from the side-floating helicopter, and found it to be easier. This was reflected in the fact that subjects were significantly more satisfied with how they coped with escape in the side-floating condition (Figure 15) compared with the fully inverted condition (Figure 16). When escaping from the fully inverted simulator, difficulties caused by disorientation, breath-holding, locating and using the exit were more prominent than in the side-floating condition. This was especially true when subjects were required to make their way across the cabin to escape.

Subjects had some difficulty releasing the harness when seated on the upper side of the simulator in the side-floating condition. None of the problems associated with escape from a side-floating helicopter was considered to be life-threatening, however, and none outweighed the advantages of escape from a side-floating helicopter. On the contrary, the evidence suggested that the occupant of a side-floating helicopter would have a much better chance of escape and survival than someone inside a fully inverted aircraft.

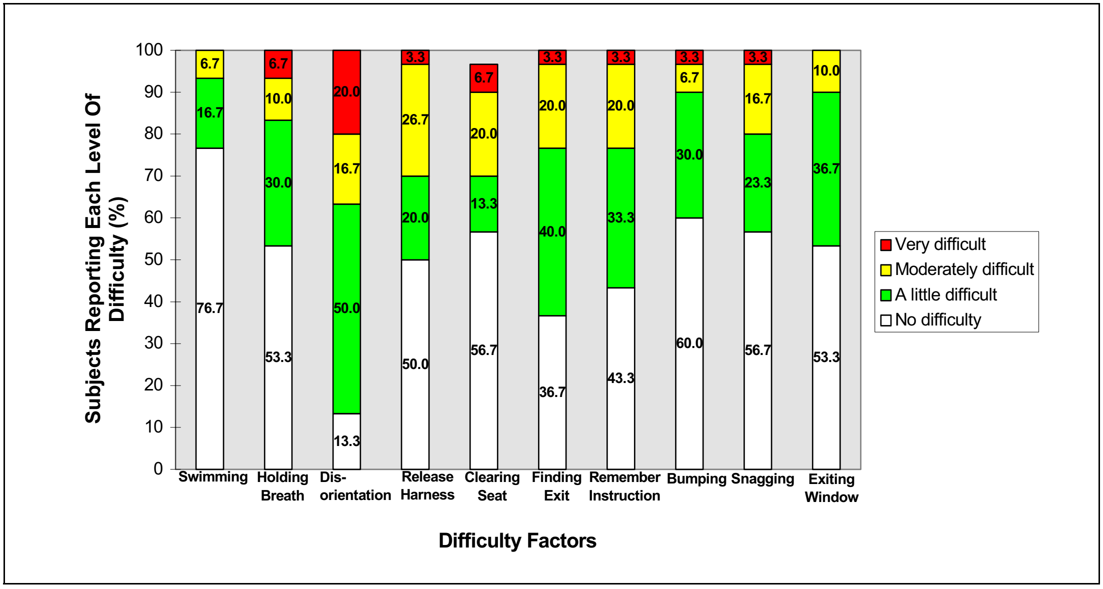

Figure 15 Subjects' rating of difficulty factors when escaping from a side-floating cabin.

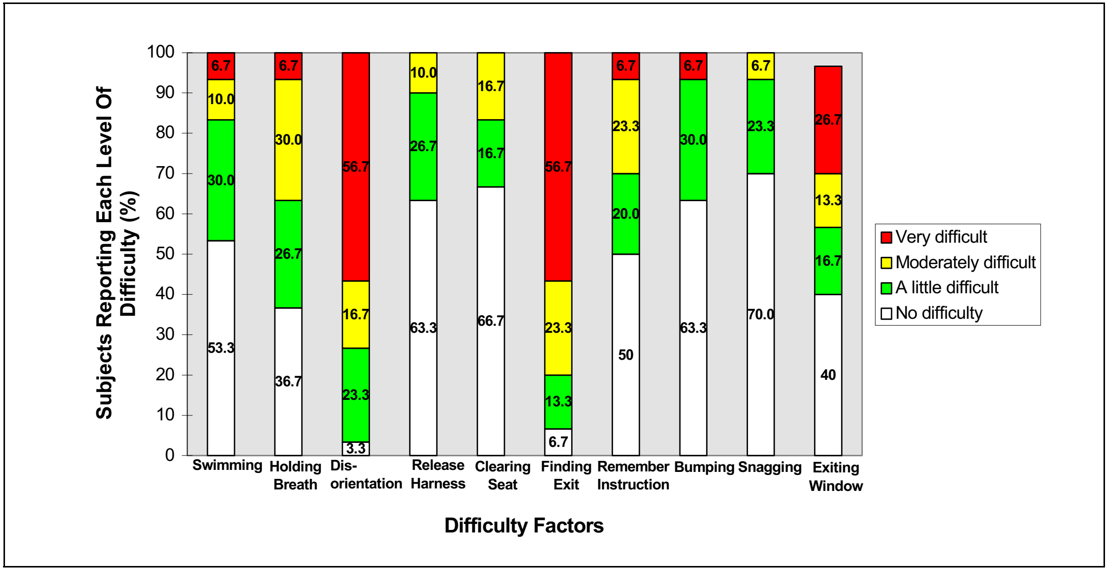

Figure 16 Subjects' rating of difficulty factors when escaping from a fully inverted cabin.

3.3.6 Further Work

In view of the very positive results obtained from the research summarised above, and endorsement by the JAA HOSS working group (Appendix F), and the JAA/FAA Joint Harmonisation Working Group on Water Impact, Ditching Design and Crashworthiness (WIDDCWG) (Appendix G), CAA recommends that a detailed design study for the modification of the EFS of a specific helicopter type to prevent total inversion following capsize be commissioned.

The design study should include an initial review of previous research and the development of a functional specification for the necessary additional flotation, followed by a design study to address hydrodynamic, buoyancy and structural aspects of the EFS modifications, aerodynamic and systems design aspects, issues relating to passenger egress and survival, and consequences for the aircraft's weight and costs. Proposals should also be made for any additions or changes to JAA and FAA requirements that are considered desirable to support the side-floating concept. In particular, the study should consider the following aspects of the design:

- The amount of additional buoyancy required, taking account of buoyancy already present in the upper part of the fuselage and engine area, possible mounting locations, and the helicopter's required floating attitude and draught.
- How best to provide additional buoyancy, taking account of weight, costs, aerodynamic drag, effects on stability and control, the consequences of inadvertent deployment, and the consequences of flotation unit failure.
- Flotation system loads, methods of attachment, mountings of existing flotation units, and modifications to the EFS activation and deployment system.
- Whether life-rafts can be deployed satisfactorily in the normal upright and side-floating attitudes.
- Any additional measures, such as foot/ hand holds within the helicopter cabin, that will be necessary for efficient egress when side-floating.
- Effects of uneven loading, when side-floating, on the release of seat harness buckles.

4 Water Impact Crashworthiness Research (1993-2001)

4.1 Introduction

The primary purpose of emergency flotation systems has always been to keep the helicopter afloat following a controlled landing on water. These systems tend to be much less effective when a helicopter crashes onto water, however, either because they are destroyed by the impact, or because they have to be manually activated by the pilot who may be disabled by the impact.

An initial study undertaken in response to recommendations in the HARP Report [1] found that water impact was the most important aspect of crashworthiness to address. The study reached this conclusion because, although the crashworthiness requirements had recently been updated at that time, they did not address water impacts. The loads and loading mechanisms experienced in water impacts were known to be significantly different from those experienced during land impacts.

4.2 Initial Investigations into Water Impact Crashworthiness

The CAA therefore commissioned Westland Helicopters Limited (WHL) to review UK military and world civil helicopter water impacts over the period 1971 to 1992 [23] and, in a second study, to analyse the response of the helicopter structure to water impact [24]. These two studies were published together in CAA Paper 96005, and the key conclusions were as follows:

- Where a cause of death was identified, the majority of fatalities in both world civil (57%) and UK military (83%) helicopter impacts on water were attributed to drowning. Underlying factors causing the occupants to drown were invariably not investigated, although incapacitation due to injury, inability to escape through disorientation, entrapment and jammed/ obstructed exits were cited in some cases as probable causes of drowning.
- In cases where information on flotation system effectiveness was available, over 50% of water impacts resulted in the helicopter inverting or sinking before

evacuation of the occupants was completed. A significant number of accidents therefore involved underwater escape. Previous studies had shown that an inrush of water, contributing to disorientation and difficulties in reaching and opening escape hatches, is the major hazard facing survivors in inverted or submerged helicopters.

- Improving the capability of helicopters to remain afloat after impact for long enough to allow survivors to escape was considered to be the most significant factor that would improve occupant survivability. This could be achieved by improving the robustness and reliability of current systems (flotation bags and inflation mechanisms), and ensuring that such systems are better able to withstand representative water impact conditions.
- Occupant fatalities resulting from excessive crash forces or as a result of structural collapse during impact were found to be a secondary issue. Structural loads and the probability of occupant injury in helicopter water impacts depended on both the impact velocity and the behaviour of the structure on entry into the water. Designing the airframe to withstand water pressures without excessive deformation and without water entry into the internal structure or occupied areas, was seen to be the key issue for water impact resistance. There were no requirements calling for the airframe to be so designed at the time the study was performed.
- Military and civil airworthiness requirements at that time only required flotation systems to withstand a controlled alighting onto water. Recognition of water impacts as a representative and realistic crash case was seen to be a first step towards improving occupant safety.
- Mathematical modelling techniques were considered to be a potentially valuable tool for analysing aircraft structural behaviour on impact with water. Validation of these techniques against experimental data would be required, however, before they could be considered for use as a design tool.

The US Federal Aviation Administration (FAA) also undertook investigations into rotorcraft ditchings and water-related impacts that had occurred between 1982 and 1989 [25, 26]. The data came from the US National Transportation and Safety Board (NTSB), US military sources and from the International Civil Aviation Organisation. One of the criteria was that the aircraft involved had to be representative of the civilian rotorcraft fleet. The FAA's findings were similar to those reported by WHL. In particular, they concluded that:

- The two main post-impact hazards to occupant survivability were drowning and exposure. Drowning was the most significant hazard.
- Aircraft flotation equipment was generally found to be inadequate to keep the rotorcraft upright and afloat in both ditchings and water impacts. Several cases of successful upright flotation were nonetheless noted. A significant number of drownings occurred in cases where the aircraft overturned immediately.
- Float inflation prior to impact seemed to be preferred for controlled ditchings. In water impacts, however, inflated floats were more likely to be torn from the aircraft or damaged by the generally more severe impact conditions. In these instances an immersion sensor seemed to be the preferred activation method.
- Structural failures of the rotorcraft did not contribute significantly to occupant injury.

A follow-up FAA study [27] re-examined records from 67 accidents in the NTSB's database, most of which were considered to be survivable. Figure 17 shows the estimated vertical and horizontal impact velocities of the helicopter in each of these accidents, and compares these values with the FAA's existing ditching requirements and emergency landing requirements (for ground impacts), and with a proposed 95% survivability boundary for water impacts.

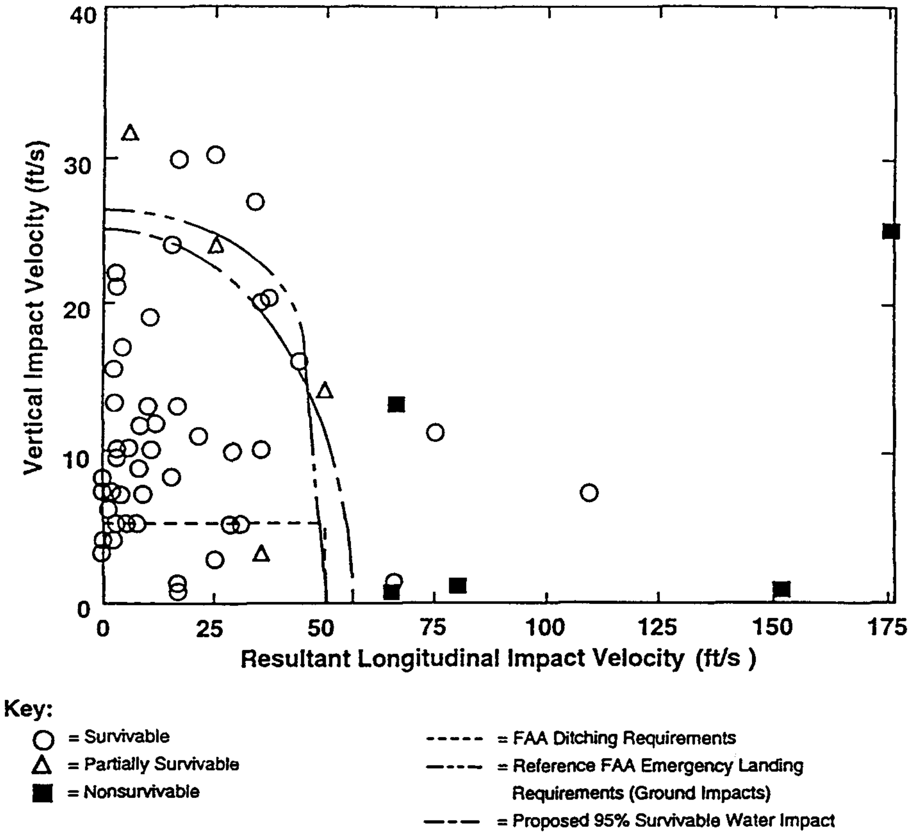

Figure 17 Rotorcraft crash survivability in landings on water between 1982 and 1989 (from [27]).

The FAA study [27] concluded that:

- The accident data review showed that occupants generally survived impact conditions more severe than those defined in the FAA's ditching regulations. Drowning was found to be a leading cause of death, even in rotorcraft equipped with floats.
- Rotorcraft were found to overturn immediately on impact in both ditching and water impact scenarios, both with and without deployed floats. Rotorcraft overturning can trap survivors beneath the water surface.
- Other design-related float problems were identified, including arming or activation methods, uneven deployment, and float separation on impact.
- FAA regulations allowed certain over-water operations to be undertaken without floats, and a significant number of water impacts had in fact occurred to rotorcraft that were not equipped with floats. A possible need to develop emergency flotation systems suitable for light-weight aircraft was identified.
- Inspections showed that the majority of flotation system service difficulties resulted from float bag leaks and corrosion of valves, gauges and fittings.

- Current analytical tools were found to cover only certain aspects of water impact, although it was considered possible that several such methods could be combined to model the complete scenario.
- The following solutions were suggested to increase occupant survivability in a water-related accident or incident:
  - Supplementary floats located near the top of the rotorcraft.
  - Automatic float activation systems that would not require pilot interaction.
  - Standard, high-visibility fabric colours and contrasting stripes to assist aircraft search-and-rescue.
  - Tear-resistant fabric for float construction.
  - Hand-holds on the floats to supplement personal flotation, regardless of rotorcraft orientation.

4.3 Water Impact Modelling

The RHOSS Report [2] reinforced the views expressed in the WHL and FAA reports [23, 24, 25, 26, 27], and stressed the need to improve provision for flotation after a severe water impact, including the possibility of installing extra flotation devices specifically to cater for a crash. It expressed the view that improved flotation would make a major contribution to prospects for safe escape after a water impact.

The CAA therefore commissioned two research studies to investigate possible ways to improve crashworthiness of helicopter emergency flotation systems. The first study, by WS Atkins, investigated water impacts and their effect on the helicopter airframe in general, and on the emergency flotation system in particular. The second study, by BMT, evaluated the statistics and variability of a wide range of possible survivable crash scenarios and sea conditions. Reports on these two studies have been published together in CAA Paper 2001/2 [28].

Both investigations were based around three specific accident scenarios that had occurred in UK waters. These three accidents occurred when a helicopter flew into the sea off the Isles of Scilly in 1983, when a helicopter fell from the deck of the Brent Spar platform in the North Sea in 1990, and when control was lost near the Cormorant Alpha platform in 1992. The RHOSS Report followed directly from the Cormorant Alpha accident, and placed particular emphasis on improving crashworthiness after a severe but survivable impact onto water.

There had been a significant number of survivors from all three accidents, but all lay well outside the Federal Aviation Administration's (FAA) proposed 95% survivability ditching envelope [27] shown in Figure 17. These three crashes represented three very different types of survivable water impact accident:

- A 'fly-in' scenario, where the helicopter is flown into the water at a shallow angle (high horizontal speed, low vertical speed).
- A vertical impact scenario, where the helicopter falls from the helideck of an offshore platform (high vertical speed, low horizontal speed).
- A loss-of-control scenario, where mechanical failure or human error causes the pilot to lose control over the helicopter in flight (intermediate horizontal and vertical speeds).

4.3.1 WS Atkins Study

WS Atkins investigated the above three accident scenarios using the non-linear finite element program, LS-DYNA3D. There was a variable level of correlation between the analysis results and test data. The helicopter FE model was validated against drop test data for a similar airframe with good results. The water model was also successfully validated for vertical impacts using NASA Gemini space capsule data; the Eulerian version was found to perform better than the Lagrangian formulation. Validation of the water model for horizontal impacts using NASA Orbiter data, however, was disappointing. It was concluded that a very fine mesh size would be required which, given the long impact durations involved with horizontal impacts and the complexity of the vehicle models, would lead to excessive simulation run times. In addition, questions arose about the validity of some of the test data. Figure 18 presents a sample result from this investigation, showing the plastic strain experienced by the airframe during a mainly vertical water impact.

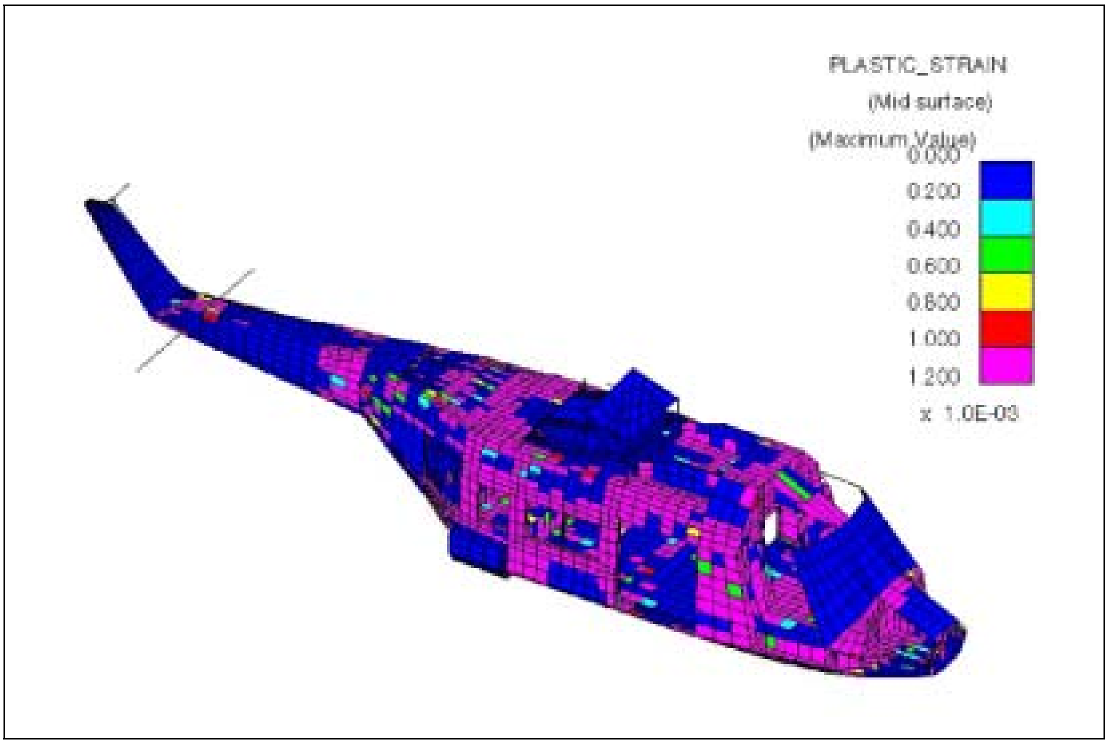

Figure 18 Example result from [28] showing plastic strain experienced by the airframe during a vertical water impact.

WS Atkins also carried out a review of accident data, to identify accidents where an EFS failure contributed to the consequences. They identified a number of causes of EFS deployment failure other than impact damage, and EFS design features that would improve overall system functionality, reliability and operation following an impact. Having carried out a high-level cost-benefit analysis, and a review of regulatory requirements, WS Atkins recommended several EFS design modifications (in particular automatic EFS arming/ deployment) that would improve performance following a severe impact. The modifications were considered to be cost-effective, and a number are already incorporated into modern EFS design.

Figure 19 shows a probability tree constructed to analyse the EFS deployment process. The upper branches indicate the probability of success at each stage, given that the previous event has been performed successfully. The lower branches indicate the probabilities of failure at each stage. The overall probability for each of the three outcomes was determined by multiplying together the probabilities along each branch, and adding those that led to the outcome of interest. The letters along the bottom line indicate possible modifications to the EFS as follows:

A - arm the system at all times, except when hazardous to do so,
B - activate the system automatically by means of immersion switches,
C - provide inflation bottle redundancy,
D - minimise the effect of varying ambient conditions on gas leaving bottles,
E - provide flexible hoses to minimise impact damage,
F - provide more even flow distribution and bag deployment,
G - increase float attachment design loads and protection from impact,
H - relocate existing floats to regions less susceptible to damage,
I - incorporate flotation unit redundancy, in addition to existing floats,
J - provide additional flotation so that the helicopter floats on its side.

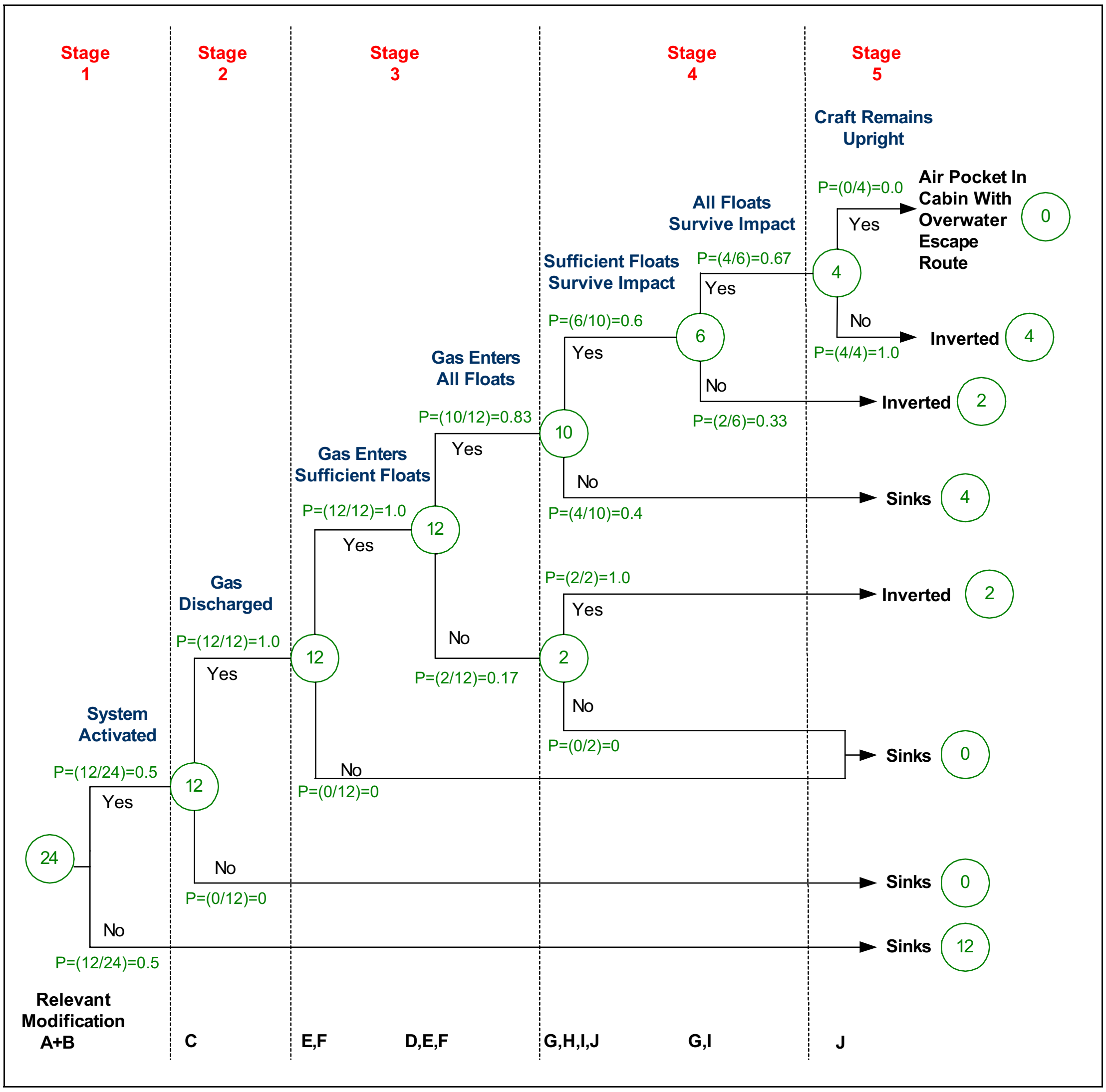

Figure 19 Probability tree for deployment of the emergency flotation system (from [28]).

4.3.2 BMT Fluid Mechanics Study

The associated BMT study evaluated the variability in water impact loading on typical flotation components (a flat panel and cylindrical float) over a wide range of possible survivable water impact scenarios and sea conditions. The investigation was based around the same three basic water impact scenarios as the WS Atkins study, plus a forced landing (or ditching) onto water. The analysis was based on Monte Carlo simulations to assess the consequences of varying impact velocities, angles and sea states. The four clouds of points in Figure 20 show the variability in vertical and horizontal impact velocity experienced by the helicopter in these four water impact scenarios. As expected, the variability in crash velocity and impact loading was found to be extremely large. In each case a green cross (x) indicates occurrences where the flotation system design loads were not exceeded, whilst a red cross (+) indicates overload and presumed failure of the flotation component. This Figure also shows impact velocity boundaries defined in ditching flotation system certification requirements, and the FAA's proposed 95% survivability envelope [27] shown in Figure 17. These boundaries include most of the ditching events, but generally lie below the ranges of velocities associated with the three crash scenarios.

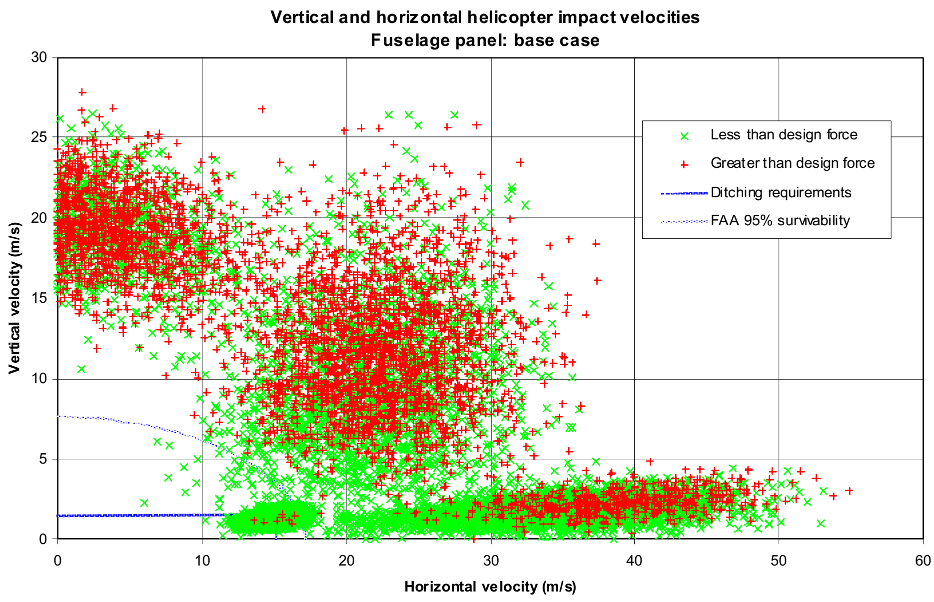

Figure 20 Vertical and horizontal impact velocities in four scenarios: loads on fuselage panel greater and less than design load (from [28]).

Figure 21 shows results from the same Monte Carlo simulation study, based on three alternative flotation configurations with different levels of redundancy. The results show that in high-impact crashes there is a 30% probability that a conventional helicopter with four flotation units will sink, whereas the helicopter with six units remained afloat in the most severe of the crashes modelled. The main difference here was that the system comprising four conventional units did not possess sufficient redundancy to allow the helicopter to float in the event of flotation unit failures. In addition, all flotation units in a conventional system are installed at the helicopter's floor level, close to the most likely point of impact. In contrast, the six-float configuration provides redundancy at a bag level using additional flotation units, which are installed high on the cabin walls where they are well protected from all but side impacts.

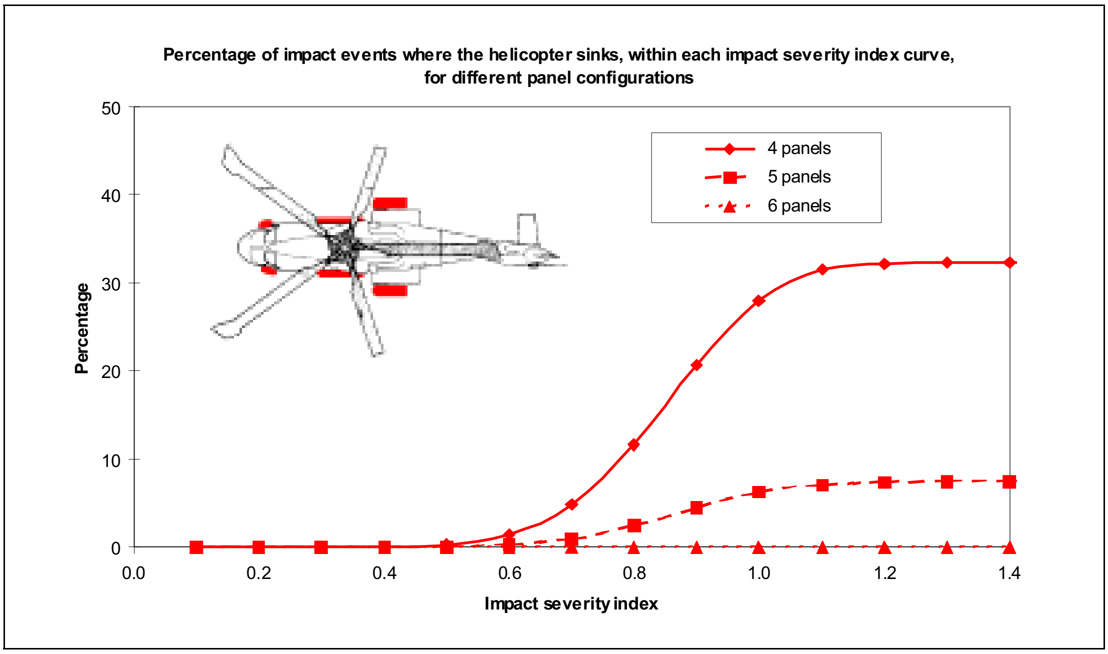

Figure 21 Percentage of water impacts causing the helicopter to sink. Up to six flotation units, with four required to remain afloat (from [28]).

This study also concluded that a very substantial increase in flotation design loads would be required in order to make a significant difference to survivability with a conventional four-float configuration. Doubling the design loads would only result in a very modest improvement in crashworthiness.

The most important outcome of this study was in highlighting the major benefits of flotation redundancy, particularly having additional flotation units installed in a location less vulnerable to water impact, high on the cabin walls. Similar floats had also been proposed to prevent total inversion after ditching (see Sections 2.2.1 and 3.3). It should also be noted that the largest gain in crashworthiness was obtained when the first high-mounted flotation unit was added (i.e. the five-float configuration). This configuration provides the asymmetry required to prevent the undesirable second post-capsize rotation experienced with symmetric configurations during earlier ditching research (see Section 3).

5 Emergency Breathing Systems (2003)

5.1 Introduction and Background

RHOSS considered that there was no clear advantage to be gained from the introduction of emergency underwater breathing equipment and that, on the evidence currently available, the CAA would not be justified in pursuing this as a regulatory measure. The review considered that the chances of successful underwater escape might be more reliably improved by measures aimed at facilitating egress.

In October 2000, however, a workshop on emergency breathing systems (EBS) was convened, largely in response to the wide-scale deployment of EBS by the offshore industry. This workshop was supported and attended by the Joint Aviation Authorities' Helicopter Offshore Safety and Survivability (HOSS) working group. As a result of this exercise, a study on the implementation and use of the various forms of EBS was commissioned by the CAA on behalf of HOSS.

5.2 EBS Implementation and Use Study

This study [29] was undertaken by Dr Susan Coleshaw, who had previously performed the side-floating helicopter human factors study while employed with RGIT Limited (see Section 3.3.5).

Published data on helicopter water impact accidents were analysed to determine the frequency of different impact conditions and the incidence of drowning. Evidence from accident reports indicated that the helicopter inverted or sank immediately or after a short delay in about 60% of all water impacts. If a helicopter does capsize it will generally invert to a position where all the exits are underwater, meaning that those who survive the water impact must make an immediate underwater escape. Survivors have to cope with in-rushing water, cold shock, severe disorientation caused by inversion, difficulties in releasing seat belts, and then locating and opening exits.

The high incidence of drowning is largely due to cold shock, which greatly reduces breath-hold time and thus limits the time available for escape. EBS are designed to help overcome cold shock by allowing individuals to breathe underwater for a short time, thus extending underwater survival time. In this way EBS can provide a means of bridging the gap between maximum breath-hold time and escape time, and thus reduce the incidence of drowning.

The risks from an accident in UK waters are potentially more serious than in more temperate waters due to the higher risk of cold shock. Flights for the oil and gas industry nonetheless differ from other civilian flights as all passengers are flying in an occupational role. They wear protective immersion suits and receive training on survival in the event of an accident. Thus, while conditions may be more severe, the chances of making a successful escape are improved by the training, and by the level of personal protection provided to individuals.

The report considered that reliance on EBS for escape should be minimised, but noted that successful use of EBS can reduce levels of stress experienced during helicopter escape under simulated conditions. Satisfactory performance of EBS does, however, depend on good design, reliability of the equipment, ease of use and performance on demand. Other key factors include individual human capabilities, training, environmental conditions, helicopter design, and the circumstances of the helicopter accident.

Training is required to maximise the benefits of EBS and minimise the risk of human error during deployment and operation. When reviewing current knowledge on EBS equipment, particular attention was given to the testing and development of two products: a re-breather and a compressed gas system. The report discussed the background and rationale behind their selection.

An example draft technical standard was also prepared, identifying minimum performance requirements to ensure that equipment is manufactured to consistent and satisfactory standards, and that basic health and safety requirements are met. Compatibility with other personal protective equipment was also considered to be an important issue that a technical standard would address.

The main conclusions from the study were that EBS could provide a viable solution to bridge the gap between breath-hold time and escape time, but that careful attention would have to be paid to equipment design and user training. The study recommended that a technical standard should be produced for EBS, and highlighted the knowledge gaps that would need to be filled.

At the end of this study the CAA reviewed its policy with respect to EBS, and concluded that there was no compelling case to either mandate or ban the use of EBS. The CAA also decided not to produce a formal design specification, largely because it is not normal practice to do so for non-mandated equipment. The final report on the study, including the example draft technical standard, was published in CAA Paper 2003/13 [29].

6 Future Regulatory and Research Activities

6.1 HOSS and WIDDCWG Recommendations (2000)

The CAA presented the findings from its ditching and water impact research to the JAA Helicopter Offshore Safety and Survivability (HOSS) working group and to the FAA/ JAA/Industry Joint Harmonisation Working Group (JHWG) on Water Impact, Ditching Design and Crashworthiness (WIDDCWG). The HOSS group produced a working paper [30], reproduced in Appendix F of this report, and the WIDDCWG produced a report [31], reproduced in Appendix G.

Both working groups recommended changes to current JAR/FAR 27 and 29 airworthiness requirements relating to helicopter ditching and water impact crashworthiness. HOSS noted that occupant survivability considerations do not take account of service experience, and that accepted methods for demonstrating compliance and determining flotation stability are no longer considered to be acceptable.

Similar recommendations came from both groups, and composite recommendations relevant to this report include the following:

- The current interpretation of 'reasonably probable water conditions' for ditching equipment certification should be amended to take account of regional climatic sea conditions. Having regard to current FAA and JAA operating rules, and industry requirements for straightforward certification standards, the following recommendations were made:
    - In non-hostile environments, emergency flotation equipment should be the standard, and the current interpretation based on sea state 4 was considered to be appropriate.
    - In hostile environments, a higher standard of sea state 6 should be required for ditching equipment certification.
    - Capsize boundary targets should be defined in terms of significant wave height, zero crossing period and wave spectrum shape rather than sea state number.
- Flotation stability should be substantiated by representative model testing in irregular waves, with an appropriate exposure period and target probability of capsize. Associated standard test conditions and a standard test protocol, with pass/ fail criteria, should be developed and adopted.
- Structural ditching requirements should not be expanded to consider crashworthiness, because of the high variability in impact loads, and the high magnitude of impact loads in survivable accidents, which can be too high to design for in a practical manner.
- The flotation system should be automatically activated on sensing water immersion (to include automatic arming where appropriate), and the possibilities for disabling automatic float activation (during any flight over water) should be minimised.

- The flotation stability benefits of fitting scoops to flotation bags should be identified in guidance material.
- The potential benefits of the side-floating helicopter concept, in respect of post-ditching capsize, should be recognised, and support for its further development should be given. JHWG should consider incorporating this concept into the requirements once research has been completed, if shown to be technically feasible and economically justifiable.
- The costs and expected benefits/ disbenefits should be established for redundant flotation units configured to produce a side-floating helicopter following capsize.
- Appropriate requirements/ advisory material should be generated and adopted to reflect current practice in terms of EFS crashworthiness.
- In view of the disparity between breath hold capability and escape time, the regulatory need and expected benefits/ disbenefits of EBS, for enhancing prospects of successful egress from an inverted and flooded cabin, should be established as a matter of urgency.

The papers produced by the HOSS and the WIDDCWG were submitted to the JHWG (later renamed the Rotorcraft Steering Group (RSG)) in June 2000. Having reviewed and debated both papers, the JHWG concluded that there remained some controversial issues that required further research. To ensure that progress continued, however, the JHWG committed in June 2001 to progressing those recommendations where full consensus within the working groups had been achieved. The issues were split into those requiring changes to the advisory material only, and those involving rule changes. The JHWG was empowered to progress the former, but the latter had to be endorsed by the JAA Harmonisation Management Team (HMT) and the FAA Regulatory Council prior to requesting the Aviation Rulemaking Advisory Committee (ARAC) to form a working group. The HMT subsequently endorsed the setting up of a rulemaking group in February 2002, but the FAA Regulatory Council, despite support from the FAA Rotorcraft Directorate, declined to progress this issue in the short-term due to its low priority status (from their perspective) and lack of resources. Unfortunately, and largely due to the events of 9/11 in the USA, little progress has been made since then.

It was originally considered desirable to run the working groups covering the advisory material and the rule changes in parallel in order to make the most efficient use of resources. In June 2003, however, due to the lack of progress on the rule change proposal, the RSG agreed to initiate work on the advisory material separately. At the time of writing, AC material is in draft form. In addition, both regulatory activities (advisory material and rule changes) are listed on EASA's 2005/2007 Future Rulemaking Plan.

6.2 Future Work

Although the CAA believes that an improvement in the sea-keeping performance of ditched helicopters is practical at reasonable cost, it is recognised that it is not realistic to expect helicopters to remain upright in the more severe conditions experienced in the northern North Sea, in the event of water impact, or due to post ditching aspects other than stability. The RHOSS Report noted that all drownings that had occurred in offshore helicopter accidents had been associated with water impacts rather than ditchings.

In view of this, and the results of the ditching and water impact research described above, the CAA believes that the side-floating helicopter concept has significant potential to address both the ditching and water impact safety issues. CAA therefore recommends that this work be progressed by commissioning a helicopter type-specific design study. The purpose of this study will be to address the areas of concern highlighted by the WIDDCWG and HOSS reports.

7 Conclusions

The reports covering the various helicopter ditching and water impact research activities described in this document each contain their own detailed conclusions. For clarity, this section comprises a summary of the major overall conclusions only.

7.1 Ditching

- Demonstration of compliance with the certification requirements for helicopter ditching (JAR/FAR 27/29.801) in respect of flotation stability through model testing in **regular** waves is unreliable. The associated Advisory Circular (AC) material should be revised to specify testing in **irregular** waves with an appropriate exposure period and target probability of capsize.
- The present reference to sea state 4 as the "reasonably probable water condition" in the ditching certification AC material is unsatisfactory as a global standard, and should be replaced with a requirement for the designer to select a sea state with an appropriately low probability of exceedance in the intended area of operation. The sea conditions should be defined in terms of a significant wave height, zero crossing wave period and wave spectrum.
- Float scoops fitted to emergency floats can significantly enhance flotation stability at minimal cost and weight and should be recommended in the ditching certification AC material.
- Model tests on helicopters with raised floats (the 'wet floor' scheme) were inconclusive. The effect on static stability was found to be very variable, depending on helicopter weight and type. No consistent improvement in resistance to capsize in waves was found either.
- The upper practical capsize limit for helicopters lies in the region of sea state 5 or 6, but there is a significant risk of ditching in seas greater than sea state 6 in some areas of operation (e.g. the northern North Sea). Other circumstances, such as damaged or malfunctioning flotation equipment, or imperfect alighting onto the sea (e.g. due to tail rotor failure), may also lead to capsize in more moderate seas.
- A potential way to mitigate the consequences of post-ditching capsize would be to locate additional flotation devices high on the fuselage in the vicinity of the main rotor gearbox and engines, with the aim of preventing total inversion of the helicopter following capsize. This 'side-floating' scheme serves to retain an air space within the cabin thereby removing the time pressure for escape, and ensuring that some of the doors and windows that form the escape routes remain above the water level facilitating egress.
- Practical trials of the human factors aspects of escape from a side-floating helicopter using a helicopter underwater escape trainer (HUET) concluded that "... the evidence suggests that the occupant of a side-floating helicopter has a much better chance of escape and survival than someone inside a fully inverted aircraft".

7.2 Crashworthiness

- The primary cause of loss of life in helicopter water impacts is drowning. Occupant fatalities resulting from excessive crash forces or as a result of structural collapse are a secondary issue.
- Designing the airframe to remain afloat for sufficient time to enable evacuation following a water impact should be a major objective if survival is to be improved.
- A high-level cost-benefit analysis based on historical accident data indicated that the most cost-effective means of significantly improving post water impact flotation is automatic arming and activation of emergency flotation systems. The provision of additional flotation equipment to prevent total inversion following capsize (the 'side-floating' scheme) was judged to be the second most cost-effective measure.
- A computer modelling study based on simplified empirical and theoretical formulae indicated that the most effective means of mitigating the consequences of survivable water impacts is through the provision of redundancy in the emergency flotation system. For the purposes of the study, redundancy was provided by the additional flotation bags required for implementation of the 'side-floating' scheme.

7.3 General

- Overall, the single most effective means of improving occupant survival in the event of a post-ditching capsize or a survivable water impact is through the provision of additional flotation devices to prevent total inversion following capsize.
- Further work is required to confirm the technical feasibility and economic viability of the side-floating scheme. This should consist of a detailed design study for the modification of the EFS of a specific helicopter type.
- Emergency breathing systems (EBS) are capable of significantly extending underwater survival time, and can provide a means of bridging the gap between breath-hold time and escape time. Although not considered to be as effective as the 'side-floating' helicopter approach, particularly in the event of water impact, EBS could provide short-term mitigation pending the implementation of the 'side-floating' scheme, or an alternate solution in the event that the 'side-floating' scheme proves to be impractical for retro-fit to existing helicopters.

8 Abbreviations

AC	Advisory Circular
ARAC	Aviation Rulemaking Advisory Committee
BCAR	British Civil Airworthiness Requirements
BHC	British Hovercraft Corporation
BMT	BMT Fluid Mechanics Limited/ BMT Offshore Ltd.
CAA	(UK) Civil Aviation Authority
CAP	Civil Aviation Publication
EASA	European Aviation Safety Agency
EBS	Emergency breathing systems
EFS	Emergency flotation systems
FAA	(US) Federal Aviation Administration
FAR	(US) Federal Airworthiness Regulations
HARP	Helicopter Airworthiness Review Panel
HMT	JAA Harmonisation Management Team
HOSS	(JAA) Helicopter Offshore Safety and Survivability working group
HUET	Helicopter underwater escape trainer
IOS	Institute of Oceanographic Sciences
JAA	(European) Joint Aviation Authorities
JAR	(European) Joint Aviation Requirements
JHWG	(FAA/JAA) Joint Harmonisation Working Group
NTSB	(US) National Transportation Safety Board
RGIT	RGIT Limited
RHOSS	Review of Helicopter Offshore Safety and Survival
RSG	Rotorcraft Steering Group
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
US(A)	United States of America
WHL	GKN-Westland Helicopters Limited
WIDDCWG	(JHWG) Working Group on Water Impact, Ditching Design and Crashworthiness

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Appendix A Review of Helicopter Ditching Performance

Executive Summary

BMT Offshore Ltd. was asked by the Civil Aviation Authority to perform a review of helicopter ditching performance.

The review was to look critically at the various research reports and review documents that CAA had commissioned in recent years, and to summarise and comment on their findings.

The stated objective in the certification of a helicopter in relation to ditching in the sea is that the helicopter should remain upright for sufficient time for the occupants to escape (say 5 minutes). This implies that there should be an acceptably low probability of meeting a wave large enough to capsize the helicopter in this short period of time. The probability of experiencing a capsize is dependent on two key factors:

a) The height and period or slope of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

This report concludes that the more important gaps in current understanding lie in the first category rather than the second. Attempts to correlate the dynamic stability in waves of different helicopter types with their physical and static stability properties have identified some weak relationships, but there is a lack of confidence that this information could be used to design modifications that would be guaranteed to result in improved performance in a seaway. Further theoretical and computer simulation work is required to confirm these basic dependencies.

However, there is clear evidence that helicopter resistance to capsize could be improved by the addition of float scoops.

Raising flotation so that the helicopter floats at a lower level in the water (the `wet floor' approach) does not currently enjoy evidence to support it as an improving measure, but this may be due to a lack of understanding on exactly how the floats should be positioned.

The attachment of floats to the engine cowling can prevent permanent complete inversion of the helicopter and permits the helicopter to float in a stable side-on attitude following any initial capsize.

This report presents a number of conclusions on the results of the research work to-date, and also makes recommendations about further work aimed at reducing the risk of capsize.

1 Introduction

BMT Offshore Ltd. (BMT) was asked [1][1] by the Civil Aviation Authority (CAA) to propose a review of helicopter ditching performance. BMT responded with a proposal [2], and based on this proposal, CAA put in place a contract for the work to be performed [3].

The review was to look critically at the various research reports and review documents that CAA had commissioned in recent years, and to summarise and comment on their findings.

1.1 Objectives

The objectives of the overall study were stated to be [2] as follows:

a) Perform a critical review of a number of documents (Refs [4] - [8]) with the objective of drawing conclusions from this work and prepare an overview document (or documents) suitable for publication by CAA.

b) Perform a critical review of the current UK Emergency Alighting on Water helicopter design requirements as specified by BCAR Paper No G779 dated 7th October 1985, and where appropriate make recommendations on how these requirements might be improved, and whether there are better ways of assessing a helicopter's water-borne stability.

c) Based on the results of (a) and (b) above, and the results of a separate study, review North Sea helicopter ditching performance over the past 20 years and assess the practicality of imposing a new probability-based methodology for North Sea helicopter operations, taking account of specific type's ditching rates, capsize probability and operating environment.

This first report deals with the results of (a) above only.

1.2 Background

The stated objective [7] in the certification of a helicopter in relation to ditching in the sea is that the helicopter should remain upright for sufficient time for the occupants to escape (say 5 minutes). This implies that there should be an acceptably low probability of meeting a wave large enough to capsize the helicopter in this short period of time.

The probability of experiencing a capsize is dependent on two key factors:

a) The height and period or slope of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

This report reviews the current understanding on these two factors as evidenced by the contents of references [4] - [8]. It attempts to draw attention to the gaps in current understanding and thus recommend where further research work should be directed.

2 Conclusions and Recommendations

The study has attempted to identify the key issues influencing the ability of helicopters to resist capsize whilst floating on the surface of the seas following ditching. The issues identified, and the implications for future work or regulatory activity, are outlined in the following:

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[1] References are to be found in Section 9 on Page 30.

2.1 Conclusions

2.1.1 This study has only considered helicopters that are floating upright and intact, and therefore have presumably alighted on the water in a reasonably controlled manner. No consideration has been taken of the stability of helicopters that are damaged prior to, or in the course of, alighting on the water.

2.1.2 The results of model tests on some eight different helicopter types has been studied, many over a range of different weights and float configurations.

2.1.3 The model test reports [4] and [5], present the results of numerous tests in regular and irregular waves. Little or no attempt is made in these reports to interpret the capsize boundary results in terms of the key factors influencing the static stability properties of the helicopter or its other physical properties.

2.1.4 The results of these tests show that the helicopter types tested generally had little difficulty in complying with the BCAR regular wave steepness criterion, but all capsized in irregular waves less severe than the BCAR limit for stability investigation of sea-state 6.

2.1.5 The results of [4] and [5] have been re-analysed and re-presented in an attempt to discover the major helicopter properties that influence capsize. The results of this extensive exercise were generally disappointing, but there is some evidence that the following assist in the prevention of capsize:

- greater helicopter weight;
- greater roll inertia;
- greater peak righting moment;
- greater area under righting moment curve;
- greater range of stability;
- greater helicopter beam;
- greater roll gyrates/beam.

Clearly a number of the above are interrelated.

2.1.6 Model tests of the type reported in [4] and [5] are extremely difficult to perform. The capsizing of the model helicopter is very sensitive to precise details of the model and precise details of the waves. This may explain some of the difficulty experienced in correlating the results.

2.1.7 Ideally such tests should provide a quantitative measure of the probability of capsize in a given duration of exposure to a given sea-state. However, this information requires many repeat runs in different realisations of the same wind and wave conditions in order to be reliable, and is thus very time-consuming and expensive. The results of such tests should however be much more useful than those described in [4] and [5].

2.1.8 It is clear that model tests in the presence of wind result in fewer capsizes. This is due to a tendency to weather vane, i.e. turn into the winds and waves. Evidently any device (e.g. sea anchor) which promotes the adoption of a nose to wave heading is beneficial to the survival of the helicopter.

2.1.9 The capsize of helicopters is essentially only caused by breaking waves. It is unlikely that an undamaged helicopter will capsize in non breaking waves.

2.1.10 Ignoring the results of the model tests, consideration of the physical mechanism of capsize in a breaking wave suggests that the following properties of the helicopter will enhance resistance to capsize:

- high roll inertia;
- large range of static stability;
- large angle of peak righting moment;
- low lateral resistance to movement through the water;
- low above water profile.

2.1.11 Model tests on float scoops have demonstrated a significant benefit in terms of resistance to capsize on all but one helicopter type. It is not clear however, whether this benefit comes primarily from the improvements to the static stability curve, or to the dynamic (inertia and damping) properties of the helicopter.

2.1.12 Work on the development of float scoops seems to have been halted due to difficulties in predicting the increased flotation loads. However, these loads should not be any more difficult to predict using empirical data than the loads experienced by conventional floats.

2.1.13 Model tests on helicopter models with raised flotation (the ‘wet floor’ approach) have been inconclusive. The effect of raising the floats on the static stability of the helicopter varies markedly depending on aircraft weight and type. The effect on resistance to capsize in waves is also very variable. It is likely that the new raised location of the floats must be carefully chosen in order to obtain any beneficial effect. Further work is in progress on this issue.

2.1.14 Theoretical analysis of the likely influence of float ‘scoops’ [6] which has been previously conducted is flawed because of a failure to incorporate basic wave kinematics into the model. However, proper numerical simulation of the behaviour of a helicopter floating on the surface of the sea probably offers one of the best opportunities to assist understanding of the capsize process and the helicopter and wave properties that influence it.

2.1.15 Work performed by IOS has demonstrated a method for estimating the probability that a capsizing wave will be experienced in a given period of time chosen at random. This technique offers part of the answer in the search for a means for the estimation of the overall risk of capsize.

2.1.16 The results of the IOS work show probabilities of capsize in a 10 minute period in the North Sea of about 5% (it is not clear why 10 minutes was chosen, when the CAA stated period is 5 minutes). These results seem to be inconsistent with practical experience of ditchings, and the results of model tests in irregular waves which both suggest that this probability is more likely to be in the region of 30%. The selection of the wave height capsize criterion assumed by IOS may be at fault.

2.1.17 The CAA has suggested [7] an objective for this probability of capsize following a ditching of 1%.

2.1.18 Whilst it seems that significant improvements to resistance to capsize are possible (e.g. using scoops), it is difficult to imagine a practical design improvement that will guarantee an order of magnitude change to the current levels of probability of capsize. This implies that more serious consideration should be given to measures (such as engine cowling floats) that prevent a permanent inverted attitude following initial capsize.

2.1.19 The apparent rejection of cowling floats on the basis of one model test, and possibly a faulty interpretation of the results of this model test, is unfortunate. This test demonstrated that a stable side-floating condition could be maintained on an S76. There was, however, a tendency for the helicopter to roll through more than 270^{o}, in two stages, to reach this attitude, and previous writers have pointed to the danger to escaping personnel this represents. The author of this report does not agree with this view, believing that the risk to escaping personnel is not greater than that represented by trying to escape during or following capsize to a fully inverted attitude, and that it is better to have the guarantee of an eventual floating attitude where there is at least one escape hatch well above water level.

2.2 Recommendations - General

2.2.1 Future wave model tests performed on helicopters for certification or research purposes should concentrate on behaviour in long sequences of realistic irregular waves so that the probability of capsize can be properly estimated.

2.2.2 Most of the evidence on probabilities of capsize for current helicopter types in the North Sea suggests that the risk of capsize is considerably higher than the CAA stated objective. Therefore means should be sought to reduce this risk.

2.3 Recommendations for Further Work

2.3.1 The development of a time-domain computer simulation model of the motion of a helicopter floating on waves is justified in terms of the understanding it is likely to bring of the main parameters controlling resistance to capsize. Earlier attempts at this seem to have failed primarily due to the inexperience of the computer modellers with the simulation of water wave processes.

Initial dynamic simulation work should concentrate on regular waves, but it is important that the methods chosen can be extended to breaking waves (using the best available research on breaking wave kinematics) and to irregular wave spectra.

Work with the simulation model should concentrate on (a) attempting validation against model tests, and (b) using the simulation model to perform systematic variations of stability properties.

Collaboration with those in possession of model tests on a fully instrumented helicopter model might be particularly beneficial in this context.

2.3.2 Consequently, it is recommended that an approach be made to the owners of the results of some helicopter model tests conducted in the Marintek facilities in 1991, to see if they would be prepared to release some or all of their information. The objective would be discover whether the data could be used to validate theoretical predictions of helicopter motions on the point of capsize.

2.3.3 The concept of float scoops should be developed further because they appear to provide significant benefit. It should not be necessary to wait for the results of computer simulations in order to make reasonable estimates of the flotation loads. The work should also concentrate on establishing whether it is the static stability or dynamic effects of the scoops that are primarily responsible for the benefit, as this may point the way to significant design improvements.

2.3.4 The 'wet floor' concept requires further detailed investigation before it can be determined whether, and how, floats should be raised on any individual helicopter type. Initial steps in this direction are already in progress with the detailed hydrostatic modelling of a partially flooded helicopter.

2.3.5 More serious attention should be given to measures (such as the cowling floats) that prevent a permanent inverted attitude following initial capsize.

2.3.6 Consideration should be given to extending the IOS probabilistic analysis to cope with varying probability of capsize with breaking wave height. Whether or not it is decided to extend the theory in this way, it is recommended that the analysis should be performed for a range of capsize criteria for some long term good quality North Sea data-sets such as BP Forties and Shell Brent, in order to obtain a better estimate for the central and northern North Sea areas respectively (this may require the collaboration/permission of BP and Shell, but this is not expected to be withheld). Furthermore, if estimates of probability of capsize are required covering a greater area, it is recommended that BMT's PC Global Wave Statistics EUROPE database is used to derive values.

3 Model Tests

3.1 Model Test Reports

Model tests are described in two main reports [4] and [5]. These two reports together cover a very large range of helicopter types and conditions, but unfortunately they do not present a body of data that is fully consistent in terms of the results presented.

In particular the results of irregular wave tests are poorly presented, there being few tables summarising the stability/capsize properties in all the different conditions. When one tries to recover this information from the narrative, there are often ambiguities which make the process very uncertain.

The reliance in the narrative, and in the tables, on using sea-state numbers also causes considerable confusion - particularly as the definitions of these conditions (in terms of significant wave height and modal period) vary, sometimes considerably, from one set of tests to the next. Wave spectrum shapes are also poor in many cases. In some cases spectra have been modelled in the basin with what seems to be completely the wrong peak period, leading to very steep waves.

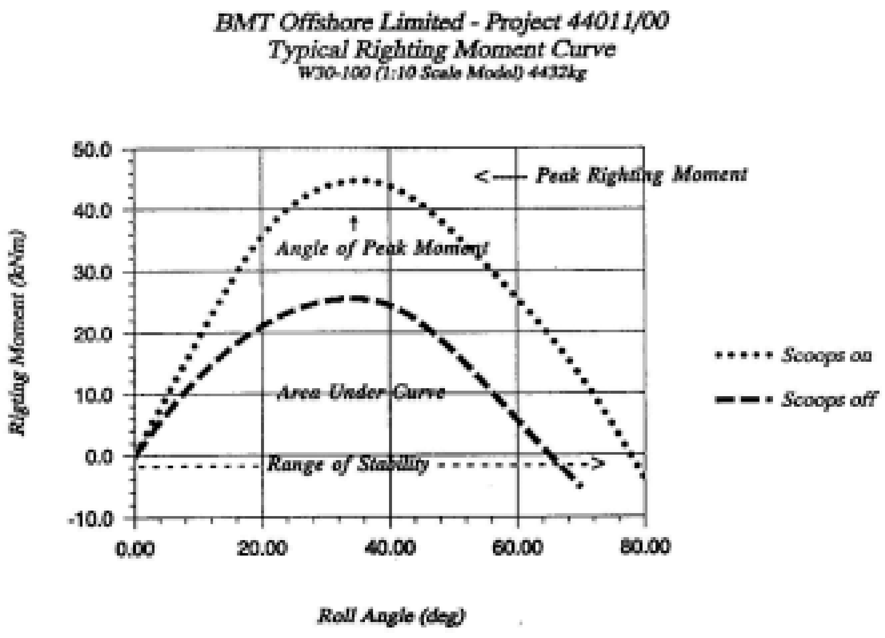

Figure 1 The Main Static Stability Properties.

What is lacking from this work is any systematic investigation of what the parameters controlling capsize are for a given helicopter, or for helicopters in general. The work rather concentrates on measuring capsize boundaries for a large number of different types and conditions.

The main properties of the static stability of a helicopter are illustrated in Fig 1.

Some helicopter properties likely to have some influence on capsize are:

static stability properties:

- peak righting moment,
- angle of peak moment,
- range of stability,
- minimum stability axis (not necessarily roll).

dynamic properties:

- roll inertia (or radius of gyration),
- roll natural period.

other properties:

- helicopter beam,
- floating trim angle,
- tendency to weathervane in waves,
- tendency to weathervane in wind and waves,
- underwater lateral area (resistance to being pushed sideways by breaking wave),
- above water area (vulnerable to impact from breaking wave).

3.1.1 BHC Draft Report No. X/O/3282, Nov 1985, Study of Float Positioning

The main body of this report [4] deals with the static stability of an S-76 helicopter as calculated by a computer model, with many different static stability curves being presented for a number of different float positions. There are five addenda which deal with model tests for W30-100, S-76, and AS-332L types, and compare results of the computer studies with the physical model tests. The helicopter types and conditions studied in this report are summarised here in Annex A.

The main work of the report deals with the effects of raising of floats and the results are described in Section 3.3 below.

3.1.2 BHC Report No. X/O/3257, April 1986, Study of Fitting Scoops to Emergency Floats

This report [5] deals with the adding of scoops to the floats on nine different helicopter types. The scope and results of the report are summarised in Annex B and the conclusions on the influence of scoops are discussed in Section 3.4 below.

3.2 Helicopter Static/Dynamic Properties and Capsize in Waves

In an attempt to discover what are the main properties of the helicopter that influence the resistance to capsize, data was extracted from [4] and [5] and plotted for all helicopter types and for all configurations against various properties of the static stability curves and various physical properties of the helicopter.

Some 70 different graphs comparing the wave height or wave slope at which capsize occurred with some physical property of the helicopter were plotted. In the vast majority of cases it was not possible to discern any correlation and so this report presents a few example plots where the correlation was of interest.

In most cases the full body of data for all helicopter types in all conditions (of weight, float position, with/without scoops etc.) were plotted together, but in some cases data was isolated for individual types or conditions.

The parameters plotted included:

Helicopter Property	**Comments**
Angle of Peak Righting Moment (deg)	
Area under static stability curve (kN m deg)	
Area under curve / Weight / Beam (deg)	
Beam (m)	Estimated across the outside extremities of the flotation equipment.
Natural roll period (s)	Estimated very approximately from inertia and static stability.
Peak righting moment (kN)	
Peak righting moment / Angle of Peak Righting moment (kN/deg)	
Peak righting moment / Angle of Peak Righting moment / Weight (deg)	
Peak righting moment / Weight / Beam	
Range of Stability (deg)	Angle at which righting moment ceases to be positive.
Roll inertia (kg $m^{2)}$	I
Mass (kg)	M
Roll Gyradius (m)	Radius of gyration $(I/M)^{0.5}$
Roll Gyradius / Beam	

Separate plots were prepared for:

- Tests in regular waves
- Tests in irregular waves (without wind)
- Tests in irregular waves (with wind)

Overall the results of this exercise were quite disappointing with very few clear trends emerging. However the more interesting results are discussed in the following:

3.2.1 Tests in Regular Waves

All the regular wave model tests reported in [4] and [5] were conducted without wind. The helicopter model was set in the water at a given heading to the waves and allowed to drift freely. In most tests the helicopter was started beam-on to the waves, and most helicopters (in common with boats) tend to turn and remain beam to waves in the absence of wind or any other yaw restraint such as a sea anchor.

In these reports the regular wave results have been presented in terms of points representing stable/capsize conditions plotted on axes of wave height and wavelength. The authors of the report have then drawn lines to represent the boundary between the stable and capsized conditions.

In most cases these boundaries approximate to lines of constant wave slope (wave height / wavelength) - Fig 2 is an example.

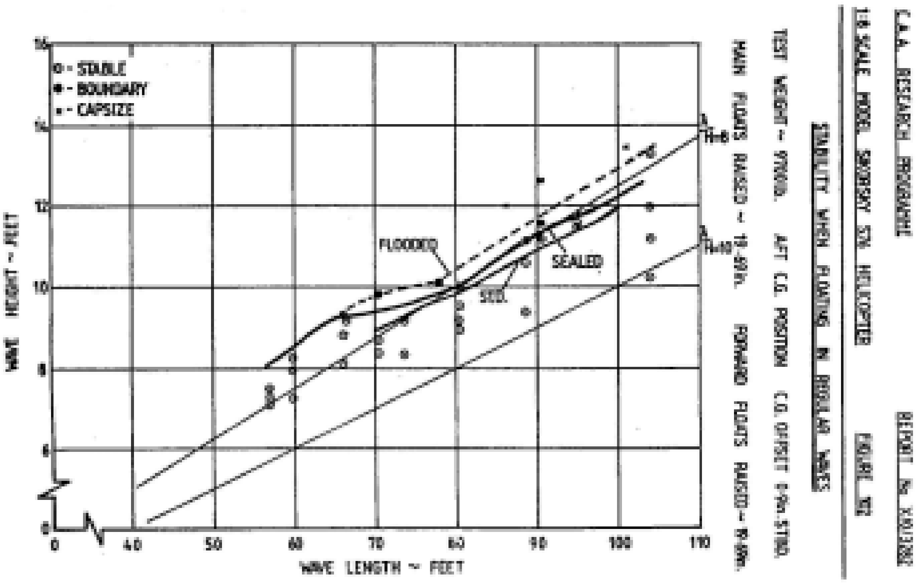

Figure 2 Example Capsize Boundary Plot from Ref [4].

This implies that the capsize of the helicopter is purely dependent on the steepness of the waves experienced (although see Annex C for discussion on the limitations of these tests).

In view of this apparent dependence on wave steepness, the steepness capsize boundaries for all the helicopter types were plotted against various physical properties of the helicopters concerned in order to identify trends. The steepness boundaries were not always quite constant with wave height and so, for consistency, the capsize boundary steepness was always determined at a wave height of 3.6m (12ft).

The more interesting correlation results are shown in Figures 3 - 5. In these plots the vertical axis is wave height / wave length, thus a steeper wave has a higher numeric value.

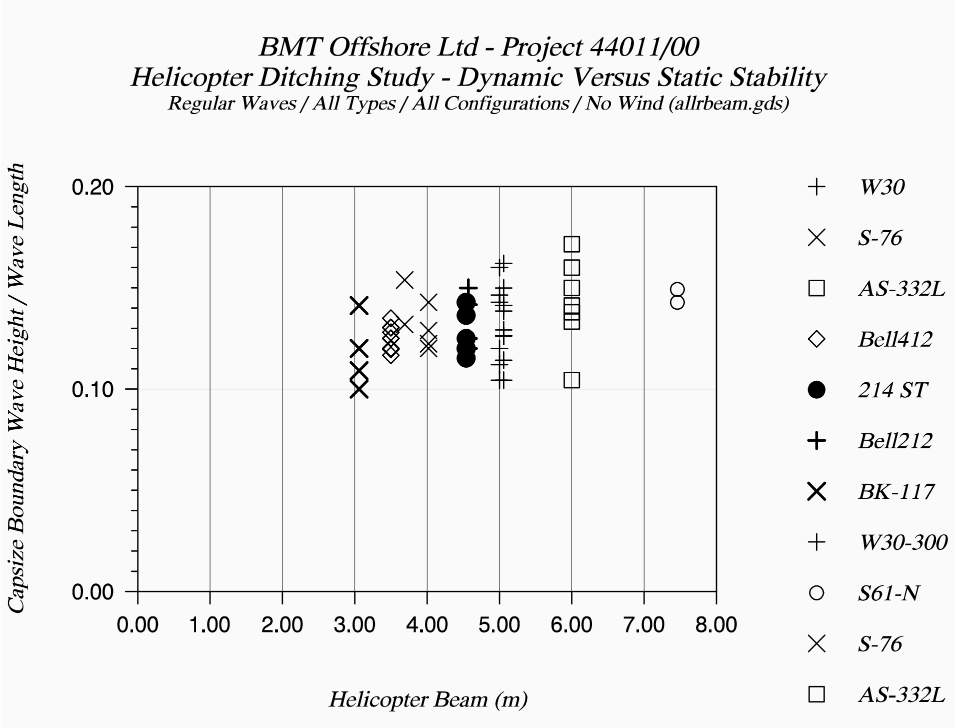

Figure 3 Influence of Beam on Regular Stability Boundary.

It can be seen from Fig 3 that there is a general trend for the capsize boundary to be lower when the beam of the helicopter is smaller. Thus the narrower the helicopter beam, the less dynamically stable it is in steep waves.

Fig 4 plots the capsize steepness boundary against the weight of the helicopter. This indicates that, as a general trend, the heavier the helicopter type, the more steep waves it can tolerate without capsize. (This general trend is also usually true for a single helicopter type where it has been found that heavier loading conditions tend to be more stable.) However, the weight of different helicopter types will normally be correlated with their beam, and so these two parameters cannot be considered to be independent. [1]

When the capsize boundaries were plotted against the roll gyradius, no clear trends were seen. However, the roll inertia showed some slight correlation with the higher inertias being associated with greater resistance to capsize - see Fig 5.

There also seemed to be some weak correlation of the results with properties of the static stability of the helicopter such as the area under the stability curve, the peak righting moment, the range of stability, but not usually with the non-dimensionalised versions of these parameters. Overall there did seem to be some tendency for the helicopter to exhibit greater dynamic stability (as indicated by the capsize steepness boundary) with increased peak righting moment and increased area under the stability curve.

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[1] **Note added in 2005:** The helicopter's weight is also correlated with the height of its centre of gravity, because the main variable is the quantity of fuel in the underfloor tanks. A higher weight implies that there is more fuel in the underfloor tanks, and therefore a lower centre of gravity.

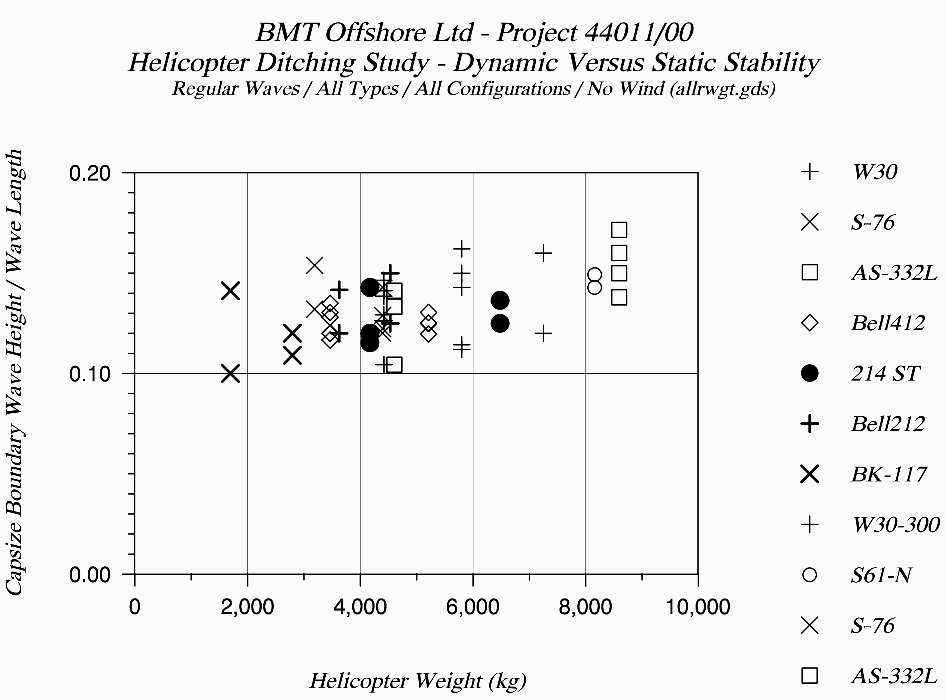

Figure 4 Influence of Helicopter Weight on Regular Wave Stability Boundary.

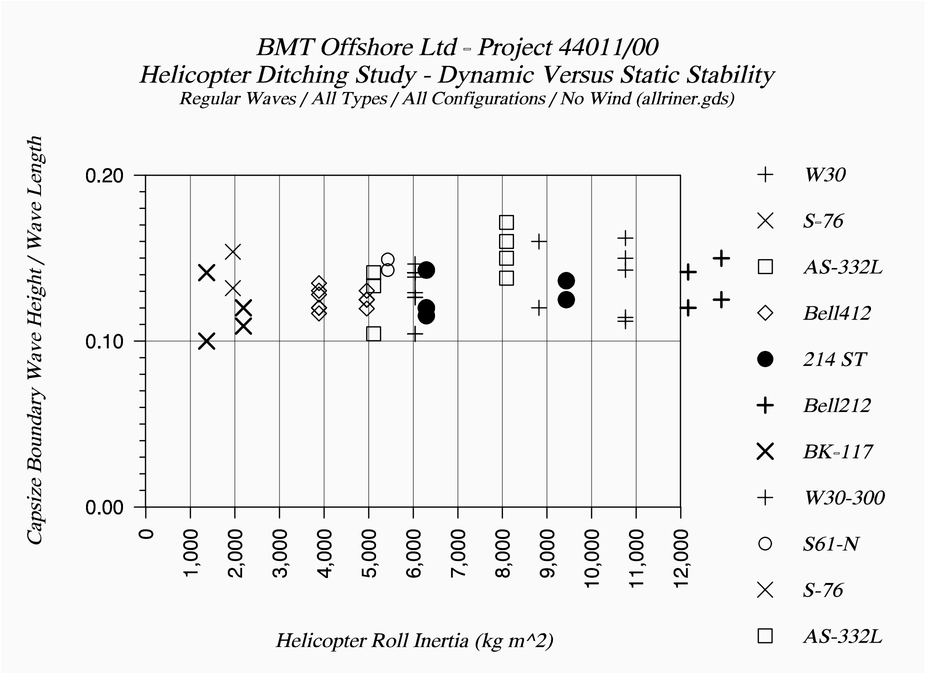

Figure 5 Influence of Roll Inertia on Regular Wave Stability Boundary.

3.2.2 Tests in Irregular Waves - Without Wind

As noted earlier, the results of the tests in irregular waves were generally much less well presented than those in regular waves. In many cases the only indication of a stability boundary could be found in the text by reference to sea-state numbers, and these were in turn sometimes ambiguous in terms of definition by wave height and period. This made the extraction of this data from the reports particularly difficult and potentially prone to misinterpretation.

Furthermore, the poor wave spectrum shapes, and common occurrence of wave periods very far from those desired for the height, meant that the wave height and period combinations (i.e. wave steepness) were sometimes unrealistic.

The tests were also carried out in quite short repeating sequences of about 100 waves (see Annex C). The absence of any statistical information on the wave height distribution makes it impossible to decide how typical these 100 waves were of the sea-state and so one cannot draw conclusions on probability of capsize from the results of these tests. The best one can do is to assume that a helicopter that capsizes in these 100 waves (about 10 minutes real time) is failing a criterion that it should remain upright following ditching for at least 10 minutes.

As it was not possible to lift capsize boundaries directly out of the model test reports for the irregular wave tests, a different data plotting strategy was adopted. Every irregular wave condition was plotted as a point on the graph, but the plotting symbol was varied depending on whether a capsize occurred or not. A solid circle ● was used to represent a stable condition, a × used for a capsize condition and a + for a marginal condition.

The evidence of the regular wave results described above was that the capsize phenomenon was mainly driven by wave steepness, and so initial attempts were made to plot the limiting sea-states for capsize in terms of a wave steepness parameter (the significant wave height divided by the wave length associated with the peak wave period - a parameter broadly comparable with the steepness value used for the regular wave data).

These plots were found to exhibit no discernible correlations. The reason for this is not clear, but may be associated with the relatively small range of wave steepness tested (all the wave spectra tended to have similar values), or it may be due to the spectrum steepness parameter calculated being a poor indicator of the steepness of the steepest (breaking) waves in the spectrum.

The data was therefore plotted against wave height instead, and then some discernible trends started to appear. The most notable was the relationship with roll gyradius/beam - see Fig 6. It can be seen that a helicopter tends to be more stable as roll gyradius / beam increases.

This is not quite consistent with what was seen in the regular wave tests where the stability seemed to be primarily influenced by roll inertia and helicopter beam. In the irregular waves the roll gyradius and the roll gyradius divided by beam seemed to show the best correlation - Figs 6 and 7.

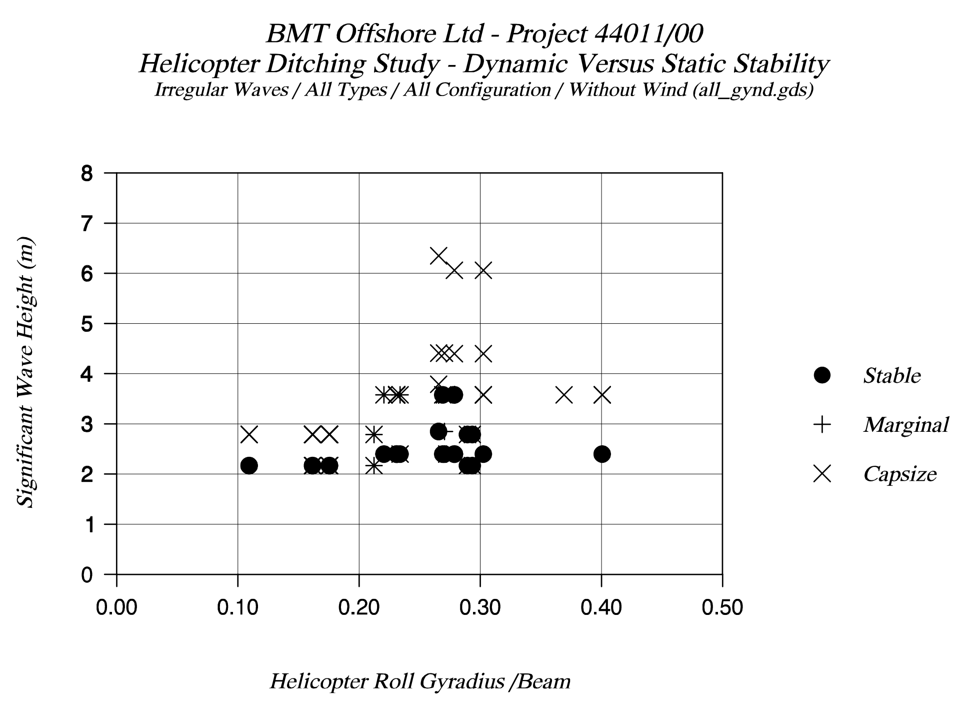

Figure 6 Influence of Roll Gyradius/Beam on Stability in Irregular Waves (No Wind).

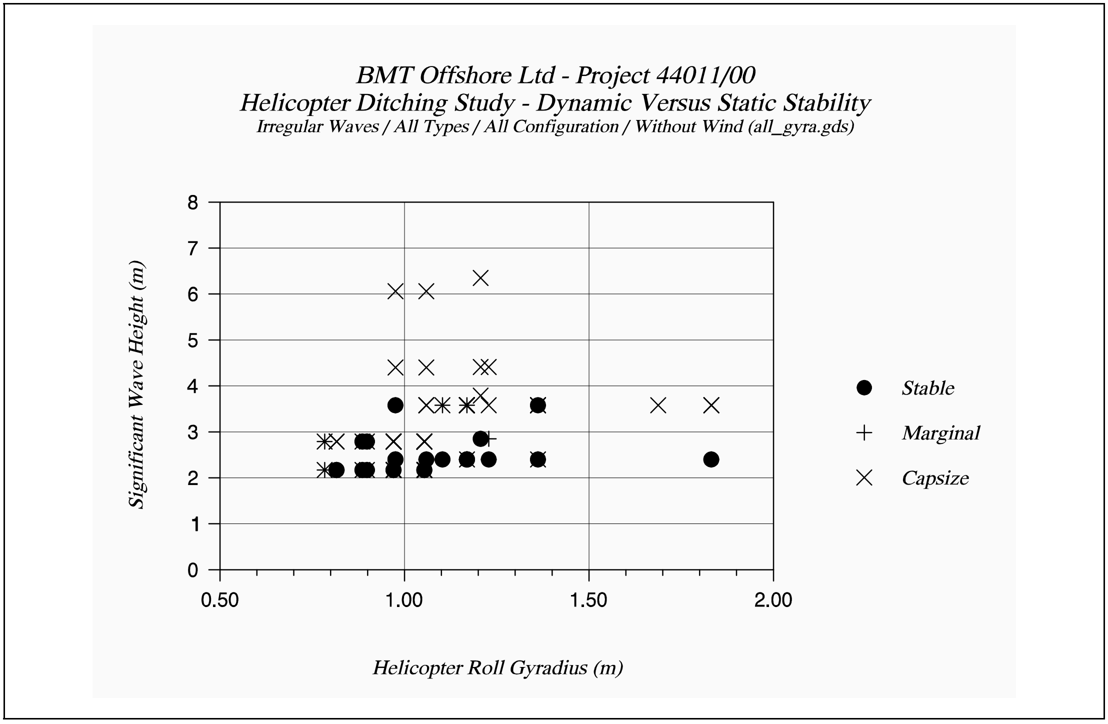

Figure 7 Influence of Roll Gyradius on Stability in Irregular Waves (No Wind).

3.2.3 Tests in Irregular Waves - With Wind

The comments made in the previous section on the difficulty of extracting the irregular wave results data obviously apply here also.

The irregular model tests with wind all had the wind and waves acting in the same direction (most common at sea, but not exclusively the case).

The best correlation in these tests seemed to be again with the roll gyradius/beam - Fig 8, but a non-dimensionalised area under the stability curve (not shown) also indicated some correlation.

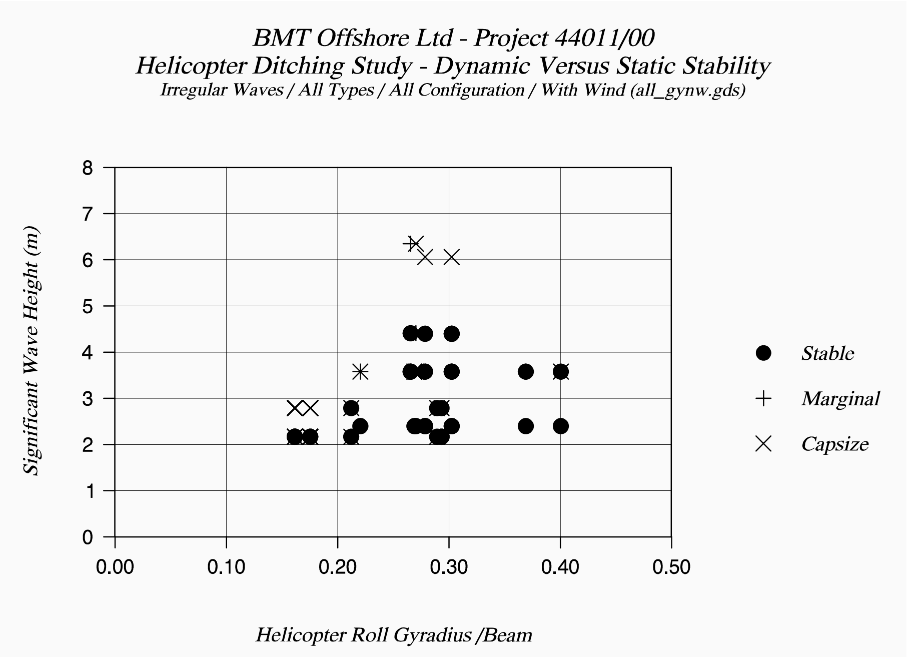

Figure 8 Influence of Roll Gyradius / Beam on Irregular Wave Stability (With Wind).

It is noticeable that the correlation seen in Fig 8 in the presence of wind is not as good as that shown in Fig 6 without wind. In Fig 8 more of the conditions are stable and there is much more overlap between the stable and capsize conditions. This can be put down to a the tendency of the helicopters to weathervane in the presence of wind and thus keep their nose turned into the waves. This is clearly an important factor in preventing capsize, but one that is not necessarily correlated with the roll properties of the helicopter.

3.3 Influence of Flotation Vertical Position ('Wet Floor')

The information on what happens to the behaviour of the helicopters as float position is raised (to make the helicopter sit lower in the water) comes from [4]. The scope of the work reported here will be found summarised in Annex A. Three helicopter types were considered; S76, W30-100 and AS-332L. Unfortunately the conditions covered in each of these three types were not the same.

In general the floats were raised 0.35m - 0.65m. This obviously results in the helicopter floating lower in the water (but this increase in draft is not as great as the movement of the floats because of the buoyancy afforded by the fuselage).

Static and dynamic tests were also performed with the cabin free flooding (doors open) and sealed. It is not clear from the results whether the sealed cases were floating at a lower draft than the open cases and this is only obvious when the floats are in their highest positions (e.g. configuration 9F for the S76 where all floats are raised 0.5m). Unfortunately, even in the best documented static conditions presented for the S76, the water line drawings do not show the location of the helicopter doors, and so it is not easy to determine the extent of cabin flooding that occurs when the doors are opened.

Comparisons between static stability properties calculated by computer and measured on the physical models identified some quite marked differences in some cases, but these differences were not large enough to disguise the trends in static stability resulting from the float position changes.

The movements of the various floats, the variations in helicopter weight and the opening/sealing of cabin doors result in a complex matrix of results which in turn cause changes in helicopter draft, trim and the extent of internal flooding. Unfortunately the authors have not tried to interpret the results in terms of these more fundamental variations, and this makes it very difficult to understand the important controlling influences on the static stability.

However, it can be deduced that raising the floats always tends to increase the range of stability and the angle of peak righting moment. The effect on the peak righting moment itself is more uncertain - sometimes it is increased, sometimes reduced. For the S76 the peak righting moment increases as craft weight increases from 3193kg to 4401 kg, but then decreases as the weight further increases to 5399kg. This is explained in the report in terms of the height of the centre of gravity above the water line, but it is not clear why this height should increase again for heavier helicopter weights.

Permitting the craft to flood through the open doors tended to reduce both the range of stability and the peak righting moment for the S76 in all float configurations. For the W30 the reverse was true with the peak righting moment being increased when the cabin and tail boom were permitted to flood.

The effect of raising the floats on the W30 was considered to be beneficial to the resistance to capsize. On the S76 the improvements did not seem to be as clear, and it is interesting that the greatest benefit seemed to come from raising just the main floats whilst the static stability calculations had shown the greatest changes to static stability occurred when the forward floats were raised.

The improvement in resistance to capsize when raising the floats on the AS-332L was disappointing. The effect of raising the floats on the static stability at the lighter 4610kg weight had been quite marked (large reduction in peak righting moment, but increased range of stability), whilst the effect at the heavier 8600kg weight was quite limited. However, the performance in waves was improved at the heavier weight and dramatically worsened at the lighter weight.

It is clear that raising the main floats can have quite markedly different effects on the static stability depending on the helicopter type and the exact way it is done. Furthermore, the influence on the dynamic stability (or resistance to capsize) is difficult to correlate with the changes in static stability.

Raising floats might well be a way of improving the performance of all helicopter types if it was known what static stability (or other) properties of the helicopter one was trying to vary by the float movement, and in what way.

There is consequently a need for better understanding of the mechanism and potential benefits and disbenefits of raised floats before recommendations are made that encourage such float placement.

3.4 Influence of Scoops

The influence of adding scoops to the sides of the floats ought to be easier to understand and interpret than the raising of floats described in the preceding section.

The function of the scoop is to trap water and therefore add weight to a float which is being pulled out of the water as the helicopter heels over. It will therefore add righting moment (increasing the slope of the righting moment curve, and increasing the peak righting moment - unless the water is spilled out before this angle is reached).

Review of the static stability curves for the nine helicopter types investigated in [5] confirms this finding. For every type the addition of the scoops has caused a significant increase to the peak righting moment and in some cases it has increased the angle of the peak righting moment. In all cases it has also increased the range of stability (see Fig 1 for example).

Furthermore, in dynamic terms, it should be noted that scoops will also add roll damping and roll added inertia[1] to the floats by increasing their effective size.

The results of the tests in waves described in [5] also indicate that scoops are generally also beneficial by improving all helicopter types resistance to capsize in waves. Most types seemed to benefit by about 1 sea-state in terms of their capsize boundary in irregular waves, although this was not universally true. The results for the S-61N were particularly disappointing, but this may be attributable to the fact that the scoops had comparatively little effect on the static stability properties of this large helicopter, particularly in terms of increasing range of stability. This type, being an old design, seems to have particularly small floats (and hence small scoops) for its size.

For at least two types (B-212 and AS-332L) the benefit of the scoops is partially attributed in [5] to a tendency to keep the helicopter more head to the waves. This is presumably due to the scoops moving the centre of resistance of the hull forwards so that the weathervaning effects become stronger.

As noted earlier, the effect of the scoops must be to increase damping and added inertia as well as static stability. In fact, there is at least one comment in the text of the report that "... roll motions seemed to be damped...".

It would have been possible to add flat plates to the outside of the model floats that just increased damping and added inertia, and thus gain some insight into whether it was the static or dynamic effects which were mainly responsible for the benefit. It is unfortunate that such tests were not carried out at the same time.

3.5 Other Issues Covered

In one set of tests described in [4] floats were attached to the engine cowling of an S-76 helicopter model. These were intended to prevent a complete inversion in a capsize, and thus provide the helicopter with a stable floating attitude on its side. A relatively limited series of tests in irregular waves was performed.

The results of these tests demonstrated a stable side-floating attitude with the top of the craft facing the 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, then a second (smaller)

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[1] Added roll inertia is that inertia due to the entrained water when the helicopter rolls.

breaking wave would rotate the helicopter a further 160° until it was again on its side, but with the top of the helicopter facing the oncoming wave.

From the point of view of personnel escape the guarantee of a stable side-floating attitude seems attractive provided the helicopter type has good means of personnel escape from both port and starboard sides. But there must be a significant risk that personnel attempting to escape following phase 1 of this process will have the helicopter roll over on top of them whilst it is progressing to phase 2. However, it is questionable whether this risk is any greater than that associated with making an escape during, or following, a complete inversion capsize.

Ignoring for the moment any practical problems of installing them on the helicopter, engine cowling floats seem to be a useful second line of defence when the primary upright flotation arrangements have been made ineffective following impact by a breaking wave. Provided they are large enough to maintain the necessary stable side-floating attitude, they guarantee an escape door remaining well above the surface of the water which must significantly improve the chances of escape for those still inside.

3.6 Other Model Tests

As part of this current study, BMT approached a number of hydrodynamic model test facilities around the world to discover whether they had performed any tests on ditched helicopters. The only organisations that responded in the affirmative were the Department of the Navy (David Taylor Model Basin) in the USA, and Marintek, Trondheim, Norway.

The US Department of the Navy cited tests on a US Navy H-3 helicopter performed in 1980. These are apparently reported in Ref [18], although at the time of writing a copy of this report has not yet been obtained.

The Norwegian Marine Technology Research Institute, Marintek, reported that they had performed some model tests for D2M Consultants SA (France) at the end of 1991. The helicopter type is not known, but it was tested at a scale of 1:13 in regular and irregular waves with hatches open/closed, with various flotation positions and with defective flotation. Wave motions were measured in 6 degrees of freedom, accelerations at a number of locations, and relative wave elevation. The information from the test series is presumed to be confidential to the client. Marintek also mentioned that they had performed tests on the Hermes space plane cabin for the European Space Agency.

From the above, it seems that there is no significant body of model test information on helicopters which exists outside the UK. The US Navy tests are unlikely to be particularly applicable to the CAA's civil helicopter interests. On the other hand, the Norwegian tests might be of considerable interest if the owner of the data would be prepared to release them to the CAA. The Trondheim test facilities are more modern than the BHC facilities and consequently have better control of the wave conditions. The instrumentation of motions and accelerations for these tests also makes them attractive for the validation of any theoretical motion prediction and capsize work.

3.7 Discussion on Model Test Work

The discussion of the model test results must be prefaced with a further comment on the difficulty of extracting and presenting the results in a consistent and reliable manner. None of the trends that will be discussed in the following were particularly strong, and consequently there is a risk that they are partly an artefact of consistent errors in the execution of the tests or data extraction and presentation.

One important issue is clear from the model test reports, that is that the vast majority of capsizes occur in **breaking waves**.

A review of the photographs from references [4] and [5] showed only one case where a capsize seems to have occurred in a non-breaking wave, and this for a helicopter in a damaged condition with part of its flotation removed. The static stability properties for this damaged condition are not given.

In [7] there is reference to a BHC report (TF/3424) which describes an analysis of photographic video evidence on the capsize mechanism. Unfortunately a copy of this document could not be located at the time of this current study, but it is presumed that this document also highlights the fact that capsize of an undamaged helicopter only occurs in a breaking wave. Furthermore, Ref [8] takes as its premise that helicopters capsize in breaking waves greater than 1.75m high. It is possible that this premise also comes from the missing BHC report TF/3424.

The lack of very clear trends in resistance to capsize related to helicopter physical properties or static stability is probably at least partly due to the fundamental difficulty of performing model tests in breaking waves. Annex C discusses these difficulties in more detail, but of particular importance is the great difficulty in producing repeatable conditions and of measuring the height and steepness of the capsizing wave.

The lack of consistency between the regular wave and irregular wave model test results is also somewhat puzzling. The regular wave results correlate best with wave slope whilst the irregular wave results correlate best with significant wave height. This may be partly due to the lack of a good irregular wave steepness measurement which characterises the steeper breaking waves in the spectrum.

Overall the tests do not provide a clear understanding of which physical properties of the helicopter, or which properties of the static stability curve, one should be trying to maximise in order to obtain the best resistance to capsize in waves.

There is some evidence however, that the following assist resistance to capsize:

- greater helicopter weight (regular wave tests);
- greater roll inertia (regular and irregular wave tests);
- greater peak righting moment (regular wave tests);
- greater area under righting moment curve (regular wave tests);
- greater range of stability (regular wave tests);
- greater helicopter beam (regular wave tests);
- greater roll gyradius/beam (irregular wave tests);

It is obvious that many of the above parameters will go together due to simple geometry.

4 Mathematical Models

4.1 Westland Simulations[1]

The Westland Helicopters report [6] describes two essentially independent attempts at predicting the effect of adding water scoops to the stability of a ditched helicopter.

The first analysis (the 'simple' analysis) considers the free oscillation of the helicopter in still water. The second analysis attempts a time domain simulation of the motions of the helicopter in waves.

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[1] **Noted added in 2005:** Subsequent discussions between BMT and Westland resulted in a re-analysis of the forces on a float scoop. Results from this re-analysis are reported in 'Helicopter Float Scoops', CAA Paper 95010, 1995.

These two methods of analysis are discussed in the following two sections.

4.1.1 'Simple' Analysis of Motion of a Helicopter when Ditched

The 'simple' analysis considers the roll motion of the helicopter in still water. Only weight and buoyancy forces are considered.

The effect of the scoops are modelled by applying a weight of water to the uplifted float. A constant weight is applied to whichever of the floats is higher. This is effectively assuming very small scoops, at the still water-line on the floats. If the scoops have a significant height, then the effective weight of water applied to the float would increase with increasing uplift of the float, until the scoop was lifted fully from the water.

The report calculates the amplitude and period of roll motion of a ditched helicopter with and without scoops, assuming that the peak roll velocity is fixed. The report contains a mathematical error which results in too long a natural period for the with-scoops case, but this does not influence the predicted motion amplitudes.

This work assumes that the ratio of with-scoops to without-scoops motion amplitude for the same peak roll velocity is a measure of the stabilising effect of the scoops. The justification of this assumption is not given and is not clear. If the scoops provide any damping they would be expected to reduce the roll velocity.

4.1.2 Dynamic Analysis of a Ditched Helicopter

This analysis is a non-linear time domain simulation of the motion of a ditched helicopter in regular waves. The motion of the helicopter is considered in three degrees of freedom (sway, heave, and roll).

This analysis, unlike the 'simple' analysis, does include the effect of the height of the scoop. The mass of water in the scoop is assumed to vary linearly with the elevation of the top of the scoop above the water surface, reaching a maximum when the scoop is lifted clear of the water surface.

The report contains a number of errors in the description of the wave kinematics. The horizontal component of the wave orbital motion has been neglected. Also the fundamental relationship between wavelength and wave period has not been appreciated.

The representation of the hydrodynamic forces on the floats is fairly simplistic. Added mass effects are ignored. The drag coefficient is independent of the direction of the relative motion. The scoops are not considered to make any contribution to the drag forces on the floats.

The report acknowledges that the forces on the hull of the helicopter have been neglected. Other effects that may also be of importance are the slam force on a float when it re-enters the water after being lifted clear, and the effects of water draining from the scoops when they are lifted above the water surface.

The results of a number of simulation runs are presented. It was found that the effect of the scoops was inconsistent, sometimes increasing the stability and sometimes reducing it. It is well known from studies of non-linear ship rolling that these types of systems have a very complicated and often unpredictable behaviour. In particular it is essential to consider a large number of different initial conditions, as these can often determine whether or not the subsequent motions result in a capsize.

4.2 Potential Benefits of Further Corrected Dynamic Simulations

The use of a time domain simulation of the motions of a ditched helicopter should in principle provide useful insight into its dynamic stability. The following features should be considered for inclusion in a simulation:

a) Correct wave particle kinematics. Both linear irregular waves and non-linear regular waves could be considered. Ideally both would be investigated. If breaking waves are considered to be the prime cause of capsize then a breaking wave kinematics model must be used. (These are much less well established than progressive wave models. A number of methods for modelling plunging breakers now exist, but we are unaware of any models of spilling breaker kinematics.)

b) Added masses of helicopter, floats, and scoops. Variation of the added mass with depth of immersion. Care would need to be taken to correctly calculate the rate of change of momentum.

c) Drag forces on the floats and scoops. Providing suitable data was available different drag coefficients could be used for horizontal and vertical motions of the floats. The drag coefficients could depend upon depth of immersion. For the scoops different drag coefficients could be used for upwards to downwards motion, and could depend upon whether the top of the scoop is above or below the surface.

d) The water in the scoops could be assumed to leak out as the scoop is lifted above the wave surface. The initial amount of water in the scoop could depend upon the depth or duration for which it was submerged before being lifted.

e) Forces on the helicopter hull. Buoyancy, wave and drag forces all need to be taken into account. The weight and sloshing forces of any water in the hull may be important.

f) Wind forces. Although initial estimates suggest not, the wind loads on a helicopter topsides, rotor blades, and raised floats might form a significant part of the total overturning moment on the helicopter.

In any study of a non-linear system it is essential to try a number of initial conditions, and for irregular waves and/or wind forces, a number of realisations of the waves or wind. Rainey and Thompson [12] have suggested that, for regular wave studies, a very good measure of the stability of a system is to perform simulations for a matrix of different starting conditions, and measure the proportion of starting conditions that lead to a stable solution (without capsize).

Such a simulation study could lead to useful information on:

- The effectiveness or otherwise of scoops.
- The optimum size and position of flotation.
- The forces on flotation with and without scoops. This is important for the design of the mounting systems.
- The importance of water inside the helicopter hull.
- The wave conditions in which the helicopter can be expected to capsize or remain upright.
- Some indication of the mechanism(s) of a capsize event.
- The significance or otherwise of wind loading on the motions.
- The relationship between static stability properties and the resistance to capsize in waves.

5 The Ocean Environment

The severity of the ocean environment over which the helicopter flies is a key factor in determining the probability of a helicopter experiencing a capsize following a ditching, and this issue has been addressed in Ref [8].

Specifically the authors of [8] were asked to calculate the probability of experiencing a breaking wave greater than 1.75m high for the area around the UK coastline. As has been noted earlier, it is not clear where this very precise definition of a helicopter capsize criterion has come from, but it is possibly from the missing BHC report TF/3425.

5.1 The Probability of Experiencing a Breaking Wave

Ref [8] derives an expression for the probability of experiencing at least one breaking wave greater than a given height H_0 during a given duration D, in a given sea-state characterised by a significant wave height of H_s and zero-crossing period T_z. The expression depends on an assumption about the steepness of wave that will break, but this is reasonably well-justified by reference to classical wave theories and experimental work.

5.2 The Probability of Experiencing a Capsize

This theory is then extended to derive an expression for the probability that a helicopter will capsize during a given duration D in this sea-state, given that the probability that the helicopter will capsize in a breaking wave is q. The theory assumes that this probability of capsize q is constant for all heights of breaking wave.

Finally the theory is extended further to estimate the probability that there will be a breaking wave and that the helicopter will capsize in any duration D chosen at random through the year's weather. This involves integrating the above results for a whole range of sea-states (combinations of H_s and T_z) representing all the sea-states that can be experienced during a year, and weighting them according to probability of occurrence of each sea-state.

Ref [8] then uses these expressions to calculate the probability of a breaking wave >1.75m during a 10 minute duration for a number of sites around the UK coastline and in the North Sea. Most of the results yield probability of a breaking wave values of less than 5%. (It is not clear why the period of 10 minutes was chosen here, when the stated duration in BCAR Paper G779 is 5 minutes.)

Some readers of this report (e.g. [7]) have interpreted the results presented as identifying certain ‘hot spots’ within the North Sea where conditions are particularly bad. There are obviously quite marked variations in wave conditions as one moves northwards in the North Sea, or if one is close to coastline, but some of the large variations shown in [8] in the central and northern North Sea are considered to be caused by unreliable or short wave data records. Attention should be focused on those instrument stations where the data is known to be reliable and extends for many years.

5.3 Practical Application of the Theory

This analysis of breaking wave probabilities prepared by IOS in [8] is basically sound, and there is no doubt that it can be used to estimate the probability that a helicopter will capsize in a given period of time (chosen at random) with the following provisos:

a) The theory, as presented, assumes that the probability of capsize of the helicopter in a breaking wave is constant for all breaking wave heights. This is very unlikely to be the case, there being a certainty of capsize if the breaking wave is large enough. But this is not a major criticism as there would seem to be little mathematical difficulty in extending the theory to include a capsize probability which varies with wave height. However, as has been noted in earlier sections of this report, the helicopter model tests have not yielded information on capsize probability in this form. In principle the model tests could have provided either; the probability of capsize when experiencing a single breaking wave of a given height, or the probability of capsize in a given period of exposure to a given sea-state. However, there are significant difficulties in providing this information.

b) The estimates of the probability of a breaking wave at various points around the UK coastline have been made on the basis of instrumental measurements at a number of locations. Unfortunately, as the authors of the report point out, a number of these are quite short-term measurements, and the variability of the weather from year to year can introduce significant errors unless the measurements are based on averages of many years. This shortcoming could be overcome by concentrating the analysis using some of the long-term instrumental data sets collected on offshore platforms such as BP Forties (representative of the central North Sea) and Shell Brent (representative of the northern North Sea), and thus obtain better quality estimates for these offshore locations that are of particular interest in the context of offshore helicopter operations. (Although [8] uses both Brent and Forties, it is not clear whether it made use of the full 20 odd years of data available from these sources.) Another possibility would be to use BMT's PC Global Wave Statistics EUROPE database, which could be used to derive estimates for the whole of the northern European continental shelf.[1]

c) The authors of the report also point out that the analysis is very sensitive to the measurement of the wave zero crossing period T_z. This parameter is known to be rather unreliable in both instrumental and visual wave data sets. Unfortunately there is little that can be done about this sensitivity to an unreliable parameter, the only solution being simply the measurement of more, and better quality, long-term wave records.

6 Helicopter Ditching - Survival Aspects - CAA Sept. 1989

In September 1989 the CAA prepared a review of the research on helicopter ditching that had been carried out at that time [7]. This review included coverage of references [2]-[6], [8] and [17].

The report gives a good overall description of the results of the model testing in [4] and [5], and most of the conclusions drawn on this work are consistent with those presented elsewhere in this report.

The report identifies the flotation scoops as being an effective 'add-on' device to improve the resistance to capsize of ditched helicopters, but reports that further work on the practicality of implementing the modification was not pursued because of the costs involved. The key issue here seems to be the additional loads that need to be transmitted from the floats to the helicopter fuselage, which might require structural modifications, and which the work of [6] was intended to quantify.

As has been seen earlier, the theoretical work of [6] was fundamentally flawed, but it is also questionable whether a sophisticated time-domain analysis is justified for the estimation of the maximum flotation loads. It may be more appropriate to use

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[1] **Note added in 2005:** Since this review was undertaken in 1993 a number of alternative sources of long term wave data have become available, and might now be preferred. These include wave hindcast data such as NEXT and NEXTRA.

empirical force coefficients and appropriate estimates of the accelerations and velocities present in waves as the basis of a conservative force estimate.

The report largely writes-off the potential benefit of raising the flotation, and a 'wet floor' approach in terms of improving resistance to capsize. The complexity of interpreting the results of [4] has already been noted in Section 3.3 above, and it is clear that the information in [4] alone is not adequate to decide whether certain helicopter types might benefit from raising the floats. However, a more detailed study that concentrated on understanding the flotation properties that lead to good capsize resistance might well in consequence identify means of improving some or all helicopter types by this method.

The report is also not encouraging on the subject of the cowling float, emphasising the risk to escaping occupants of the helicopter's 'continuing roll' in the direction of the waves. This is considered to be a misleading statement as it implies that the helicopter keeps rolling away from the waves. In fact the evidence of Ref [4] is that the helicopter eventually finds a stable attitude lying on its side with the top towards the oncoming waves. As noted in Section 3.5 above the risks to the occupants associated with this two stage rotation through about 270^o would not seem to be great compared with the consequences of a permanent inversion. There is also the possibility that this double roll might be avoided if the cowling flotation size was somewhat greater.

The report states the initial CAA risk of capsize objectives of 10^{-7} per flying hour, made up of 10^{-5} per hour that there will be a ditching, and 10^{-2} that, given a ditching, there will be a capsize (the selection of these objectives apparently took into account the fact that a capsize was not necessarily a catastrophic event). The author then compares this with records of ditchings available at that time and concludes that the actual frequency of capsize following ditching is about 30% and the overall risk per hour 2.5×10^{-6} or about 25 times the desired value.

Ref [7] then goes on to argue that only two of the capsizes occurred before those on board had evacuated, and so the actual risk of capsize prior to evacuation is about 10^{-6} per hour, or about 10 times the target value.

This higher than desired rate is partly put down to the fact that all the ditching incidents included were for the S61, an old type with poor flotation arrangements.

These ditching incidents are summarised in Annex D, and it can be seen that about half the total ditching incidents involved the S61 type. If one ignores the capsize of a Chinook which was leaking through the stern ramp, all the capsizes were S61's. However, **none of the other types ditched experienced weather worse than sea-state 2!**

It is not, therefore, possible to say much about the resistance to capsize of the S61 in relation to other more modern types on the basis of this data.

However, it can be said that the capsizes of S61's that did occur (in sea-states 4-5, 6, 7) might well have been expected on the basis of the irregular wave model tests reported in [4] and [5]. It can also be said on the basis of this evidence that many of the other types tested in [4] and [5] might also have capsized in these sea-states.

The evidence does not therefore appear to support the assertion that the reason for the high capsize rate may be due to the particular old helicopter type involved in each case.

Furthermore, it is interesting to note that ref [19] which describes experience of military helicopter ditchings, including over 70 occurrences where flotation was deployed successfully, about 45% capsized more or less immediately. Unfortunately this report does not give any details of the prevailing weather conditions. These occurrences resulted in quite a large number of fatalities.

By contrast the civil helicopter ditchings summarised in Annex D did not result in any fatalities.

Ref [7] concludes that the current ditching capsize rate is 'not necessarily at an unacceptable level' but suggests that further industry-funded research on flotation stability may be of benefit for particular types flying over hostile waters.

It also concludes that the basic safety objectives of BCAR are adequate with respect to ditching, but recommends 'avoidance of operation over severe sea-states' and the provision of better operational guidance, and guidance on ditching technique.

The recommendation regarding avoidance of operation over severe sea-states is somewhat surprising in the light of the model tests of [4] and [5] which graphically demonstrate that most helicopter types will capsize in a 100 wave sequence (approximately 10 minutes) in sea-states 4 or 5. Such conditions are exceeded in the North Sea for a substantial proportion of the time, and it is difficult to see how they could be avoided.

7 The Mechanism of Helicopter Capsize

The capsize of ships and boats has been studied by naval architects for many years. Some of the more recent events that have driven research have included; the loss of a number of lives during the Fastnet ocean yacht race of 1979 [13], the loss of a number of fishing vessels during the late 1970's [14], and the capsize of the RoRo Ferries European Gateway in 1983 [15], and Herald of Free Enterprise in 1987 [16].

It should be recognised firstly that there are two quite different capsize phenomena affecting floating bodies. In the first, capsize occurs due to progressive loss of stability (perhaps due to flooding or build up of water on deck) over a relatively long period of time (i.e. a number of wave cycles). In the second capsize occurs more or less immediately as the result of a single wave.

This latter is often referred to as a 'knock-down' and, as has been demonstrated in an earlier section, is generally the type of capsize experienced by the helicopters in the model tests. It is also the type of capsize that smaller vessels including sailing yachts are most likely to experience in severe weather conditions.

It is possible to show theoretically that vessels and floating helicopters having positive static stability are unlikely to experience capsize in normal waves. This follows from examination of the accelerations present in the sea surface. It is necessary for the wave to break in order for a capsize to occur. Ref [10] illustrates this for the helicopter using the example of the Bell Jet Ranger.

The nature of capsize in a breaking wave is well illustrated in Fig 9 taken from Ref [10]. A very similar figure will also be found in Ref [11] describing the capsize of a sailing yacht, so the description is by no means limited to the twin float, fuselage out of the water, configuration of the Bell Jet Ranger.

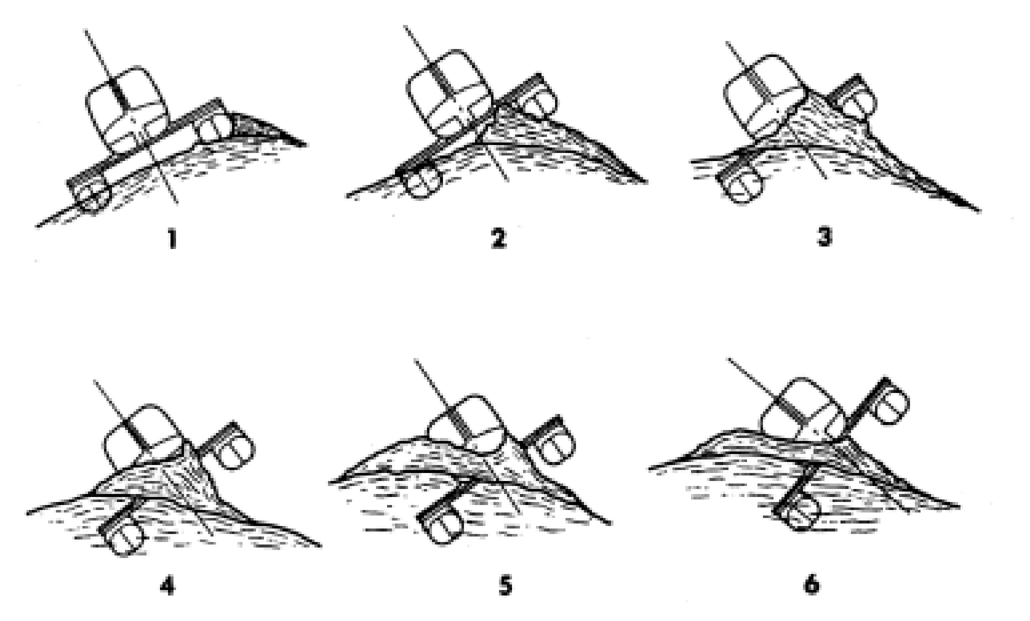

Figure 9 The Nature of Capsize in a Breaking Wave (from [11]).

In the initial phase the helicopter experiences the steepening front face of the wave. The quite stiff static roll properties afforded by the floats ensures that the helicopter tries to remain aligned with the slope of the waves and so heels away from the approaching crest. When the up-wave float is near to the crest of the wave the breaking wave projects a high velocity horizontal jet of water at the up-wave float (or in the case of larger hull-floating helicopters at the side of the fuselage). The impact of the momentum of the water in the breaking part of the wave, coupled with the tendency of the down-wave float to 'dig-in' to the water causes a number of things to happen. A sudden powerful overturning couple is generated between the water impact and the 'dug-in' float. The total immersion of the down-wave float and the fact that the up-wave float is by now completely out of the water means that the restoring roll moment (tending to maintain the hull aligned with the water surface) is now reducing. If the overturning energy imparted by the breaking wave exceeds the capacity of the reduced roll stability, then capsize will occur.

This physical explanation of capsize phenomenon suggests a number of things:

a) If the helicopter had not been so ready to roll away from the advancing wave crest and had been more nearly upright when the breaking wave struck, then there would have been more chance of resisting the additional sudden overturning impact.

b) A helicopter with a large range of stability might have continued to provide a significant restoring moment even after the breaking wave had hit.

c) If the down-wave float had not dug into the water, or the hull as a whole had not offered so much lateral resistance to movement through the water, then the impact of the breaking wave might have had more tendency to accelerate the helicopter sideways (surfing down the wave) rather than overturning it.

d) If the above-water area of the helicopter fuselage was limited, or the helicopter was lying low in the water (restricting the magnitude of the impacting force and the moment arm of this force) then the tendency to capsize should reduce.

From this we can deduce that:

- Helicopters with high roll inertia compared with their static roll stiffness are less likely to be quick to roll away from the advancing wave front and will benefit from effect (a) above. Their roll motion will have a greater phase lag.
- Helicopters with hull/float configurations which tend to remain on the surface of the water and not dig-in and present large lateral areas will benefit from (c) above.
- Helicopters which are low in the water and present a smaller and lower area for the breaking wave to impact on will benefit from (d) above.

Incidentally, there is obviously a conflict between (c) and (d) as, for a given helicopter, in decreasing the above water area we must increase the below water area and vice versa.

Roll inertia is seen to be a major factor in the resistance of sailing yachts to capsize, and a yacht that has been dismasted is much more likely to capsize [11]. The mast represents a major part of the roll inertia of a yacht.

The helicopter rotor must similarly be a significant contribution to the roll inertia of a helicopter, particularly whilst it is still rotating, when gyroscopic effects should also help. There could also be a significant effect depending on where the blades stop in terms of the roll inertia. A helicopter which loses blades due to contact with the waves during the ditching will probably be more at risk of capsize than one which maintains the rotor intact.

We can therefore summarise the expected beneficial qualities of the helicopter whilst floating as follows:

- high roll inertia;
- large range of static stability;
- large angle of peak righting moment;
- low lateral resistance to movement through the water;
- low above water profile.

Ref [11] identifies the importance of the ratio of roll gyradius divided by beam in the capsize process, and plots this ratio against wave height divided by beam. On the basis of model tests on yachts, a boundary is defined between capsize and fully stable conditions.

For comparison purposes the data from the helicopter tests in irregular waves has been plotted in a similar manner in Figures 10 and 11 (for cases with and without wind respectively).

One can see immediately from these plots that the ratio of roll gyradius/beam generally expected for yachts is more than twice the values seen on the helicopters considered in this report.

However, there seems to be some general consistency between the boundary plotted for the yachts and the capsize boundary for the helicopters, particularly in the absence of wind. It has been noted earlier that the main effect of the wind is to keep the helicopter nose into the wind and waves, and thus to reduce the tendency to capsize. The yacht model tests were performed without any wind and so more attention should be concentrated on Fig 11.

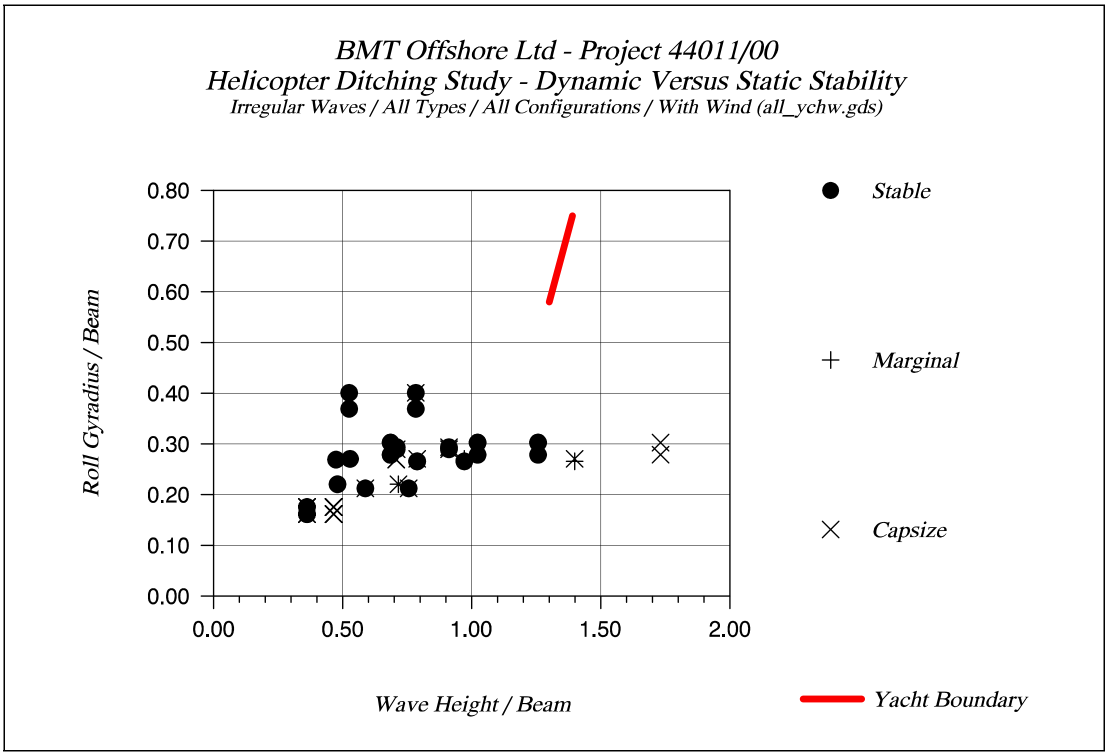

Figure 10 All Helicopter Types - Stability Boundary - With Wind.

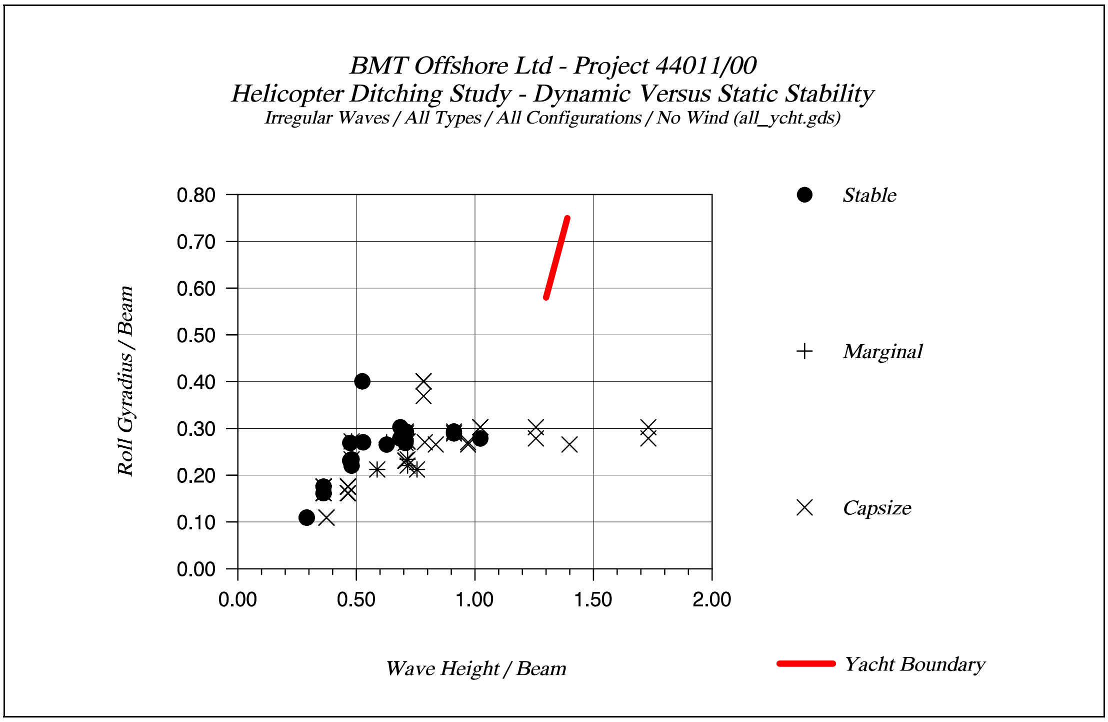

Figure 11 All Helicopter Types - Stability Boundary - Without Wind.

The plots also show that, in the absence of wind, helicopters tend to capsize in wave height/beam values about half those generally survived by yachts.

It is important to note that the roll inertias and radii of gyration plotted here are the 'dry inertia' of the helicopter or yacht. Both types of craft experience significant added roll inertia due to the water entrained when the craft rolls.

In the case of a yacht it is the keel that makes the major contribution to this added roll inertia. In the case of the ditched helicopter it is presumably the floats and any undercarriage structure that will entrain water as the helicopter rolls. It is interesting to note that the float scoops tested on the S-76 model in [4] seem to add roll inertia of similar magnitude to the original dry inertia of the helicopter.

Consequently, if it were possible to estimate the added roll inertia in each case and plot graphs on the basis of total roll inertia rather than just the dry inertia, it might be found that they would show clearer correlation and trends.

8 Discussion

The preceding sections have covered a wide range of issues influencing the ability of a helicopter to remain stable and not capsize following ditching. However, the CAA has stated certain risk level objectives in this respect which are that the probability of experiencing a capsize should be 10^{-7} per flying hour, made up of 10^{-5} per hour that there will be a ditching, and 10^{-2} that, given a ditching, there will be a capsize within 5 minutes.

Concentrating on what happens following a ditching occurrence we can say that the risk of a capsize ensuing is made up of two key factors:

a) The height and period or slope of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

It is clear that the main difficulties in fully understanding the current risk of a ditching capsize lie primarily with (a) rather than with (b).

Dealing with (b) first therefore, if capsize were purely a function of wave height then one could simply estimate the probability of meeting such a wave and hence the probability required in (b) above. Even if the capsize is a result of a more complex event, a breaking wave, then methods have been developed in [8] which permit us to estimate the probability of meeting such a wave.

It can be argued that these methods need to be extended to deal with a probability of capsize that varies with the wave parameters and that the method should be used in conjunction with some good quality long-term wave records characteristic of the North Sea. Finally it should be noted that the probabilities of capsize of the order 5% which seem to come from this work do not appear to be consistent with the 30% probability of capsize which comes from analysis of actual ditchings and a similar number which would come from a simple analysis of the occurrence of ‘capsizing sea-states’ as found in the model tests.

However, the issue of the exact mechanism of helicopter capsize, and the properties of the waves in which capsizes occur is a complex one. We have seen that:

- Capsize only occurs to an undamaged helicopter in breaking waves.
- Capsize occurs for most helicopter types in most loading conditions in sea-states of 4 or 5 and above (say 3m significant wave height and above).
- It is difficult to correlate the wave capsize boundaries in terms of the physical properties and static stability properties of the helicopter. Some weak correlations have been identified with weight, roll inertia, beam and some of the properties of the roll restoring moment curve, but nothing significant enough to provide conviction that one can improve capsize performance simply by maximising that parameter in the design.

- The results of the regular wave tests and irregular wave tests do not generally appear consistent, with one correlating with wave height and the other with wave slope (the lack of correlation with wave slope in irregular waves may be due to the absence of a slope parameter that properly characterises the steeper waves in the irregular spectrum).

The BCAR certification requirements [20] for on-water stability refer to the steepness of a regular wave that the helicopter must remain stable in, but also requires that flotation and trim should be investigated in sea-states up to 6. It is clear from the model test results given in [4] and [5] that the helicopters generally have little difficulty in satisfying the regular wave steepness criteria. It is also clear that none of them remain stable in irregular waves of sea-state 6.

Even if it is not possible on the basis of the information in [4] and [5] to be confident about which design parameters make the difference between a good helicopter and a poor one, it is possible to draw certain conclusions about some of the helicopter modifications tried in these tests.

The addition of scoops to the flotation seems to be beneficial in all cases. Interestingly, the addition of scoops **always** increases the peak restoring moment on the stability curve, and the range of stability. If it is this effect on static stability which is causing the benefit in terms of resistance to capsize, then it is surprising that one or both of these parameters does not come out more strongly as a correlator with capsize performance. The fact that these static properties don't correlate strongly in this way is circumstantial evidence supporting the theory that it is the dynamic effects caused by the scoops, enhancing roll added inertia and adding extra roll damping, that are a major reason for the benefit.

Unfortunately work on the development of practical scoops seems to have halted because of difficulty in estimating the additional flotation anchor loads. The theoretical simulation work intended to resolve this issue was flawed, but it should be possible to make reasonable and conservative estimates of maximum loads using empirical drag and inertia coefficients.

The work on raising the flotation (‘wet floor’) has been much more difficult to interpret. Raising the floats can cause quite different effects on the static stability properties of different helicopters and on the same helicopter at different weights. As we are not sure which properties of the static stability curve we are trying to maximise it is difficult to know how to position the floats to the best advantage. It is not surprising, therefore, that the model tests on helicopters with raised floats resulted in very mixed performance.

One model test investigated the possibility of using engine cowl flotation in order to provide a more stable side-floating attitude. The BHC and CAA comments on the results of this experiment seem unduly harsh in terms of the risks to the escaping occupants, and it is considered that this idea should be developed further as it does offer the prospect of a stable floating attitude with a helicopter escape hatch remaining above the water surface. Without a device of this sort the fundamentally top-heavy configuration of a helicopter means that there will always be a wave high enough or steep enough to capsize it into a fully inverted attitude.

Consideration of the mechanism of capsize in a breaking wave tends to lead one away from the premise that prevention of capsize lies entirely in the static stability curve, and the lack of strong correlation of model test results with the properties of this curve tends to confirm that the answer, if answer there is, must lie elsewhere. Work on the ‘knock-down’ capsize of sailing yachts has pointed to the importance of the roll inertia, and whilst we cannot ask the helicopter designer to change this physical property (he has little control over it anyway), we can look at ways of increasing the added inertia in waves. The flotation scoops are one way of doing this.

9 References

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Annex A Summary of Contents of BHC Report X/0/3282 (Nov 1985)

Table 1 Summary of Contents of BHC Report X/0/3282 (Nov 1985)

Helicopter Type	Weights	Float Position Variant	Computer Models	Regular Wave Tests	Irregular Wave Tests. Sea-state H1/3/Tp	Comments
Main Report:						
S-76	3193 kg 4401 kg 5172 kg 5399 kg	1. Standard 2. Main +.25m 3. Main +.50m 4. Fwd +.25m 5. All +.25m 6. F+.25m M+.50m 7. Fwd +.5m 8. F+.50m M+.25m 9. All +.50m	Hydrostatic Static Stability			Computer hydrostatics, compared with physical model measurements. Three cases done with cabin door open. General tendency for raising floats to reduce peak righting moment, but to increase the peak angle and the range of stability.
Addendum 1:						
W30-100	4431 kg 5818 kg	Raised main floats. Scoops.		Various	S4 2.4m/6.54s S5 3.6m/6.80s (with and without wind)	1:10 scale physical model. Poor spectral shape. V. Low Tp for sea-state 5. Regular wave results compared with standard configuration results from another report. 'Flooded' and 'sealed' configurations. Raising the floats seemed to improve stability whether cabin flooded or sealed. Suggested that perhaps the floats were raised too high.
Addendum 2:						
S-76	not given	Additional floats near the engine cowling.			S5 (actual conditions not given)	1:8 scale physical model. Static floating tests in calm water and Sea-state 5 irregular wave tests. Additional floats of sufficient volume near the engine cowling prevent complete capsize.

Table 1 Summary of Contents of BHC Report X/0/3282 (Nov 1985)

Helicopter Type	Weights	Float Position Variant	Computer Models	Regular Wave Tests	Irregular Wave Tests. Sea-state H1/3/Tp	Comments
Addendum 3:						
S-76	4409 kg	1. Main +.5m (3F) 2. Mn +.5m, Ns +.5m (9F)	T-Fast static stability program	Various	S4 S5 (with and without wind) (- actual conditions not given)	Comparisons between computer and 1:8 scale physical model static stability for two different float configurations, sealed and unsealed. Tests in irregular and regular waves. No conclusions on the effectiveness of raising the floats. Seems to be little effect in dynamic situation.
Addendum 4:						
AS-332L	8600 kg 4610 kg	Main floats raised 0.65m		Various	S4 2.17m/6.62s S5 2.79m/6.08s (no wind)	1:8 scale physical model. Tests in regular and irregular waves (Sea-state 5 period very low). Conducted with doors on and doors off, at two aircraft weights. Concludes that effect of raising the floats is disappointing.
Addendum 5:						
W30	4432 kg 5818 kg	'Standard' and 'raised' floats	Static stability T-Fast			Comparison of floating waterlines and righting moment curves from computer and 1:10 scale physical model for standard and raised floats. Raising the floats tends to reduce the peak righting moment but increases range of stability. Permitting craft to flood (doors open) seems to increase peak righting moment and range of stability. (Is this information consistent with data given in addendum 1? Doesn't seem to be.)

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

Table 1 Summary of Contents of BHC Report X/0/3257 (April 1986)

Helicopter Type	Weights	Float Position Variant	Computer Models	Regular Wave Tests	Irregular Wave Tests. Sea-state H1/3/Tp	Comments
B-412	3476 kg 5227 kg	Scoops fitted to main and rear floats.		Various	**1:10 scale:** S4 2.40m/6.5s S5 3.58m/6.80s **1:28 scale:** S5 2.80m/7.47s S5 3.94m/9.43s S6 4.40m/9.17s S7 6.06m/11.21s (with and without wind)	Both 1:10 and 1:28 scale models used. Concluded that scoops cause marginal improvement of limiting steepness of regular wave before capsize (from about 1:8.5 to 1:8). Improvement of about 1 sea-state in irregular waves. But note the wide range of conditions called Sea-state 5.
B-214ST	4184 kg 6500 kg (static tests only) 7955 kg	Scoops fitted to outside of main floats.		Various	**1:10 scale:** S4 2.40m/6.54s S5 3.58m/6.80s **1:26 scale:** S5 2.85m/7.19s S5 3.79m/9.08s S6 4.41m/9.09s S7 6.35m/11.60s	Both 1:10 and 1:26 scale models used. At 1:10 scoops improved regular wave boundary from 1:7.5 to 1:8.5. Larger model seemed less stable (in larger waves) and showed less difference. General improvement with scoops in irregular waves (not clear that results from the two models consistent though). NOTE two very different 'sea-state 5's referred to in the text for 1:26 scale model.
B-212	3636 kg 4545 kg 5091 kg (static tests only)	Scoops fitted outside each float.		Various	S4 ?? S5 3.58m/ ?? (with and without wind)	1:10 scale physical model. General improvement in stability with the addition of scoops. (Some tendency to adopt a more head to wave direction with scoops?) Removal of the doors reduced stability slightly.

Table 1 Summary of Contents of BHC Report X/0/3257 (April 1986)

Helicopter Type	Weights	Float Position Variant	Computer Models	Regular Wave Tests	Irregular Wave Tests. Sea-state H1/3/Tp	Comments
BK-117	1700 kg 2800 kg	Scoops fitted to fwd floats only.		Various	S4 2.17m/6.62s S5 2.79m/6.08s (with and without wind)	1:8 scale physical model. Marked increase in dynamic stability in regular waves at the lighter weight. Little difference at the heavier weight. In irregular waves improved about 1 sea-state at both weights.
W30-300	7273 kg	Scoops fitted to rear floats only. Also tests with one float compartment deflated.		Various	S4 2.40m/6.54s S5 3.58m/6.80s (with and without wind)	1:10 scale physical model. Scoops increase stability in regular waves. Marginal improvement in irregular waves. Effect of scoops much more marked with the doors open and one float compartment deflated.
W30-100/-/200	4432 kg 5818 kg	Scoops fitted on both fwd and rear floats.		Various	S4 2.40m/ ?? S5 3.58m/ ?? (still air only)	1:10 scale physical model. Clear improvement with scoops in regular waves. Increase of about 1 sea-state in irregular waves.
S-61N	8182 kg	Scoops fitted to floats. Also tests with one float removed.		Various	S4 2.17m/6.62s S5 2.79m/6.08s (still air only)	1:8 scale physical model. Very little effect caused by the floats although static stability was increased.
S-76	3199 kg	Scoops fitted to all floats.		Various	S4 2.17m/6.62s S5 2.79m/6.08s (with and without wind)	1:8 scale physical model. Scoops improve behaviour in regular wave considerably (roll motion said to have been 'damped'). Helicopter also less vulnerable in breaking irregular waves. Improved about 1 sea-state. Scoops had little effect on weather cocking behaviour.
AS-332L	4610 kg 8600 kg	Scoops fitted to main floats.			S4 2.17m/6.62m S5 2.79m/6.08s	1:8 scale physical model. Significant improvement in stability boundary in regular waves. Also improvement in irregular waves. Improvement in weathervaning.

General notes on the tests

a) Very poor representation of the irregular spectrum shape. In particular sea-state 5 far too low period (lower than sea-state 4!). This means that sea-state 5 much steeper than 4 and therefore a poor test.

b) Poor quality reports, difficult to use. Number of photos missing from the draft.

c) The important effect of wind on controlling the heading of the helicopter to head into wind (and thus into waves). Otherwise they tend to turn beam-on which usually promotes capsize. Note that many of the tests were started at different initial headings (e.g. head, quartering, beam) but thereafter the helicopter was free to choose its own heading.

d) A key issue is the presence or otherwise of breaking waves in the tests. It is often mentioned that capsize occurred in breaking waves, but when a helicopter does not capsize it is not mentioned whether there were any breaking waves present.

e) The steepness of regular waves used is such that any could be breaking in a model basin. Not clear which ones were and which ones were not.

f) Heavier aircraft always seem to be more stable.[1]

g) Much of the data is compared with results from other references which give the results of the standard floats tests. Concern about whether the wave conditions were the same in these tests.

h) Problems of waves based on sea-states (the definitions of which have changed from time-to-time).

i) Effect of scoops will be to increase static stability **and** increase damping and added inertia. Not clear which effect is more important. (They could have done tests with damping or added mass devices only.)

j) No attention to the direction of capsize? Is roll always the vulnerable axis, or do helicopters sometimes turn across a diagonal. Not clear that the calculation and static stability measurement methods would have determined this.

k) What is lacking in this work is any investigation of which parameters in the helicopter design influence the tendency to capsize. The key issues could be: the peak righting moment, angle of peak moment, range of stability, floating trim angle, tendency to weathervane, underwater lateral area (resistance to being pushed sideways by breaking wave), and the direction of minimum static stability.

l) No information of the probability of capsize in any irregular wave condition.

m) What is mostly lacking from these reports is clear tabular presentation of the capsize occurrence in the different conditions tested (should be obtainable from the experiment book notes or from video records). It is often extremely difficult to work out from the narrative exactly which weight/wind/etc. condition is being described.

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[1] **Note added in 2005:** The helicopter's weight is correlated with the height of its centre of gravity. Greater weight implies a lower centre of gravity. See footnote on page 10 of Appendix A.

Annex C Model Tests in Regular and Irregular Waves

1 Introduction

Physical model tests are often the only way of handling complicated dynamic problems such as the capsize of helicopters in waves. Models constructed with due regard to the necessary physical similarity and mass/inertia properties can give a realistic qualitative and quantitative impression of the way in which the full scale helicopter will behave. The tests can be particularly impressive to the layman who sees what appears to be a true representation of reality (particularly when filmed, and slowed down to simulated `real-time').

However, such tests do present a number of real difficulties which must be considered when such tests are designed or the results from them interpreted.

The main difficulties when considered in the context of helicopters are:

- The construction of accurate models (accurate in terms of shape, floodability, mass, inertia, etc.)
- The generation of appropriate and repeatable wave conditions.
- The conduct of tests in these waves in a controlled and repeatable manner.

2 Model Construction

It is important that models used in this type of testing are statically and dynamically similar to the full scale helicopter.

Static similarity involves ensuring that the external shape and dimensions are accurately represented on the model. When the model is going to be permitted to flood through open doors it is also necessary to ensure that the internal voids are properly modelled. This latter can be quite difficult to do precisely owing to the need for very thin walls, and the many internal details (passenger seats etc.).

The model must also have the correct weight and centre of gravity location. This can be quite difficult to arrange (particularly for small models when it is sometimes difficult to make the model light enough). Obtaining the appropriate centre of gravity location involves balancing the model and adding ballast weights until the correct CG location is achieved.

Dynamic similarity involves ensuring that the inertia of the models in the three rotational axes is correct. The most important in the context of capsize is obviously the roll inertia or radius of gyration.

It is usual in wave model test reports to list all the static and dynamic properties of the model both as 'desired' and 'obtained' so that the reader can judge the accuracy of the modelling. In the case of the BHC model test reports [4] and [5], information on the means of balancing the model and achieving the desired properties is rather sketchy, and tables showing full scale and model properties do not seem to be 'as measured' properties of the model, but rather just desired values scaled down from full scale.

In the context of helicopters there are some specific modelling problems:

- How to model the interior spaces when water is permitted to flood in and wash through the cabin.
- How to model the rotor. The prototype rotor assemblies are quite flexible, and it is not immediately clear how the inertia of the rotor influences the total inertia of the helicopter at wave frequencies. The rotor tips are also likely to touch the water surface in extreme conditions and it is not clear how this should be modelled. (It is noticeable that most of the helicopter models tested by BHC did not have rotors fitted, but in some cases a mast with a weight on the top was used to help obtain the required total CG and inertias.)

3 Wave Conditions

3.1 Regular Waves

'Regular' waves (the reason for the quote marks will become apparent later) are intended to be regular in terms of the wave amplitude and frequency, the wavemaker paddle normally moving with a sinusoidal movement.

Until the late 60's almost all wave model tests were performed in regular waves because this was the only wave generation technology available. All realised that these regular waves were a very poor model of the real waves experienced in the ocean, but if one was able to assume linearity of response, harmonic or Fourier analysis provided ways of interpreting this information to predict the behaviour in irregular seas.

In addition to not being representative of real ocean waves the apparent simplicity of sinusoidal regular waves is, to some extent, illusory. Only the least steep (small wave height compared with wave length) approximate to sinusoidal shape. The steeper these waves become, the less sinusoidal they are - the peaks get more sharp and the troughs flatten. Somewhere between a wave length/wave height of 10 - 7 these waves also break.

In longer model basins it also becomes apparent that such 'regular' waves do not propagate unchanged down the tank. Depending on their steepness, and the distance they have travelled, and the purity of the initial wave form, these waves degrade and change shape as they propagate. Eventually they become quite irregular and break. This means that the shape and properties of the wave are different in different parts of the tank, and also tend to change with time as reflections and other 'noise' build-up in the tank accelerate the degradation process.

Furthermore, waves steeper than 1:10 will often break as they are generated at the wavemaker paddle.

Once breaking is occurring in a 'regular' wave train, an energy conversion process is occurring that ensures that the wave cannot continue to propagate with the same shape and regular properties. It can no longer be a regular wave.

It is clear from the above that tests performed in steep regular waves are fraught with difficulties. The wave shape changes with position in the tank and with elapsed time, and one run will usually be different from the next. This presents particular problems for the testing of a free-drifting model as the helicopter model will tend to drift down the tank from a region of smooth regular waves into a region of steadily increasing irregularity and wave breaking. (The model cannot be constrained to remain in the same place, as these constraining forces would have a major effect on its behaviour.)

These factors were well-understood by those who performed the helicopter model tests in steep 'regular' waves. It is clear from the work reported that no capsizes occur unless the vehicle is hit by a breaking wave. Thus 'regular' waves in this context have really been used as a way of making breaking waves - which are inevitably irregular by nature.

It is understood that the wave height, wavelength and steepness were estimated as best as possible for an individual wave that capsized (or failed to capsize) the model. This was in itself very difficult in practice as the model was not necessarily alongside a wave probe at the moment of interest.

3.2 Irregular Waves

The use of 'more realistic' irregular waves has been on the increase since the 60's. Understanding of the ocean environment was improving, and later the availability of cheap computer technology and servo-controlled wavemakers started to impact on the science, and permitted more sophisticated control of wavemakers.

Early irregular wavemakers were electro-mechanical, driven by a variable speed electric motor via an eccentric crank, where the speed of the motor was controlled by some kind of programming device (often a punched card). In these systems the irregular sequence was usually quite short (say 100 waves) before the program repeated, and this type of control made it difficult to produce waves with a spectrum shape and Gaussian randomness (or pseudo-randomness) that was representative of the real ocean.

Later wavemakers, actuated by hydraulic servo systems or linear electrical actuators and controlled by computer, solved these problems and made it possible to generate more or less infinite sequences of pseudo-random waves with the desired spectral and statistical properties. More recently this technology has been extended to multi-directional irregular waves in some tanks.

A good quality irregular wavemaker makes it possible to generate irregular waves in a closely controlled and repeatable fashion that is a good representation of a given sea-state. In fact wavemaker technology today is capable of generating waves to much closer tolerances than the ocean environment is generally understood.

The strategy adopted in the irregular wave test is rather different from a that used in a regular wave test. The usual policy is to set a given sea-state (usually defined in terms of a significant wave height, mean period and spectrum shape) and record the behaviour of the vessel under test for a long period of time (often about 3 hours prototype time). The reason for the long run times is that the results of the test can only really be interpreted properly in a statistical fashion if there are a lot of waves. In principle, a helicopter ditching test could be run on many occasions in different time-history realisations of the same sea-state, and an accurate determination made of the probability of capsize in any period of time. In practice there are some difficulties with this approach.

The free drifting nature of the model means that eventually the model will drift down the tank and the run must be stopped. Also when capsize occurs, the test must obviously be halted and the model recovered.

In addition to this inherent difficulty it is unfortunate that the model tests conducted in irregular waves described in [4] and [5] have been performed using an electro-mechanical wavemaker of the early type. This has lead to very poor spectral shaping and very short run sequences.

All that is known from such a test is whether the helicopter capsized or not. If it did, then there is still no information about the probability of capsize in a given period of exposure. If the size of the wave that capsized the helicopter were known, then it might be possible to calculate the probability of this wave, but this has not been recorded.

Similarly, if a helicopter remained upright through a sequence of 100 waves (about 10 minutes prototype time) then there is nothing to say that a 101st wave would not have capsized it. A detailed statistical analysis of the 100 wave heights experienced would reveal whether these 100 waves represented a typical distribution of heights, but again this information is not believed to be available for the tests concerned.

3.3 An Ideal Helicopter Capsize Model Test

Given that the requirement for a ditched helicopter is to remain upright long enough for crew and passengers to make a safe evacuation to the life rafts, the real requirement for a helicopter model test is to demonstrate that the probability of capsize within a given short period (say 5 minutes) is adequately low.

The only way of demonstrating this in a physical model test is to run a large series of realistic irregular wave conditions and record the mean frequency of capsizes that occur. This will enable the probability of capsize to be estimated. Alternatively, if the wave height and period characteristics which cause capsize can be recorded in each case (difficult because of the drifting position of the helicopter model), then the probability of meeting this wave can be estimated and the probability of capsize arrived at in this way.

This implies that a large number of long tests must be performed in a long tank with good wave generation properties.

Annex D Helicopter Ditching Occurrences Summary

Table 1 Summary of Helicopter Ditching Incidents (Excludes crashes into sea where significant damage was sustained)
Sources: CAA Database, plus Paper HARP 11 10/8/83

Date	Type	Sea-state	Wind (kn)	Location	Damaged on landing?	Capsized?	Fatalities	Survivors	Comments
??/11/70	S-61	4-5		North Sea		Y		3	Capsized just after evacuation, probably due to loss of sea anchor.
8/3/76	Wessex	Calm		North Sea		?		14	Appears to be a fairly uncontrolled descent. Aircraft lost. (Capsized later?)
??/7/76	Bo 105	1-2							No problems reported.
1/10/77	S-61	7	30-40	North Sea		Y		3	Large wave lifted nose up and to left. Capsized in 30s No time to deploy sea anchor.
31/7/80	S-61	0-1		North Sea				15	
11/3/83	S-61	0-1		North Sea				17	Not damaged in accident, but eventually sank as a result of damage caused during attempted recovery.
2/5/84	Chinook	1		North Sea		Y		47	Capsized after about 10+ minutes following flooding. (Lack of flotation integrity.)
15/5/84	Bell 214	low		North Sea	Y	?		20	Flotation bags punctured. Not clear whether it capsized.
13/7/88	S-61	4		North Sea				21	Successful ditching and evacuation. Burned, broke up and sank.
10/11/88	S-61	5-6		North Sea		Y		12	Rolled to the right and capsized (immediately?) in 45mph winds.
25/4/89	B 105	low		SCATSTA	Y			2	Right front and both rear floats partially detached in forward speed landing. No capsize mentioned.

There are 11 ditchings listed with 4 clear capsizes. This indicates that the overall capsize rate is about 36%.

The stated objective in HARP 11 and 9/31/R50-11C-3 is 1% (based on an overall target risk of 'ditching + capsize' of 10^{-7} per hour and an actual ditching rate of 10^{-5} per hour).

Appendix B1 Review of Helicopter Ditching Certification Requirements

Executive Summary

BMT Offshore Ltd. was asked by the Civil Aviation Authority to perform a review of helicopter ditching performance and current certification requirements.

An earlier report [4] considered and discussed the existing information on the factors influencing the on-water stability of current helicopter types. This second report in the series deals with the current certification requirements for helicopters in this respect.

The current CAA requirements are mainly defined in British Civil Airworthiness Requirement BCAR Paper G779 dated 7th October 1985 [5]. This document amended the previous BCAR Chapter G4-10 and associated Appendix dated 20th January 1975 [6].

The study has found that the requirements of this paper are ambiguous in terms of the performance expected in regular waves and in irregular sea-states. The paper seems to have been interpreted in the past to mean that the helicopter may pass one or other of the criteria, but does not have to pass both. None of the existing helicopters considered in [4] seem to pass the irregular sea-state criterion, but all seem to pass the regular wave steepness criterion.

It is considered that this ambiguity is undesirable, and the requirements should be clarified.

Furthermore it is considered that the results of regular wave tests may be misleading, and that consequently an irregular wave criterion is a more realistic measure of the likely actual performance of the helicopter ditched in the ocean. It is suggested that the current reliance on defining wave conditions using sea-state numbers should be dropped in favour of a more precise definition of the sea-state requirements in terms of significant wave height, period and spectrum shape. It is also suggested that a minimum model testing standard should be considered.

An alternative to the definition of a required performance in specified sea-states is also discussed. This would instead define a maximum probability of capsize when ditched in the 'operational area'. This would place more responsibility on the designer to test his helicopter to the appropriate operational conditions. This possibility will be investigated further in the next report in this series.

1 Introduction

BMT Offshore Ltd. (BMT) was asked [1][1] by the Civil Aviation Authority (CAA) to propose a review of helicopter ditching performance. BMT responded with a proposal [2], and based on this proposal, CAA put in place a contract for the work to be performed [3].

The review was to look critically at the various research reports and review documents that CAA had commissioned in recent years, and to summarise and comment on their findings.

1.1 Objectives

The objectives of the overall study were stated to be [2] as follows:

a) Perform a critical review of a number of documents with the objective of drawing conclusions from this work and prepare an overview document (or documents) suitable for publication by CAA.

b) Perform a critical review of the current UK Emergency Alighting on Water helicopter design requirements as specified by BCAR Paper No G779 dated 7th October 1985 [5], and where appropriate make recommendations on how these requirements might be improved, and whether there are better ways of assessing a helicopter's water-borne stability.[2]

c) Based on the results of (a) and (b) above, and the results of a separate study, review North Sea helicopter ditching performance over the past 20 years and assess the practicality of imposing a new probability-based methodology for North Sea helicopter operations, taking account of specific type's ditching rates, capsize probability and operating environment.

This second report deals with the results of (b) above only.

1.2 Background

The stated objective in the certification of a helicopter in relation to ditching in the sea is that the helicopter should remain upright for sufficient time for the occupants to escape (not less than 5 minutes). This implies that there should be an acceptably low probability of meeting a wave large enough or steep enough to capsize the helicopter in this short period of time.

The probability of experiencing a capsize is dependent on two key factors:

a) The height and period or slope of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

The first report in this series [4] studied model testing and theoretical research reports on the topic. The main conclusions of this part of the study were that the model test results were very difficult to interpret in terms of the known physical properties of the helicopters, but it was noted that helicopter models only seemed to capsize in breaking waves.

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[1] References may be found in Section 6 on page 9.

[2] **Note added in 2005:** This report was written in 1993, at a time when all helicopters operating in the UK North Sea were certificated according to BCAR. BCAR ditching certification requirements have since been superseded by JAR/FAR requirements 27 and 29.801. JAR requirement 29.801 was reviewed and compared with BCAR G779 in a follow-up BMT report 44035r32 dated November 1995. Both sets of requirements were found to suffer from similar ambiguities.

2 Conclusions and Recommendations

2.1 The current helicopter certification requirements in relation to ditching and afloat stability are ambiguous or incomplete in some respects.

2.2 The main areas of ambiguity are:

a) Whether regular waves, or irregular waves, or both, should be tested.

b) How irregular waves are to be defined in terms of steepness or spectrum shape.

c) Whether conditions more severe than sea-state 6 are intended to be considered (say in the context of northern North Sea operations) and how these should be chosen.

d) What damage the helicopter should be considered to have sustained in the course of the ditching.

e) Exactly what results are required from the (compulsory) model tests.

2.3 It is recommended that the requirements should be amended to remove these ambiguities.

2.4 There are two clear options available in removing the ambiguities and improving the certification requirements:

a) Include a clear specification of the wave conditions to be used in testing.

b) Remove all reference to specific sea-states and require the designer to simply demonstrate an adequately low risk of capsize in the intended operational area.

2.5 If the approach 2.4 a) above is to be followed, it is recommended that this should focus on model testing in irregular waves, and should cover:

a) A definition of the wave conditions in terms of significant wave height, period and spectrum shape required for the model tests.

b) A definition of the way in which the severity of the conditions is to be selected. If there is a table of wave conditions analogous to the current requirement, then the circumstances under which more severe (or less severe) conditions may be applied.

c) A specification of the minimum model testing standards required (e.g. wave generation techniques, duration of runs, type of analysis of results etc.), and a clear definition of the objective of the tests (e.g. to demonstrate a probability of capsize during a given period of time of less than a given required value).

2.6 The use of regular wave tests against a specific wave steepness criterion should be discouraged as, owing to the fact that capsize only normally occurs in breaking waves, the results are likely to depend more on the wave basin properties than on the helicopter model properties.

2.7 The next report in this series will pursue the possibilities of 2.4 b) above in more detail and report on their practicability in certification terms.

3 BCAR Paper G779

Paper G779 issued on 7th October 1985 [5] amended Chapter G410 Emergency Alighting on Water, and the G410 Appendix. Previously the G410 Chapter had been issued on 20th January 1975 [6], and had therefore been in force for about 10 years.

The main changes brought in by the 1985 amendment were;

a) the reduction of the sea-state range from 0 - 7 to 0 - 6 (but no change in the 9.15m maximum wave height),

b) the amendment of the sea-state table,

c) the introduction of a period of time for which the rotorcraft must remain stable ".. for not less than 5 minutes",

d) the fact that a sea anchor, or similar device, "may not be assumed", when demonstrating compliance,

e) the fact that "more severe criteria will be applicable" in particular geographical areas, and

f) the change to more severe "individual wave" steepness criteria.

The Paper G779 can be studied on three levels; the clarity of its meaning, the effect of this meaning in seakeeping or stability terms, and the way in which it seems to have been interpreted in practice since 1985.

The following sections deal with these three separate issues in turn.

3.1 Clarity of Meaning / Ambiguities

In most respects the intended meaning of G779 in terms of helicopter stability following ditching is clear:

> Section 2 requires that the craft should **remain afloat for the time required for everybody to escape**, and further indicates that this time should **not be less than 5 minutes in severe seas**. (Note that 'severe seas' are not defined here, but from later sections we may assume that their definition is to be found in G4-10 Appendix which implies that a severe sea is therefore sea-state 6). This section also mentions that **allowance for damage to the helicopter should be made,** although the nature or extent of this damage is not defined in any way.
>
> Section 4 requires that satisfactory flotation and trim characteristics shall be **demonstrated by investigation and model tests conducted** so that the results would be valid in the declared conditions. (Note that the conduct of a model test is compulsory.)
>
> Section 5.2 defines the declared conditions as **those in which compliance with the requirements have been demonstrated,** and that if these are less than the conditions given in the Appendix (i.e. sea-states 0 - 6), then these **limitations shall be included in the flight manual**. Furthermore it indicates that in particular geographical areas **more severe criteria will be applicable.**

The main potential ambiguity in G779 lies in the definition of the sea-state conditions in the G410 Appendix, as follows:

> Firstly these are stated to be the conditions which should be investigated. The concept of demonstrating compliance has been lost at this point and the requirement consequently seems much weaker. However, presumably reference back to Section 4 makes it clear that it is really **demonstration by investigation** that is required - a much stronger concept.
>
> Secondly, whilst 1.2(a) makes it clear that the compliance must be investigated in sea-states 0 - 6, the second part 1.2(b) says that it should be in **individual waves** with height/length ratios with given requirements in all sea-states of (a). It is not at all clear what is required here. If the requirement were just 1.2(a), then we would understand that we must test in the range of sea-states listed 0 to 6. There might be some question about how we were to choose the spectrum shape (or the steepness of the irregular sea-state) but otherwise the meaning would be clear. The addition of 1.2(b) which refers to individual waves of particular steepness, and links these in some way to the irregular sea-states is, however, confusing.

It could potentially mean:

a) You must test in regular waves of this steepness, and choose the height of these regular waves to be consistent with the heights of the irregular sea-states.

b) You must test in irregular waves and ensure that your irregular waves include individual waves of the steepnesses stated (i.e. an implied constraint on the spectrum shape and wave time series).

c) You must do both (a) and (b).

d) You may test in irregular waves and ignore any capsizes which might occur caused by individual waves steeper than the given values.

Further interpretations are possible.

All the above interpretations are very different in terms of the model test that would be conducted, and how it is decided whether the helicopter has passed the test or not.

3.2 Naval Architectural Sense

The ambiguities in the definition of the waves in which satisfactory characteristics are to be demonstrated by investigation have been highlighted in the previous section. It is considered here what type of requirement might be expected from consideration of the underlying objective which is taken to be to ensure that the helicopter remains upright for a time sufficient for the occupants to escape.

This most general objective covers two quite separate aspects:

a) The height and period of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

Dealing with (a) first, it would seem to be a prime requirement that one should consider realistic sea conditions in which to determine the limiting conditions in which capsize occurs. This implies that such tests should be performed in irregular waves characteristic of the spectrum shapes and mean periods anticipated in the area of operation.

It is worth considering in more detail here the consequences of model testing helicopters in steep regular waves, if the capsize of the helicopter is only likely to occur in breaking waves [4]. Theoretically regular waves break at a steepness (wave height / wavelength) $H/\lambda \approx 1/7$. However, in practice in model basins waves often break at lower steepnesses. Indeed it is not uncommon for breaking to be seen at the face of the wavemaker for steepness greater than 1/10. Other factors that influence breaking in a model basin include; the purity of the original wavemaker motion, the distance travelled by the waves along the model basin, the height of the waves and the presence of other spurious waves in the basin. If the helicopter certification requirement is to remain upright in a regular wave of a given steepness, and helicopter capsize is only caused by breaking regular waves, then a model basin which can produce the steepest non-breaking waves will be able to demonstrate the best wave steepness performance for each helicopter type. In other words this regular wave steepness criterion is perhaps more a test of the wave quality in the basin than it is a measure of the helicopter performance.

Dealing now with (b) above. This aspect contains two components; the probability that the helicopter will be capsized in a given period of time (5 minutes) in any given limiting sea-state, and the probability of meeting such a limiting sea-state (or worse) in a random ditching incident in the area of operation. The latter component is not really addressed in the BCAR G779 at all, except to the extent of stating that more severe criteria **will be applicable in certain areas.**

From the above we might deduce:

Model testing should be in irregular waves.

- The wave spectra used should be typical of the operational area.
- The objectives of the model test should be to demonstrate an adequately low probability of capsize in a 5 minute period of exposure.
- A wave climate analysis for the operational area should be performed to demonstrate that the overall risk of capsize in a randomly occurring ditching event is adequately low.

3.3 Apparent Historical Interpretation

Whilst it has not been part of this study to examine all the certification model test reports for the various currently certified helicopters, it is possible to draw some tentative conclusions about historical interpretation from the model test results contained in the BHC research model test reports for the CAA.

These indicate that all the helicopter types tested had little difficulty in complying with the wave steepness requirements of BCAR G779, but none remain stable in irregular waves of sea-state 6 (many capsized in sea-state 4 and the remainder capsized in sea-state 5).

Furthermore it is understood that no currently certified helicopters contain any stated limitations in their flight manuals.

From the above it can be deduced that the regular wave steepness criterion is being applied in isolation, and the results of any irregular sea-state tests ignored.

4 Proposed Improvements to the Certification Requirements

As has been noted above, the current certification requirements include a number of ambiguities. They may be summarised as follows:

a) Whether regular waves, or irregular waves, or both, should be tested.

b) How any irregular waves are to be defined in terms of steepness or spectrum shape.

c) Whether conditions more severe than sea-state 6 are intended to be considered (say in the context of northern North Sea operations) and how these should be chosen.

d) What damage the helicopter should be considered to have sustained in the course of the ditching.

e) Exactly what results are required from the (compulsory) model tests.

Dealing with (d) first, detailed examination of the likelihood and consequences of damage to the helicopter hull or flotation system are beyond the scope of this current study. However, it is suggested that the extent of damage to the helicopter should be defined in some way. It might be defined in terms of a specific failure, e.g. loss of buoyancy of any one complete flotation unit or hull compartment. Alternatively it might be defined in terms of any worst single credible failure, leaving the designer to demonstrate how he has selected such a case.

It is clear from the current requirements that it is compulsory to perform model tests, but it is not so clear exactly what results constitute a demonstration that the performance of the helicopter is satisfactory. It might be considered that it is best to leave this open, so that the onus is on the designer to devise a model test that demonstrates the point. Alternatively, if a risk-based or probabilistic approach is to be adopted by the CAA it might be best to ensure that such probabilistic information will be an output from the model test analysis.

The following sub-sections examine the options for definition of limiting wave conditions in more detail.

4.1 Option 1 - Keep the Definition of Limiting Wave Conditions

This option would retain the current practice of defining wave condition(s) in which the helicopter must be demonstrated to survive, but would ensure that these requirements are framed in a clearer and less ambiguous manner.

The main principles of the changes would be:

a) Settle on a regular or an irregular wave criterion. It is strongly recommended that an irregular wave criterion is more appropriate to determination of the risk of capsize because the results of regular wave tests may be misleading.

b) Define irregular sea-states in terms of significant wave height, peak period, spectrum shape.

c) Define an acceptably low risk of capsize (in the 5 minute exposure) that must be achieved in the limiting sea-state. Alternatively define the limiting sea-state as that wave condition which results in the required risk of capsize in the 5 minute exposure.

d) Provide a list of irregular sea-states in which the designer must demonstrate that his helicopter has the adequately low risk of capsize. Define the geographical areas for which these limiting conditions apply. Provide guidance on how other limiting conditions are to be derived for other geographical areas (e.g. specify the sea-states with a given percentage exceedance over the whole year). (Note that, in combination with the risk level defined in 3 above, this last element would imply the definition of a CAA required overall level of risk of capsize in 5 minutes exposure following any random ditching incident.)

4.2 Option 2 - Define a Probability of Capsize in the Operating Area

This option would move completely away from defining any sea-states or wave conditions in which the performance of the helicopter must be demonstrated. It would instead make it a requirement to demonstrate an overall adequately low risk of capsize in a randomly occurring ditching incident.

There are two ways of doing this:

4.2.1 Option 2A

Largely follow Option 1 above, but remove the table of sea-states and replace them with a requirement for the designer to select a family of limiting sea-states with given annual probabilities of exceedance in the operating area.

This would preserve the requirements for testing in irregular waves, and the adequately low risk of capsize to be demonstrated, but would put the onus on the designer to test in sea-states that are appropriately severe for the intended area of operation.

4.2.2 Option 2B

Require the designer to define the operating area, and demonstrate an overall risk of capsize in 5 minutes exposure following a random ditching. This risk to be less than a CAA-specified maximum level.

The designer would have to select limiting sea-states appropriate to the operating area, perform model tests in a family of such sea-states, determining the risk of capsize within 5 minutes in each case, and then combine this with climatic data on the occurrence of the sea-states to arrive at the overall risk.

Perhaps leave open the means by which the low risk is demonstrated (i.e. not making a model test compulsory).

This approach has much in common with the modern 'safety case' approach being pursued by the Health and Safety Executive in the context of offshore oil installations. The advantages and disadvantages of this approach for helicopter flotation certification will be investigated in more detail in the next report in this series.

5 Discussion

It has been shown that there is clear room for improvement in the framing of certification requirements for helicopter flotation performance following a ditching.

Two different approaches to improvement are possible:

- One would retain the basic framework and prescriptive intentions of the current requirements, but would modify them and clarify them so that there is no room for misunderstanding. Section 4.1 above has outlined the principal areas of modification required.
- The alternative is to move away from a prescriptive regulation in terms of wave conditions, and instead set in place risk or probability targets for helicopter capsize, leaving the designer to demonstrate by whatever means he chooses that these have been met.

A change to the latter is likely to have important implications for other areas of CAA certification, and so is not to be undertaken lightly. The practical techniques and limitations of this risk or probability-based approach will be developed further in the third report in this series.

Once this next phase has been completed it should be possible for CAA to make a choice over which approach to adopt. It will then be necessary to develop the appropriate modified BCAR wording for the selected approach.

6 References

[1] CAA Letter Ref 10MG/13/5 dated 1/10/92.

[2] BMT Proposal Q94004 Review of Helicopter Ditching Performance, dated 6th October 1992.

[3] CAA Contract No. 7D/S/1096 dated 16th December 1992.

[4] BMT Report 44011r12 Review of Helicopter Ditching Performance, Release 2, 2nd July 1993.

[5] Civil Aviation Authority, British Civil Airworthiness Requirements, Paper No. G779, 7th October 1985.

[6] Civil Aviation Authority, British Civil Airworthiness Requirements, Sub-section G4 - Design and Construction, Chapter G4-10 Emergency Alighting on Water, 20th January 1975.

Annex A BCAR Paper G779

CIVIL AVIATION AUTHORITY BRITISH CIVIL AIRWORTHINESS REQUIREMENTS

SECTION G
ROTORCRAFT

PAPER NO. G779

7th October 1985

EMERGENCY ALIGHTING ON WATER

INTRODUCTION

The requirements of this Paper have been agreed by the Rotorcraft Requirements Coordinating Committee, and are made effective upon acceptance of the advice of the Airworthiness Requirements Board.

TEXT OF AMENDMENTS

Material differences between the current requirements of Section G and those of this Paper are indicated with a marginal line.

CHAPTER G4-10 EMERGENCY ALIGHTING ON WATER

Paragraph 2 is amended to read as follows:-

2 GENERAL

2.1 Such design measures as are compatible with the general characteristics of the rotorcraft, shall be taken where these are necessary to ensure as far as possible, that, where an Emergency Alighting on water is made, in accordance with the recommended procedures (see 3),

(a) the behaviour of the rotorcraft in the declared conditions would not be such as to cause injury to the occupants or make it impossible for them to escape from the exits provided;

(b) the flotation time and trim of the rotorcraft in the declared conditions and allowing for damage will allow the occupants to leave the rotorcraft by the exits provided and enter liferafts (see also G4-3,5).

NOTE: The rotorcraft should float in a stable position for not less than five minutes. This allows time for the deployment of the liferafts and for passengers to transfer from the rotorcraft to the liferafts in severe seas.

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2.2 In assessing the general characteristics of the rotorcraft any projecting features, or other factors likely to affect hydrodynamic characteristics, shall be taken into account.

2.3 External doors and windows shall be designed to withstand the probable maximum local water pressures occurring during an alighting on water conducted in accordance with the established technique (see 3.1).

Paragraphs 4 and 5 are amended to read as follows:-

4 FLOTATION AND TRIM (See G4-10 App. 1.2) Satisfactory flotation and trim characteristics shall be demonstrated by investigation and model tests conducted so that the results would be valid in the declared conditions. A sea anchor, or similar device may not be assumed to be used in demonstrating compliance with the requirements of this Chapter, but may be assumed to be used to assist in the deployment of liferafts in accordance with G6-6.

5 PROCEDURES AND LIMITATIONS

5.1 Procedures. The techniques and procedures established in accordance with 3.1 shall be included in the Flight Manual.

5.2 Declared Conditions. These are the conditions in which compliance with the requirements has been demonstrated. If these conditions are less than those detailed in G4-10 Appendix they shall be included in the Flight Manual as limitations.

NOTE: Chapter G4-10 Appendix defines generally applicable criteria. In particular geographical areas more severe criteria will be applicable.

CHAPTER G4-10 APPENDIX

Paragraph 1.2 is amended to read as follows:-

1.2 Flotation and Trim (see G4-10, 4). The flotation and trim characteristics should be investigated under the following conditions:-

(a) in sea states in the range 0 to 6 of Table 1 (G4-10 App.) (but with a maximum wave height of 9.15m (30 ft));

G4-10, 2.2

(b) in individual waves with height/length ratios in accordance with (i) or (ii) in all sea states of (a);

(i) 1 : 8 for rotorcraft in Group B;

(ii) 1 : 10 for rotorcraft in Group A.

NOTE: The wave height/length ratio may be changed with the increase in the declared time interval (See G1-2, 8.1) up to a maximum of 1 : 12.5 when there is no limit on the declared time interval.

Table 1 of the Appendix to G4-10 is amended as follows:-

TABLE 1 (G4-10, APP.)
SEA STATE CODE

(WORLD METEOROLOGICAL ORGANISATION)

Sea State Code	Description of Sea	Significant Wave Height	
		Metres	Feet
0	Calm (Glassy)	0	0
1	Calm (Rippled)	0 to 0.1	0 to $^1/_3$
2	Smooth (Wavelets)	0.1 to 0.5	$^2/_3$ to 1 $^2/_3$
3	Slight	0.5 to 1.25	1 $^2/_3$ to 4
4	Moderate	1.25 to 2.5	4 to 8
5	Rough	2.5 to 4	8 to 13
6	Very Rough	4 to 6	13 to 20
7	High	6 to 9	20 to 30
8	Very High	9 to 14	30 to 45
9	Phenomenal	Over 14	Over 45

NOTES: (1) The Significant Wave Height is defined as the average value of the height (vertical distance between trough and crest) of the largest one third of the waves present.

(2) Maximum Wave Height is usually taken to be 1.6 x Significant e.g. Significant Wave Height of 6 metres gives Maximum Wave Height of 9.6 metres.

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CHAPTER G4-3 COMPARTMENT DESIGN AND SAFETY PROVISIONS

Paragraph 5.2.7 is amended to read as follows:-

5.2.7 Marking. Emergency exits, together with their means of access and means of opening, shall be adequately marked for the guidance of occupants using the exits in light and in darkness (e.g. by the use of luminous paint or emergency lighting). For rotorcraft in the configuration for overwater flight such marking shall remain adequate if the helicopter is capsized and the cabin submerged. Adequate marking shall also be provided for the guidance of rescue personnel outside the rotorcraft

Paragraph 5.2.9 is amended to read as follows:-

5.2.9 Ditching Emergency Exits. With the rotorcraft in the configuration for overwater flight, the most adverse static water level(s) shall be established. Emergency exits located above the water level(s) so established shall be provided on each side of the fuselage and the number and size shall be related to the seating capacity as shown in Table 2 (G4-3).

Table 2 (G4-3)

Passenger Seating Capacity (inclusive)	Ditching Emergency Exits each side of fuselage	
	Type III	Type IV
1 to 19	1	-
20 to 29	1	1
30 to 39	1	2
40 to 59	2	1
60 to 79	2	2

NOTE: Type IV exits are not to be considered for liferaft deployment and boarding purposes but are required to facilitate egress in the event of a capsize.

D36/79/4

Appendix B2 Helicopter Ditching JAR Certification Requirements

Executive Summary

BMT Fluid Mechanics Ltd. was asked by the Civil Aviation Authority to perform a review of helicopter ditching performance and current certification requirements.

The current CAA requirements are mainly defined in British Civil Airworthiness Requirement (BCAR) Paper G779 dated 7th October 1985. This document amended the previous BCAR Chapter G4-10 and associated Appendix dated 20th January 1975. These requirements were reviewed by BMT and commented on in a previous report [3].

This study has reviewed the similar Joint Airworthiness Requirements (JAR) on ditching, and compared them with the BCAR requirements reported earlier. The main conclusion was that the requirements were very similar in many respects, but an important difference is the requirement for survival in sea state 4 in JAR and sea state 6 in BCAR (but both imply that higher sea states might be appropriate).

Both JAR and BCAR requirements are ambiguous with regard to the steepness of the waves that should be used.

Various recommendations have been made regarding potential improvements to the JAR documents.

1 Introduction

BMT Fluid Mechanics Ltd. (BMT) was asked [1][1] by the Civil Aviation Authority (CAA) to perform a review of helicopter ditching performance. The review was to look critically at the various research reports and review documents that CAA had commissioned in recent years, and to summarise and comment on their findings. A number of reports have been presented on this work [2, 3, 4, 5, 6].

This present report concerns a review of the Joint Airworthiness Requirements (JAR) for the certification of helicopter ditching. This additional study was ordered in [7]. The report is similar to [3] which considered the British Civil Airworthiness Requirements (BCAR) [8].

The objective of the study was to compare the provisions of the JAR with the BCAR documents, and produce a short report highlighting any naval architectural issues or flotation issues in the JAR documents which appeared to be ambiguous or inadequately defined.

The JAR documentation provided by the CAA for this study were [9] and [10]. For convenience these are reproduced in Annex A.

2 Conclusions

2.1 In many ways the provisions of the JAR and BCAR on ditching are similar. They have very similar statements of objectives which require that the occupants should not be injured and should be able to escape the rotorcraft. There is some difference in wording relating to: **"practicable design measures"** in the case of the JAR, and **"as far as possible"** in the case of the BCAR. It might be argued that the latter is a more onerous requirement.

2.2 The scope of the JAR document is somewhat broader than the BCAR and it includes more requirements relating to water entry and strength than found in the particular BCAR document reviewed. These aspects may be covered in more detail in other BCAR sections, but were not of prime interest for this study where flotation, trim and stability are the main concerns.

2.3 With regard to the severity of the wave conditions that the designer must demonstrate that the rotorcraft can cope with, the key phrase in the JAR is **"reasonably probable water conditions"**. The wording is not ideal, but it is believed that this should be interpreted to mean the majority of wave conditions that the rotorcraft might be expected to meet, with the consequence that the probability of meeting a more severe condition is reasonably rare. Taken on its own, this would require the designer to select a reasonably severe wave condition for the area in which he expects the aircraft to operate. However, later in the JAR guidance this is interpreted to mean **"not less than sea state 4"**. It is expected that most designers will therefore just demonstrate compliance with sea state 4, a condition which is exceeded for a large percentage of the time in many of the world's oceans.

2.4 BCAR is more onerous in terms of sea states, quoting sea state 6, and also inviting the possibility that even more severe conditions should be considered in particular geographical areas.

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[1] References are to be found in Section 4 on page 8.

2.5 Both JAR and BCAR have difficulties in relation to wave steepness. BCAR mentions **"individual waves"** and steepness values, and this seems to have been interpreted in the past to require testing in regular waves. JAR quotes much the same steepness values but does not explain how these steepnesses should be interpreted with the sea state numbers, and so it is suspected that again this may have historically been taken to mean a requirement to model test in regular waves. BMT has noted previously in [3] that model tests in regular waves may give very misleading results.

2.6 The guidance to JAR makes it clear that the rotorcraft should be investigated in the most critical loading condition. Presumably this means the most unfavourable from a flotation, trim and stability point of view. BCAR gives no instruction on this. Unfortunately in JAR 29.801 (d) there is also some very loose wording relating to buoyancy and the jettisoning of fuel which could prove to be misleading.

2.7 With regard to damage, both JAR and BCAR indicate that damage to the rotorcraft hull and airframe (presumably caused by the ditching) should be considered, and the implication is that such damage should be considered in all sea states. However, JAR is rather more specific in its requirements on damage to the most critical flotation compartment. However, the sea state 2 requirement for this damaged flotation condition is so low as to call into question the real effectiveness of the requirement.

2.8 If future ditching certification is to be performed according to the JAR documents, then BMT recommends that the following changes should be made:

a) Remove the potentially misleading reference to buoyancy and jettisoning of fuel in 29.801 (d). Perhaps replace with a requirement to consider the most unfavourable loading condition, and to provide type-specific guidance in the flight operations manual about whether fuel should be jettisoned or not.

b) Replace the reference to sea state 4 as the **"reasonably probable water condition"**, with a requirement for the designer to select a sea state which has an appropriately low probably of exceedance in the intended operations area.

c) Add a rigorous definition of the requirements for the sea state steepness. This could also be linked to actual wave conditions in the operational area using probabilities of occurrence.

d) If damage to the flotation system is considered to be a reasonably likely occurrence, then consideration should be given as to whether the sea state requirements for a damaged condition should be the same as for that for the intact (or damaged hull/airframe) condition.

2.9 Taken as a whole the BCAR requirements seem to be more onerous than the JAR. However, the ambiguities in the definitions of the waves and their steepness have reduced their effectiveness in practice. The conclusion of [1] was that the helicopters examined did not meet the BCAR sea state 6 criterion. However, they did meet the JAR sea state 4 requirement.

3 The JAR Ditching Requirement

3.1 Overview

The requirements of JAR and BCAR are summarised and compared in the following table.

Table 1 Comparison of JAR and BCAR Ditching Requirements

JAR - 29.801 + Guidance	BCAR - G779
General Requirements: Each practicable design measure, compatible with the general characteristics of the rotorcraft, must be taken to minimise the probability that in an emergency landing on water, the behaviour of the rotorcraft would cause immediate injury to the occupants or would make it impossible for them to escape.	Such design measures as are compatible with the general characteristics of the rotorcraft, shall be taken where these are necessary to ensure as far as possible, that, where an emergency alighting on water is made... the behaviour of the rotorcraft in the declared conditions would not be such as to cause injury to the occupants or make it impossible for them to escape...the flotation time and trim of the rotorcraft in the declared conditions and allowing for damage will allow the occupants to leave the rotorcraft by the exits provided and enter the life-rafts.
Detailed Scope: Water entry, flotation and trim, occupant egress, and occupant survival.	Mainly flotation and trim only, but some mention of water entry procedures. Requirement that doors and windows will be strong enough.
Wave Height: Reasonably probable water conditions. Zero to a maximum value to be selected by the applicant, but at least sea-state 4 (significant height 1.25 - 2.5m), but only sea state 2 following damage to most critical float compartment.	Sea states in the range 0 - 6 (but with a maximum height of 9.15m). In particular geographical areas more severe criteria will be applicable.
Wave Steepness (or period): Height/Length = 1:8 for Cat B rotorcraft. Note - No definition of what this wave height / length ratio really means in the context of the above sea states.	Individual waves with height/length ratio of 1:8 for Cat B rotorcraft. (Has normally been interpreted to mean regular waves of this steepness.)
Time of flotation: Long enough to allow the occupants to leave the rotorcraft in an orderly manner and enter the life rafts.	Not less than 5 minutes. This allows time for the deployment of the life-rafts and for passengers to transfer.
Damage to rotorcraft: Probable damage to airframe/hull to be taken into account. Most critical float compartment to be damaged (but then only sea state 2 survival required).	Damage is to be allowed for.

Table 1 Comparison of JAR and BCAR Ditching Requirements

JAR - 29.801 + Guidance	BCAR - G779
Rotorcraft loading conditions: The most critical condition must be investigated. (But beware of misleading comments about fuel jettisoning and buoyancy in 29.801 (d).)	
Sea Anchor: Not to be used for demonstrating compliance with minimum requirements, but can be used to demonstrate compliance in more severe conditions.	May not be assumed when demonstrating compliance.
Model Testing: May be conducted... where satisfactory correlation between model testing and flight testing has been established. (May also use model tests and other data from other similar rotorcraft configurations.)	Seems to be compulsory (shall be demonstrated by investigation and model tests.)
Alternative approaches: Demonstration of compliance to other criteria may produce acceptable results if adequately justified by rational analysis.	
Sea state table: From WMO, but with wind speed ranges added.	From WMO.

The JAR documents considered in this study are in two parts: JAR 29.801 [9] is a relatively few paragraphs which set the overall requirements, whilst [10] are explanatory notes published in the form of an Advisory Circular by the FAA, but which have been adopted by Joint Aviation Authorities (JAA) as the advisory circular to JAR 29 (unless amended by the Advisory Circular Joint (ACJ) material contained in JAR 29).

One of the main differences between the JAR documents considered here and the BCAR document considered in [3] is that the JAR documents go into greater detail over a broader scope encompassing guidance for water entry and on structural issues. These issues are presumably dealt with in different parts of the BCAR, and are not of prime concern for this present study because the current objective is to focus on flotation, trim and stability issues.

JAR 29.801 (b) is a good short summary of the overall objective the designer should have in mind with regard to ditching:

"b) Each practicable design measure, compatible with the general characteristics of the rotorcraft, must be taken to minimise the probability that in an emergency landing on water, the behaviour of the rotorcraft would cause immediate injury to the occupants or would make it impossible for them to escape."

Taken on its own, this is quite an onerous statement for a designer to read, the only limitation on his efforts to ensure safety in a ditching being the word **"practicable"** and the phrase **"compatible with the general characteristics of the rotorcraft"**.

In many ways this statement is very similar to initial paragraphs of the BCAR G779 where the same overall objectives (not to cause injury to occupants, and to enable them to escape) are given. The main difference is the use of the words **"as far as possible"** in the BCAR document, which it might be argued placed a stronger requirement on the designer to search for **all possible ways** of improving the ditching safety.

In some ways all the prescriptive requirements and guidance that follow this statement in both the JAR and BCAR make the requirements less onerous (for example the BCAR document goes on immediately to require that the rotorcraft floats in a stable position for not less than 5 minutes).

3.2 Detailed Comments

It is noted that on page 553 of [10] a ditching is defined to be **"an emergency landing on water"** which is **"deliberately executed"**, and that the rotorcraft is assumed **"to be intact prior to water entry"**. However, later on page 558 it says that **"probable damage to the airframe/hull ... should be considered"** when demonstrating compliance with the flotation and trim requirements. Thus damage sustained during the ditching process is to be considered, and more specifically on page 557 it is clear that the **"flotation and trim should be evaluated with a simulated, ruptured deflation of the most critical float compartment"**, although in this condition the required sea state is relaxed from sea state 4 to 2. These requirements on damage are rather more specific than the BCAR requirements.

The BCAR paper requires the helicopter to float in a stable position for **"not less than 5 minutes"**. No specific period of time is mentioned in the JAR requirements, but it is clear that the rotorcraft must remain floating at a reasonable attitude for a time sufficient for all the occupants to escape (29.801 d).

The essence of the JAR requirement in terms of sea-states that the helicopter must be able to cope with is given in (d) of JAR 29.801 where they are defined as **"reasonably probable conditions"**. In [10] this is interpreted to mean **"at least sea state 4"**, the explanation being that **"sea state 4 is representative of reasonably probable water conditions to be encountered"**.

It is not completely clear what is intended here. If the helicopter were to be just capable of handling average conditions, then we might expect it to capsize on many occasions (50% of ditching occasions if the sea state probability distribution were to be symmetrical). It seems more likely that the writer of the JAR intended that the helicopter would be able to cope with the **majority of** or **all of** the reasonably probable water conditions. This would mean that it should cope with sea states forming most of the sea-state population, and a capsize following a ditching should be a **relatively rare occurrence**. This would also be consistent with the initial statement of objectives regarding not causing injury to occupants, and enabling them to escape.

Clearly the helicopter designer is at liberty to choose any sea-state condition that he wishes to demonstrate compliance with, and presumably he could justify in his submission that these represent **"reasonably probable conditions"**. However, the guidance that sea state 4 represents such a sea condition seems to absolve the designer of selecting one himself, and obviously takes no account of the vast range of ocean wave climates that exist around the world. The sea state code table defines a sea state 4 as 1.25 - 2.5m and a wind speed in the range 17 - 21 kn. In the Gulf of Mexico 2.5m significant wave height is exceeded for only about 20% of the time, whilst in the northern North Sea or West of Shetlands it is exceeded 50-60% of the time. In the Gulf of Mexico 21kn wind speed is exceeded for only 10% of the time whilst in the northern North Sea or West of Shetlands it is exceeded for 35% of the time.

If the presumption about the intention of the writer is correct (that he intended capsizes following a ditching to be relatively rare) then we can deduce that the writer was thinking of an area of the sea where the incidence of sea state 4 and higher was reasonably unusual (such as the Gulf of Mexico).

The major contrast here is with the BCAR document which implies that the helicopter should be able to cope with sea state 6, and also offers the possibility that more severe criteria may be appropriate in particular geographical areas. However, as has been shown in [2] none of the helicopter types considered in the BHC model tests seemed to comply with a sea state 6 requirement. On the basis of existing helicopters therefore, sea state 4 might seem to be the requirement that they can currently comply with, but it obviously carries with it a significant risk of immediate capsize following ditching in many parts of the world.

Paragraph (d) of JAR 29.801 seems to make the classic mistake of confusing buoyancy with weight when it refers to the ability of the helicopter to jettison fuel. If the helicopter and its fuel tanks remain structurally intact, then the buoyancy (ability to displace water volume) is unchanged however much fuel is on board. What does change if fuel is jettisoned is the helicopter **weight** and **centre of gravity position**. The weight will reduce and the centre of gravity position will be raised (which is quite likely to lead to a degradation of static stability).

It seems that there ought here to be instead a statement on the lines of ensuring that the helicopter is stable for the most critical weight conditions (whatever these are), and a requirement to provide guidance in the flight manual about whether fuel should be jettisoned or not. In fact the guidance document [10] does mention the most critical loading condition on page 557.

BCAR G779 does not mention rotorcraft loading conditions at all.

Wave steepness is a serious area of ambiguity in the JAR as it is in the BCAR. The latter also has mention of `individual waves' of certain steepness, which has lead to model testing in regular waves of a particular steepness, and BMT has previously indicated in [1] how results from model tests in such steep regular waves might be misleading.

The problem with the wave height / length ratios stated in the JAR is that there is no guidance on how these steepnesses are to be interpreted in the context of the sea state criteria. The reliance on a sea state implies that the model testing or analysis must be performed for irregular waves which realistically represent an ocean sea state. Unfortunately, in irregular waves it is possible to define many different wave steepnesses: Some examples are:

a) Significant height H_S: Wave length associated with the Significant Period T_S.

b) Significant height H_S: Wave length associated with the Zero Crossing Period T_Z.

c) Significant height H_S: Wave length associated with the Modal (peak energy) Period T_0.

d) Significant height H_S: Wave length associated with the Average Period T_1.

e) Maximum wave height H_{max}: Wave length associated with the maximum wave height λ_{Hmax}.

f) Significant steepness (calculated from a steepness spectrum).

Unfortunately most of these definitions give very different steepness values. For example the steepness calculated according to (b) will be about a factor of 2 different from that calculated according to (c).

It is suspected that the writer of the JAR may have had in mind something akin to (v) above, but the wavelength associated with the largest wave in an irregular sea is extremely difficult to define.

The JAR (like the BCAR) therefore leaves the impression that there is a requirement to demonstrate that the rotorcraft can survive in steep seas, but it falls short of a proper definition of what the steepness should actually be. It is likely therefore that helicopter designers and model testers will consequently revert to using regular waves, where the steepness has a clear definition (as seems to have been the case with the historic interpretation of the BCAR).

3.3 Overall Impressions

The overall impression is that the JAR places a less onerous requirement on the rotorcraft designer than does the BCAR. This is certainly the case in terms of the sea states in which acceptable flotation and trim are to be demonstrated, but also seems to be the case in some of the other more general wording.

Both BCAR and JAR are very ambiguous in their definition of wave steepness (and BCAR has further unclear wording which seems to imply that tests in regular waves are acceptable).

Helicopter model tests performed by BHC and summarised in [1] demonstrated that none of the types tested met the BCAR sea state 6 requirement, but they did meet the JAR sea state 4 requirement.

4 References

[1] CAA Contract No. 7D/S/1096 dated 16th December 1992.

[2] BMT Report 44011r12 Review of Helicopter Ditching Performance, Report 1, Release 2, 2nd July 1993.

[3] BMT Report 44011r21 Review of Helicopter Ditching Certification Requirements, Report 2, Release 1, 6th July 1993.

[4] BMT Report 44011r31 Review of Helicopter Ditching Performance - A Potential Probabilistic Methodology, Report 3, Release 1, 20th August 1993.

[5] BMT Report 44035r14 Helicopter Float Scoops, Report 1 Release 4, 30th June 1995.

[6] BMT Report 44035r23 Means to Prevent Helicopter Total Inversion Following a Ditching, Report 2, Release 3, 30th June 1995.

[7] Contract No 7D/S/1096/1, Review of Helicopter Ditching Performance, Amendment 2, 25th May 1995.

[8] Civil Aviation Authority, British Civil Airworthiness Requirements, Paper No. G779, 7th October 1985.

[9] JAR 29.801 from Joint Aviation Requirements JAR-29 Large Rotorcraft, Civil Aviation Authority (on behalf of the Joint Aviation Authorities Committee), 5th November 1993.

[10] Advisory Circular No. 29-2A, Change 2, Certification of Transport Category Rotorcraft, Federal Aviation Administration, 24th September 1991.

Annex A The JAR Documents

JAR-29 **SECTION 1**

JAR 29.785 (k) (continued)

(1) The berth or litter must have a restraint system and must not have corners or other protuberances likely to cause serious injury to a person occupying it during emergency landing conditions; and

(2) The berth or litter attachment and the occupant restraint system attachments to the structure must be designed to withstand the critical loads resulting from flight and ground load conditions and from the conditions prescribed in JAR 29.561 (b).

JAR 29.787 Cargo and baggage compartments

(a) Each cargo and baggage compartment must be designed for its placarded maximum weight of contents and for the critical load distributions at the appropriate maximum load factors corresponding to the specified flight and ground load conditions, except the emergency landing conditions of JAR 29.561.

(b) There must be means to prevent the contents of any compartment from becoming a hazard by shifting under the loads specified in sub-paragraph (a) of this paragraph.

(c) Under the emergency landing conditions of JAR 29.561, cargo and baggage compartments must-

(1) Be positioned so that if the contents break loose they are unlikely to cause injury to the occupants or restrict any of the escape facilities provided for use after an emergency landing; or

(2) Have sufficient strength to withstand the conditions specified in JAR 29.561, including the means of restraint and their attachments required by sub-paragraph (b) of this paragraph. Sufficient strength must be provided for the maximum authorised weight of cargo and baggage at the critical loading distribution.

(d) If cargo compartment lamps are installed, each lamp must be installed so as to prevent contact between lamp bulb and cargo.

JAR 29.801 Ditching

(a) If certification with ditching provisions is requested, the rotorcraft must meet the requirements of this paragraph and JAR 29.807 (d), 29.1411 and 29.1415.

JAR 29.801 (continued)

(b) Each practicable design measure, compatible with the general characteristics of the rotorcraft, must be taken to minimise the probability that in an emergency landing on water, the behaviour of the rotorcraft would cause immediate injury to the occupants or would make it impossible for them to escape.

(c) The probable behaviour of the rotorcraft in a water landing must be investigated by model tests or by comparison with rotorcraft of similar configuration for which the ditching characteristics are known. Scoops, flaps, projections, and any other factors likely to affect the hydrodynamic characteristics of the rotorcraft must be considered.

(d) It must be shown that, under reasonably probable water conditions, the flotation time and trim of the rotorcraft will allow the occupants to leave the rotorcraft and enter the life rafts required by JAR 29.1415. If compliance with this provision is shown by buoyancy and trim computations, appropriate allowances must be made for probable structural damage and leakage. If the rotorcraft has fuel tanks (with fuel jettisoning provisions) that can reasonably be expected to withstand a ditching without leakage, the jettisonable volume of fuel may be considered as buoyancy volume.

(e) Unless the effects of the collapse of external doors and windows are accounted for in the investigation of the probable behaviour of the rotorcraft in a water landing (as prescribed in sub-paragraphs (c) and (d) of this paragraph), the external doors and windows must be designed to withstand the probable maximum local pressures.

JAR 29.803 Emergency evacuation

(a) Each crew and passenger area must have means for rapid evacuation in a crash landing, with the landing gear -

(1) extended; and

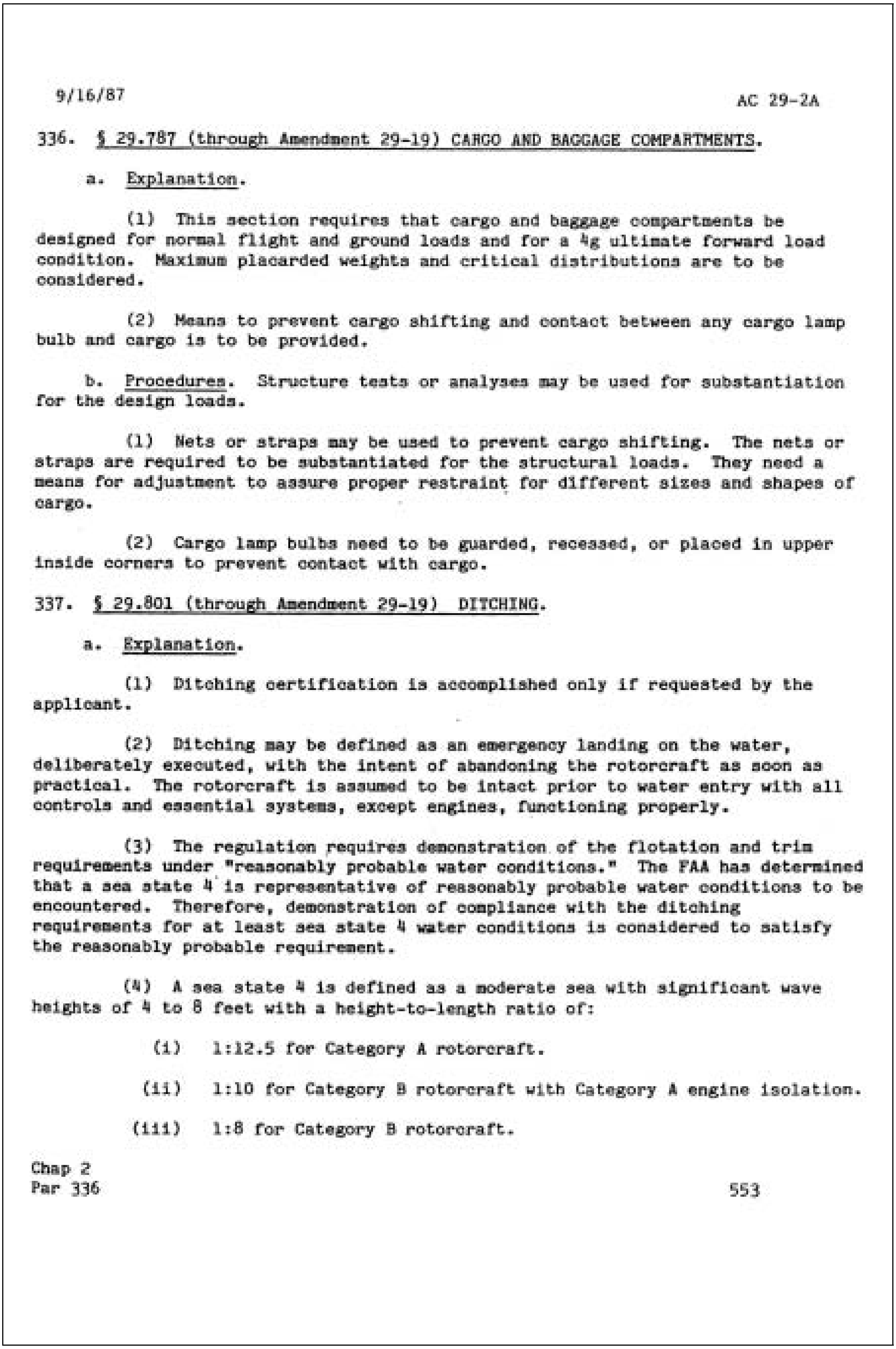
(2) retracted;

considering the possibility of fire.

(b) Passenger entrance, crew, and service doors may be considered as emergency exits if they meet the requirements of this section and of JAR 29.805 to 29.815.

(c) Reserved.

(d) Except as provided in sub-paragraph (e) of this paragraph, the following categories of rotorcraft must be tested in accordance with the requirements of Appendix D to demonstrate that the maximum seating capacity, including the crew-members required by the operating rules, can be evacuated from the rotorcraft to the ground within 90 seconds:



336. § 29.787 (through Amendment 29-19) CARGO AND BAGGAGE COMPARTMENTS.

a. Explanation.

(1) This section requires that cargo and baggage compartments be designed for normal flight and ground loads and for a 4g ultimate forward load condition. Maximum placarded weights and critical distributions are to be considered.

(2) Means to prevent cargo shifting and contact between any cargo lamp bulb and cargo is to be provided.

b. Procedures. Structure tests or analyses may be used for substantiation for the design loads.

(1) Nets or straps may be used to prevent cargo shifting. The nets or straps are required to be substantiated for the structural loads. They need a means for adjustment to assure proper restraint for different sizes and shapes of cargo.

(2) Cargo lamp bulbs need to be guarded, recessed, or placed in upper inside corners to prevent contact with cargo.

337. § 29.801 (through Amendment 29-19) DITCHING.

a. Explanation.

(1) Ditching certification is accomplished only if requested by the applicant.

(2) Ditching may be defined as an emergency landing on the water, deliberately executed, with the intent of abandoning the rotorcraft as soon as practical. The rotorcraft is assumed to be intact prior to water entry with all controls and essential systems, except engines, functioning properly.

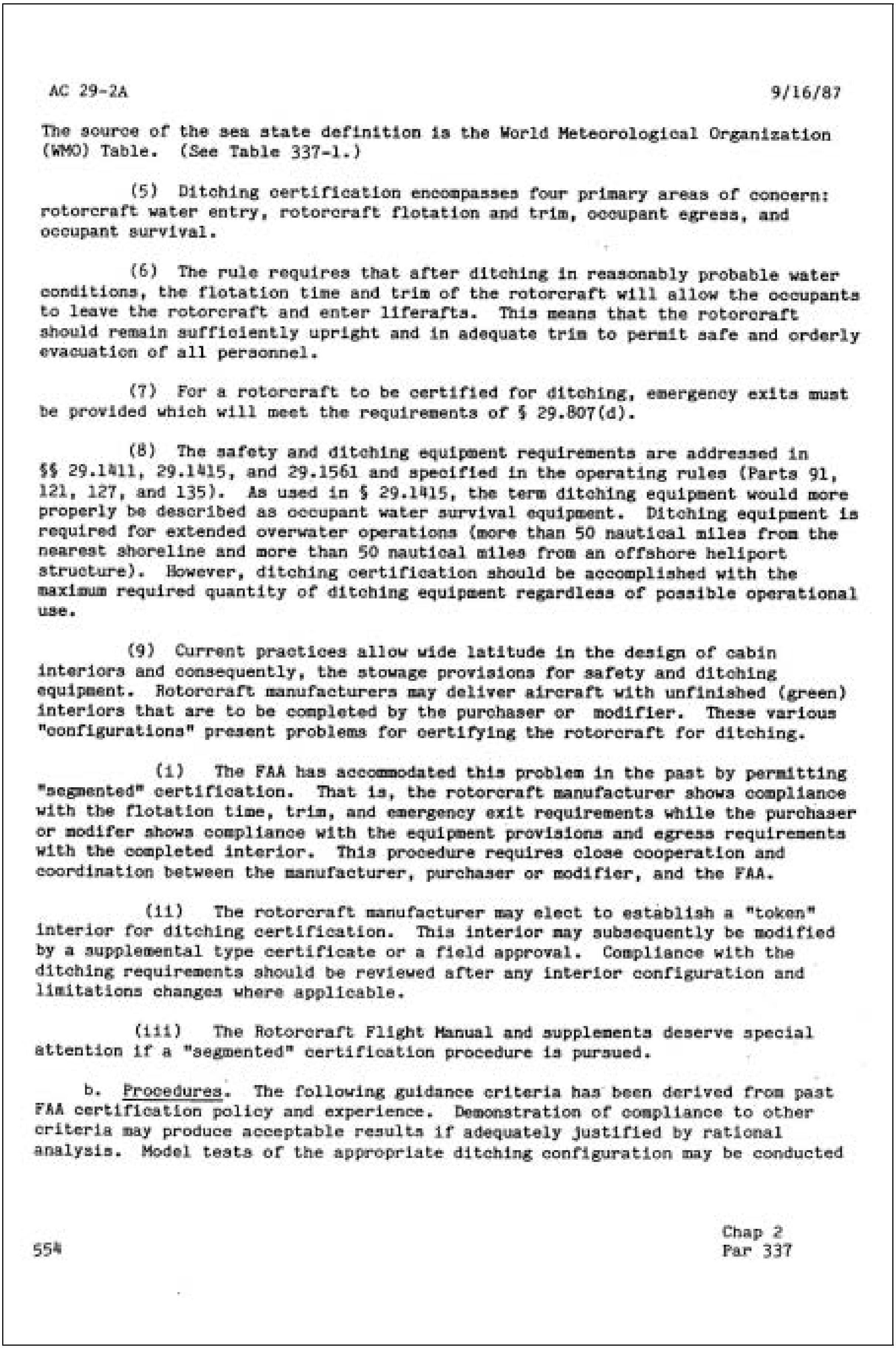
(3) The regulation requires demonstration of the flotation and trim requirements under "reasonably probable water conditions." The FAA has determined that a sea state 4 is representative of reasonably probable water conditions to be encountered. Therefore, demonstration of compliance with the ditching requirements for at least sea state 4 water conditions is considered to satisfy the reasonably probable requirement.

(4) A sea state 4 is defined as a moderate sea with significant wave heights of 4 to 8 feet with a height-to-length ratio of:

(i) 1:12.5 for Category A rotorcraft.

(ii) 1:10 for Category B rotorcraft with Category A engine isolation.

(iii) 1:8 for Category B rotorcraft.



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The source of the sea state definition is the World Meteorological Organization (WMO) Table. (See Table 337-1.)

(5) Ditching certification encompasses four primary areas of concern: rotorcraft water entry, rotorcraft flotation and trim, occupant egress, and occupant survival.

(6) The rule requires that after ditching in reasonably probable water conditions, the flotation time and trim of the rotorcraft will allow the occupants to leave the rotorcraft and enter liferafts. This means that the rotorcraft should remain sufficiently upright and in adequate trim to permit safe and orderly evacuation of all personnel.

(7) For a rotorcraft to be certified for ditching, emergency exits must be provided which will meet the requirements of § 29.807(d).

(8) The safety and ditching equipment requirements are addressed in §§ 29.1411, 29.1415, and 29.1561 and specified in the operating rules (Parts 91, 121, 127, and 135). As used in § 29.1415, the term ditching equipment would more properly be described as occupant water survival equipment. Ditching equipment is required for extended overwater operations (more than 50 nautical miles from the nearest shoreline and more than 50 nautical miles from an offshore heliport structure). However, ditching certification should be accomplished with the maximum required quantity of ditching equipment regardless of possible operational use.

(9) Current practices allow wide latitude in the design of cabin interiors and consequently, the stowage provisions for safety and ditching equipment. Rotorcraft manufacturers may deliver aircraft with unfinished (green) interiors that are to be completed by the purchaser or modifier. These various "configurations" present problems for certifying the rotorcraft for ditching.

(i) The FAA has accommodated this problem in the past by permitting "segmented" certification. That is, the rotorcraft manufacturer shows compliance with the flotation time, trim, and emergency exit requirements while the purchaser or modifer shows compliance with the equipment provisions and egress requirements with the completed interior. This procedure requires close cooperation and coordination between the manufacturer, purchaser or modifier, and the FAA.

(ii) The rotorcraft manufacturer may elect to establish a "token" interior for ditching certification. This interior may subsequently be modified by a supplemental type certificate or a field approval. Compliance with the ditching requirements should be reviewed after any interior configuration and limitations changes where applicable.

(iii) The Rotorcraft Flight Manual and supplements deserve special attention if a "segmented" certification procedure is pursued.

b. Procedures. The following guidance criteria has been derived from past FAA certification policy and experience. Demonstration of compliance to other criteria may produce acceptable results if adequately justified by rational analysis. Model tests of the appropriate ditching configuration may be conducted

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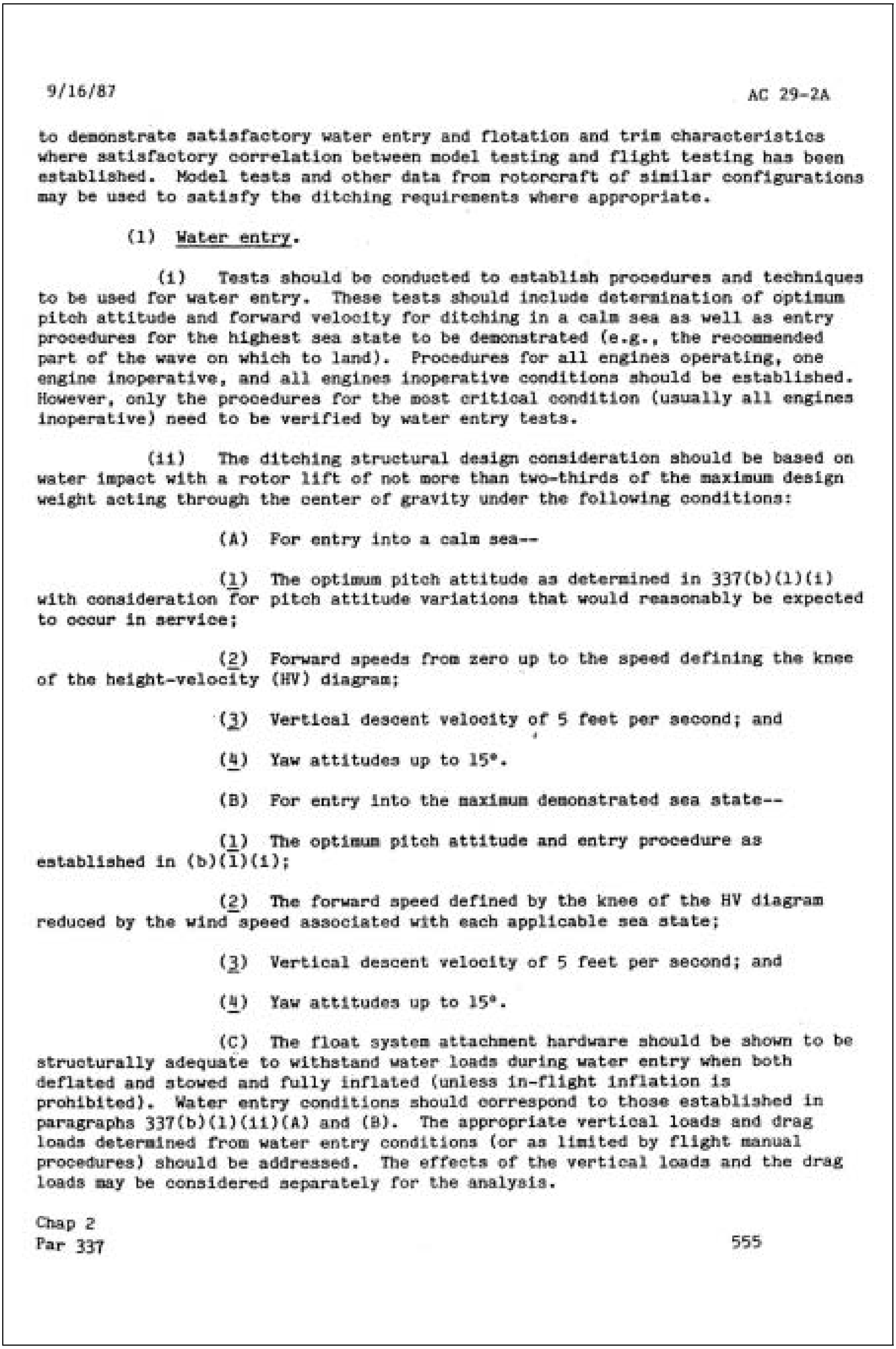
Par 337



to demonstrate satisfactory water entry and flotation and trim characteristics where satisfactory correlation between model testing and flight testing has been established. Model tests and other data from rotorcraft of similar configurations may be used to satisfy the ditching requirements where appropriate.

(1) Water entry.

(i) Tests should be conducted to establish procedures and techniques to be used for water entry. These tests should include determination of optimum pitch attitude and forward velocity for ditching in a calm sea as well as entry procedures for the highest sea state to be demonstrated (e.g., the recommended part of the wave on which to land). Procedures for all engines operating, one engine inoperative, and all engines inoperative conditions should be established. However, only the procedures for the most critical condition (usually all engines inoperative) need to be verified by water entry tests.

(ii) The ditching structural design consideration should be based on water impact with a rotor lift of not more than two-thirds of the maximum design weight acting through the center of gravity under the following conditions:

(A) For entry into a calm sea--

(1) The optimum pitch attitude as determined in 337(b)(1)(i) with consideration for pitch attitude variations that would reasonably be expected to occur in service;

(2) Forward speeds from zero up to the speed defining the knee of the height-velocity (HV) diagram;

(3) Vertical descent velocity of 5 feet per second; and

(4) Yaw attitudes up to 15°.

(B) For entry into the maximum demonstrated sea state--

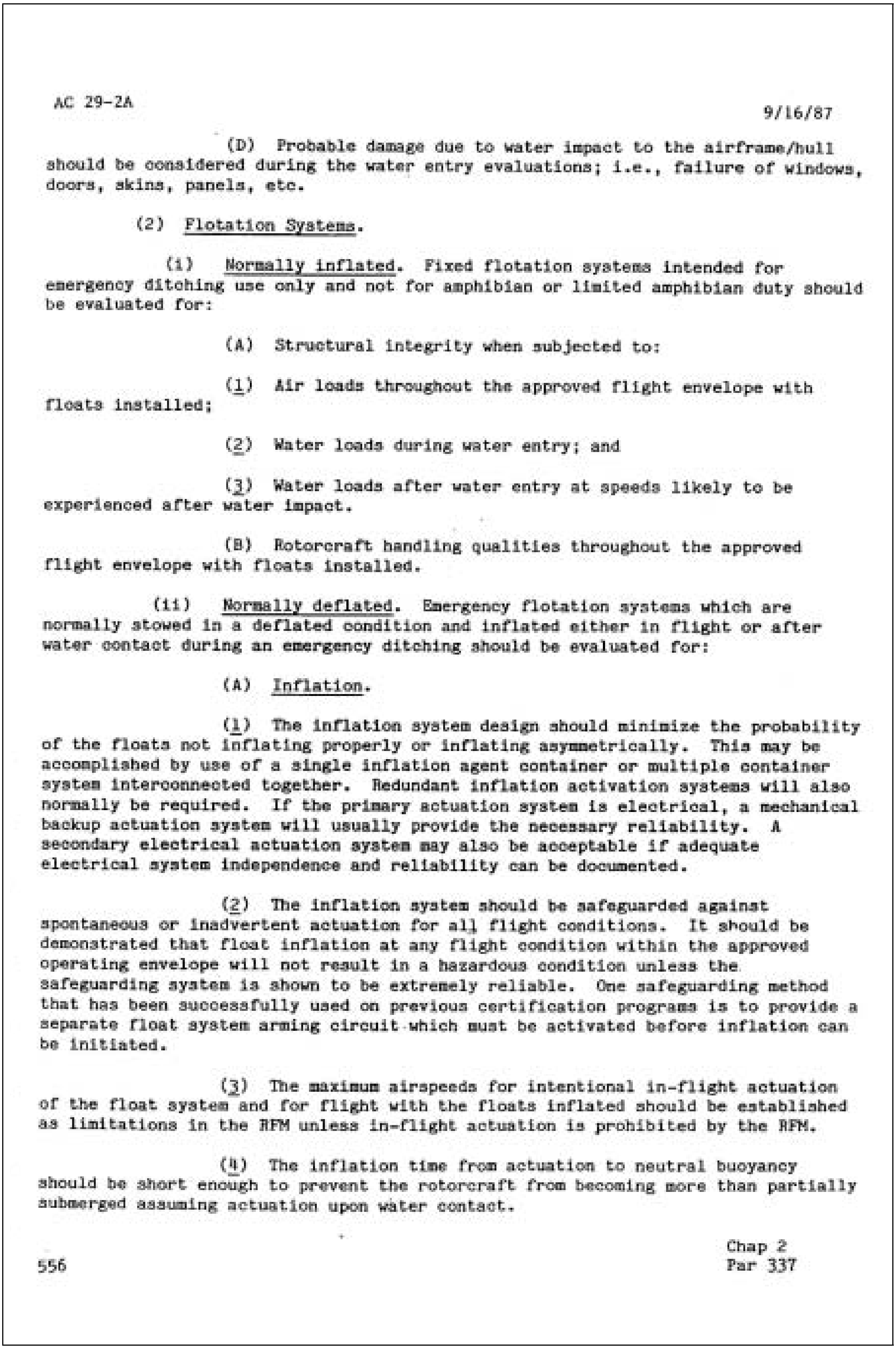
(1) The optimum pitch attitude and entry procedure as established in (b)(1)(i);

(2) The forward speed defined by the knee of the HV diagram reduced by the wind speed associated with each applicable sea state;

(3) Vertical descent velocity of 5 feet per second; and

(4) Yaw attitudes up to 15°.

(C) The float system attachment hardware should be shown to be structurally adequate to withstand water loads during water entry when both deflated and stowed and fully inflated (unless in-flight inflation is prohibited). Water entry conditions should correspond to those established in paragraphs 337(b)(1)(ii)(A) and (B). The appropriate vertical loads and drag loads determined from water entry conditions (or as limited by flight manual procedures) should be addressed. The effects of the vertical loads and the drag loads may be considered separately for the analysis.



(D) Probable damage due to water impact to the airframe/hull should be considered during the water entry evaluations; i.e., failure of windows, doors, skins, panels, etc.

(2) Flotation Systems.

(i) Normally inflated. Fixed flotation systems intended for emergency ditching use only and not for amphibian or limited amphibian duty should be evaluated for:

(A) Structural integrity when subjected to:

(1) Air loads throughout the approved flight envelope with floats installed;

(2) Water loads during water entry; and

(3) Water loads after water entry at speeds likely to be experienced after water impact.

(B) Rotorcraft handling qualities throughout the approved flight envelope with floats installed.

(ii) Normally deflated. Emergency flotation systems which are normally stowed in a deflated condition and inflated either in flight or after water contact during an emergency ditching should be evaluated for:

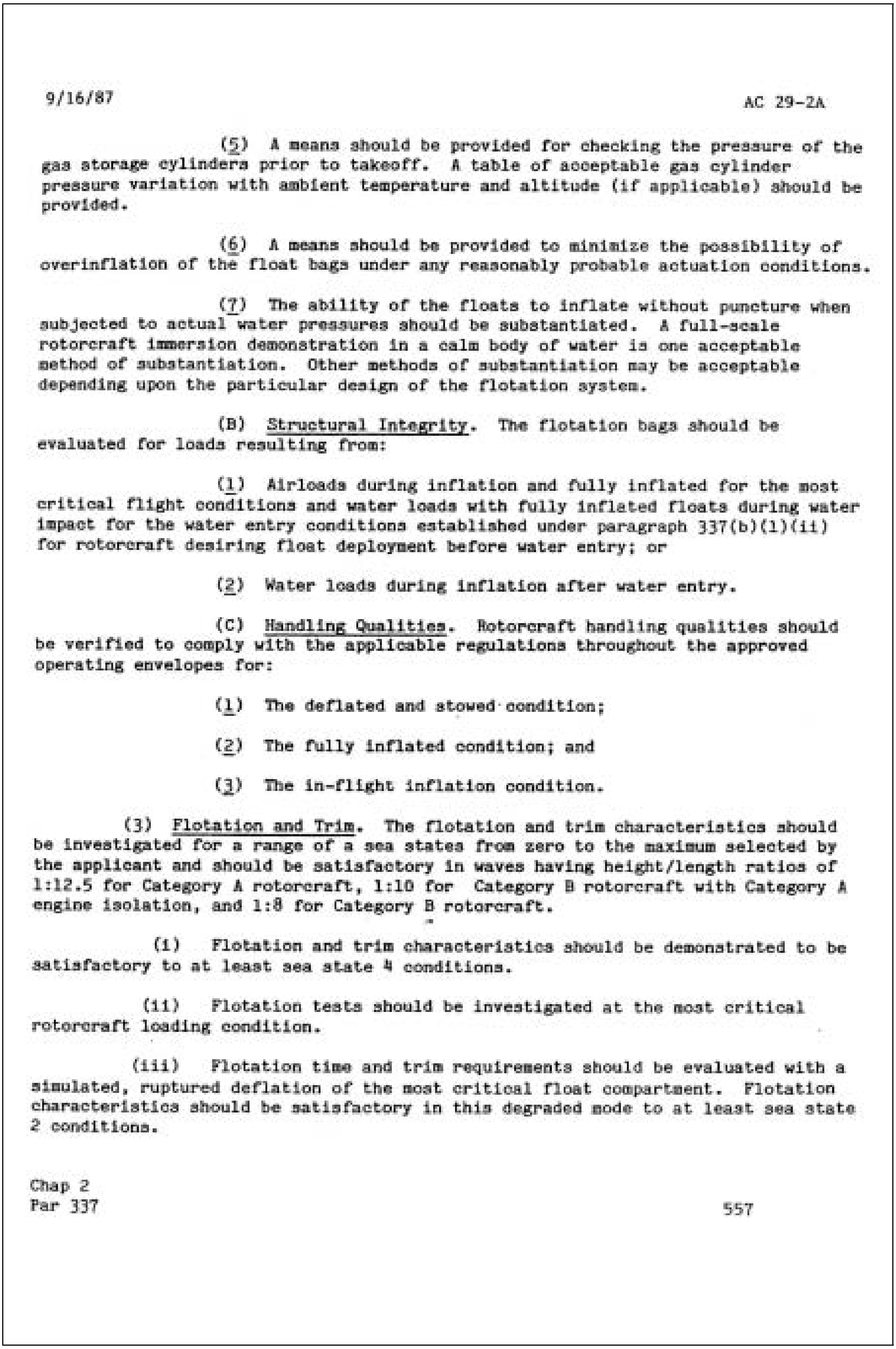
(A) Inflation.

(1) The inflation system design should minimize the probability of the floats not inflating properly or inflating asymmetrically. This may be accomplished by use of a single inflation agent container or multiple container system interconnected together. Redundant inflation activation systems will also normally be required. If the primary actuation system is electrical, a mechanical backup actuation system will usually provide the necessary reliability. A secondary electrical actuation system may also be acceptable if adequate electrical system independence and reliability can be documented.

(2) The inflation system should be safeguarded against spontaneous or inadvertent actuation for all flight conditions. It should be demonstrated that float inflation at any flight condition within the approved operating envelope will not result in a hazardous condition unless the safeguarding system is shown to be extremely reliable. One safeguarding method that has been successfully used on previous certification programs is to provide a separate float system arming circuit which must be activated before inflation can be initiated.

(3) The maximum airspeeds for intentional in-flight actuation of the float system and for flight with the floats inflated should be established as limitations in the RFM unless in-flight actuation is prohibited by the RFM.

(4) The inflation time from actuation to neutral buoyancy should be short enough to prevent the rotorcraft from becoming more than partially submerged assuming actuation upon water contact.



(5) A means should be provided for checking the pressure of the gas storage cylinders prior to takeoff. A table of acceptable gas cylinder pressure variation with ambient temperature and altitude (if applicable) should be provided.

(6) A means should be provided to minimize the possibility of overinflation of the float bags under any reasonably probable actuation conditions.

(7) The ability of the floats to inflate without puncture when subjected to actual water pressures should be substantiated. A full-scale rotorcraft immersion demonstration in a calm body of water is one acceptable method of substantiation. Other methods of substantiation may be acceptable depending upon the particular design of the flotation system.

(B) Structural Integrity. The flotation bags should be evaluated for loads resulting from:

(1) Airloads during inflation and fully inflated for the most critical flight conditions and water loads with fully inflated floats during water impact for the water entry conditions established under paragraph 337(b)(1)(ii) for rotorcraft desiring float deployment before water entry; or

(2) Water loads during inflation after water entry.

(C) Handling Qualities. Rotorcraft handling qualities should be verified to comply with the applicable regulations throughout the approved operating envelopes for:

(1) The deflated and stowed condition;

(2) The fully inflated condition; and

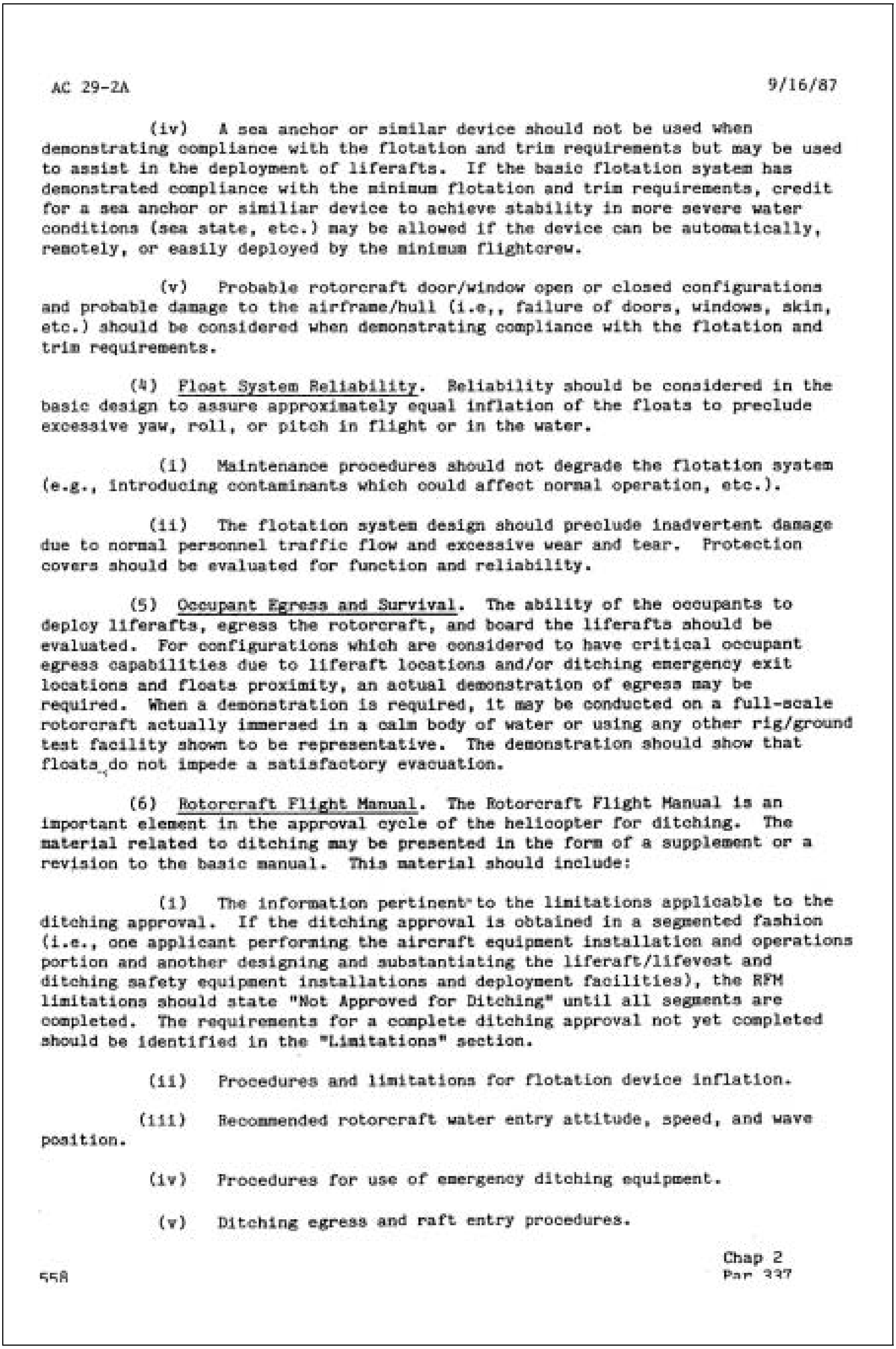
(3) The in-flight inflation condition.

(3) Flotation and Trim. The flotation and trim characteristics should be investigated for a range of a sea states from zero to the maximum selected by the applicant and should be satisfactory in waves having height/length ratios of 1:12.5 for Category A rotorcraft, 1:10 for Category B rotorcraft with Category A engine isolation, and 1:8 for Category B rotorcraft.

(i) Flotation and trim characteristics should be demonstrated to be satisfactory to at least sea state 4 conditions.

(ii) Flotation tests should be investigated at the most critical rotorcraft loading condition.

(iii) Flotation time and trim requirements should be evaluated with a simulated, ruptured deflation of the most critical float compartment. Flotation characteristics should be satisfactory in this degraded mode to at least sea state 2 conditions.



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(iv) A sea anchor or similar device should not be used when demonstrating compliance with the flotation and trim requirements but may be used to assist in the deployment of liferafts. If the basic flotation system has demonstrated compliance with the minimum flotation and trim requirements, credit for a sea anchor or similiar device to achieve stability in more severe water conditions (sea state, etc.) may be allowed if the device can be automatically, remotely, or easily deployed by the minimum flightcrew.

(v) Probable rotorcraft door/window open or closed configurations and probable damage to the airframe/hull (i.e,, failure of doors, windows, skin, etc.) should be considered when demonstrating compliance with the flotation and trim requirements.

(4) Float System Reliability. Reliability should be considered in the basic design to assure approximately equal inflation of the floats to preclude excessive yaw, roll, or pitch in flight or in the water.

(i) Maintenance procedures should not degrade the flotation system (e.g., introducing contaminants which could affect normal operation, etc.).

(ii) The flotation system design should preclude inadvertent damage due to normal personnel traffic flow and excessive wear and tear. Protection covers should be evaluated for function and reliability.

(5) Occupant Egress and Survival. The ability of the occupants to deploy liferafts, egress the rotorcraft, and board the liferafts should be evaluated. For configurations which are considered to have critical occupant egress capabilities due to liferaft locations and/or ditching emergency exit locations and floats proximity, an actual demonstration of egress may be required. When a demonstration is required, it may be conducted on a full-scale rotorcraft actually immersed in a calm body of water or using any other rig/ground test facility shown to be representative. The demonstration should show that floats do not impede a satisfactory evacuation.

(6) Rotorcraft Flight Manual. The Rotorcraft Flight Manual is an important element in the approval cycle of the helicopter for ditching. The material related to ditching may be presented in the form of a supplement or a revision to the basic manual. This material should include:

(i) The information pertinent to the limitations applicable to the ditching approval. If the ditching approval is obtained in a segmented fashion (i.e., one applicant performing the aircraft equipment installation and operations portion and another designing and substantiating the liferaft/lifevest and ditching safety equipment installations and deployment facilities), the RFM limitations should state "Not Approved for Ditching" until all segments are completed. The requirements for a complete ditching approval not yet completed should be identified in the "Limitations" section.

(ii) Procedures and limitations for flotation device inflation.

(iii) Recommended rotorcraft water entry attitude, speed, and wave position.

(iv) Procedures for use of emergency ditching equipment.

(v) Ditching egress and raft entry procedures.

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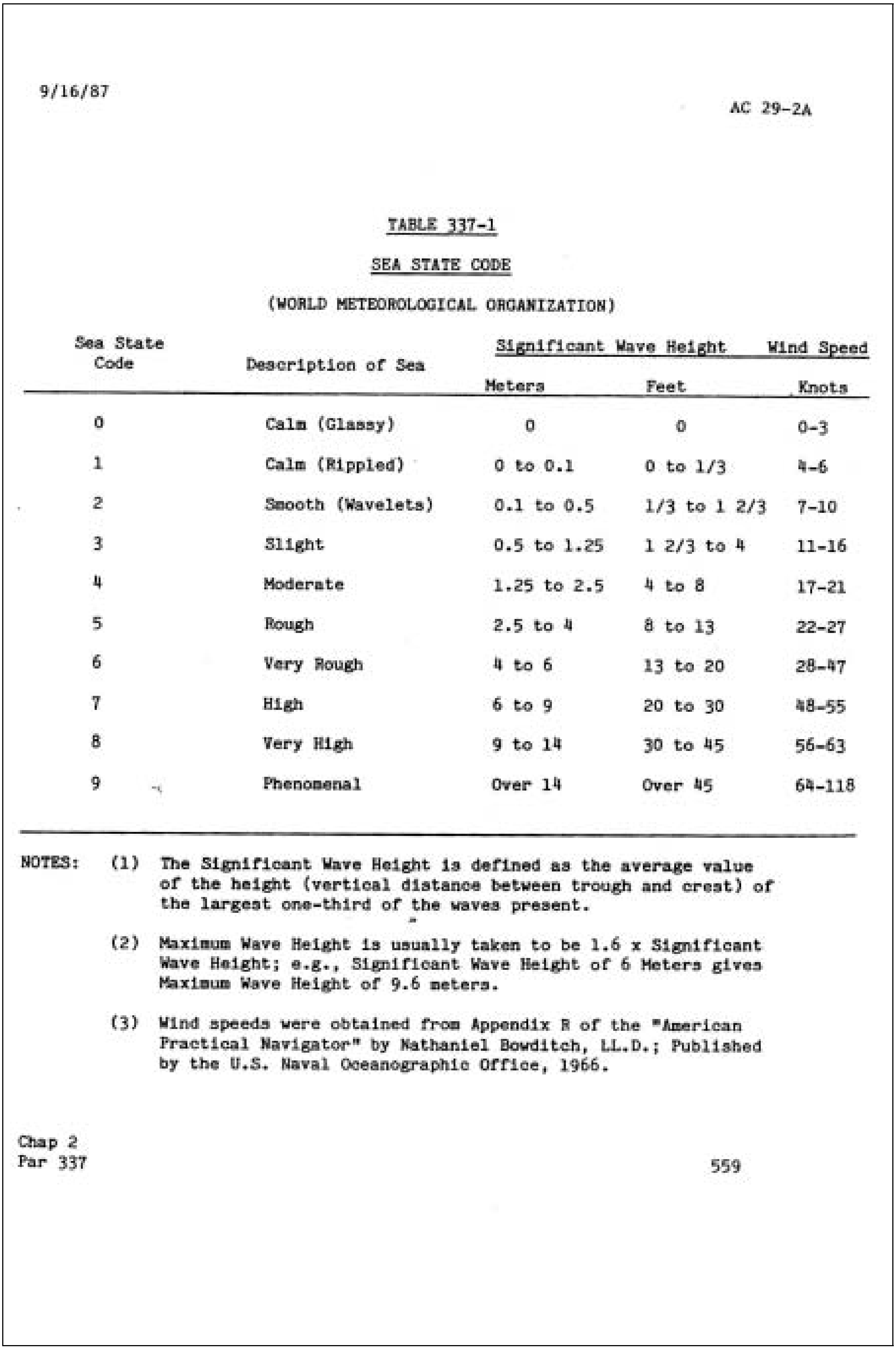

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TABLE 337-1

SEA STATE CODE

(WORLD METEOROLOGICAL ORGANIZATION)

Sea State Code	Description of Sea	Significant Wave Height		Wind Speed
		Meters	Feet	Knots
0	Calm (Glassy)	0	0	0-3
1	Calm (Rippled)	0 to 0.1	0 to 1/3	4-6
2	Smooth (Wavelets)	0.1 to 0.5	1/3 to 1 2/3	7-10
3	Slight	0.5 to 1.25	1 2/3 to 4	11-16
4	Moderate	1.25 to 2.5	4 to 8	17-21
5	Rough	2.5 to 4	8 to 13	22-27
6	Very Rough	4 to 6	13 to 20	28-47
7	High	6 to 9	20 to 30	48-55
8	Very High	9 to 14	30 to 45	56-63
9	Phenomenal	Over 14	Over 45	64-118

NOTES:

(1) The Significant Wave Height is defined as the average value of the height (vertical distance between trough and crest) of the largest one-third of the waves present.

(2) Maximum Wave Height is usually taken to be 1.6 x Significant Wave Height; e.g., Significant Wave Height of 6 Meters gives Maximum Wave Height of 9.6 meters.

(3) Wind speeds were obtained from Appendix R of the "American Practical Navigator" by Nathaniel Bowditch, LL.D.; Published by the U.S. Naval Oceanographic Office, 1966.

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Appendix C Review of Helicopter Ditching: A Potential Probabilistic Methodology

Executive Summary

BMT Offshore Ltd. was asked by the Civil Aviation Authority to perform a review of helicopter ditching performance and current certification requirements.

An earlier report [6] considered and discussed the existing information on the factors influencing the on-water stability of current helicopter types. A second report [7] considered the current certification requirements. This third report summarises the findings of the first two, and then investigates a possible probabilistic approach to this aspect of helicopter certification.

It has been shown that the mechanisms behind helicopter capsize are very complex, and are not well understood. The results of many model tests on different types have not resulted in much physical understanding of the controlling phenomena, but have demonstrated that certain measures (e.g. float scoops) can increase resistance to capsize. It is believed that physical understanding of the processes requires further theoretical simulation work backed up by appropriate good quality experimental validation.

It has been shown that the current CAA helicopter certification requirements regarding ditching appear to be deficient in a number of respects, most notably in the way in which limiting wave conditions are defined. It has been proposed that these could be improved, in particular by requiring capsize performance to be demonstrated in irregular waves which, whilst presenting some significant model testing difficulties, offer a much more realistic approach than using regular waves, which can potentially give a quite misleading impression.

A simple analysis of civil and military helicopter ditching occurrences has indicated that the risk to the individual offshore worker of suffering a fatality due to helicopter capsize following a controlled ditching is probably less than 3×10^{-5} per year (or about once every 30,000 man years).

Finally, a move away from a prescriptive wave condition requirement has been suggested. This would instead set 'risk of capsize' targets that the designer would be required to demonstrate are achieved by the helicopter in a defined 'operating area'.

1 Introduction

BMT Offshore Ltd. (BMT) was asked [1][1] by the Civil Aviation Authority (CAA) to propose a review of helicopter ditching performance. BMT responded with a proposal [2], and based on this proposal, CAA put in place a contract for the work to be performed [3].

The review was to look critically at the various research reports and review documents that CAA had commissioned in recent years, and to summarise and comment on their findings.

1.1 Objectives

The objectives of the overall study were stated to be [2] as follows:

a) Perform a critical review of a number of documents with the objective of drawing conclusions from this work and prepare an overview document (or documents) suitable for publication by CAA.

b) Perform a critical review of the current UK Emergency Alighting on Water helicopter design requirements as specified by BCAR Paper No G779 dated 7th October 1985 [4], and where appropriate make recommendations on how these requirements might be improved, and whether there are better ways of assessing a helicopter's water-borne stability.

c) Based on the results of (a) and (b) above, and the results of a separate study [5], review North Sea helicopter ditching performance over the past 20 years and assess the practicality of imposing a new probability-based methodology for North Sea helicopter operations, taking account of specific type's ditching rates, capsize probability and operating environment.

Task (a) above was reported in [6], and task (b) in [7]. This third report briefly summarises the findings of [6] and [7] and then deals with the results of task (c) above.

1.2 Background

The stated objective in the certification of a helicopter in relation to ditching in the sea is that the helicopter should remain upright for sufficient time for the occupants to escape (at least 5 minutes). This implies that there should be an acceptably low probability of meeting a wave large enough to capsize the helicopter in this short period of time.

The probability of experiencing a capsize is dependent on two key factors:

a) The height and period or slope of wave required to capsize the helicopter, and

b) the probability of experiencing such a wave, or larger, during the exposure period.

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[1] References are to be found in Section 7 on Page 14.

2 Conclusions and Recommendations

2.1 Current Understanding of Helicopter Capsize

BMT has conducted an extensive review of current understanding of helicopter resistance to capsize following ditching. This review, which is reported fully in Ref [6], concentrated on research reports commissioned by CAA over recent years, but also considered other relevant data in the public domain. The main conclusions from this review were as follows:

2.1.1 That the helicopter types studied all had little difficulty in complying with the regular wave steepness certification requirements, but all capsized in irregular wave conditions less severe than the BCAR limit of sea-state 6.

2.1.2 That only very weak correlations were seen between helicopter resistance to capsize and the physical parameters (e.g. roll inertia) expected to influence it.

2.1.3 That model tests of the type used to generate the data are extremely difficult to perform in an accurate and repeatable way, and that this may explain some of the difficulty experienced in correlating the results.

2.1.4 That ideally such model tests should provide a quantitative measure of the probability of capsize in a given duration of exposure to the sea-state.

2.1.5 That model tests in the presence of wind (where most helicopters have a stronger tendency to weathervane) demonstrate a greater resistance to capsize thus indicating that any device (e.g. a sea anchor) that maintains a heading into the waves will assist in preventing capsize.

2.1.6 That helicopter capsize is generally only caused by breaking waves.

2.1.7 That float scoops appear to give a significant benefit in reducing the helicopter's tendency to capsize.

2.1.8 That raising floats (the so-called 'wet floor' technique) requires much further investigation before it can be said to offer any advantage.

2.1.9 That previous theoretical analysis of helicopter motions (intended primarily to derive float scoop loads) was seriously flawed, but that further correctly framed computer simulations could be a useful basis on which to build future work.

2.1.10 That an initial analysis of helicopter capsize incidents suggests that about 30% capsize, which contrasts with the IOS theoretical estimate of 5% and the CAA objective of 1%.

The main recommendations resulting from the review were:

2.1.11 That future certification model tests on helicopters should be performed in irregular waves, and that consideration should be given to the development of a model testing standard.

2.1.12 That means should be sought to reduce the risk of capsize following ditching, as it seems to be significantly higher than CAA stated objectives.

2.1.13 That better understanding of helicopter behaviour in steep and breaking waves could be obtained from the development of a computer simulation, and that this simulation could be initially validated against carefully controlled model tests.

2.1.14 That the concept of float scoops should be developed further because they appear to offer a significant benefit in resistance to capsize.

2.1.15 That the 'wet-floor' technique requires further study before it can be considered as a potential means of improving resistance to capsize.

2.1.16 That further consideration should be given to measures (such as cowling floats) that prevent a permanent inverted attitude following an initial capsize.

2.1.17 That the probabilistic capsize work should be extended to cope with varying probability of capsize with wave height, and the methods then used in conjunction with the more reliable long term North Sea wave data sets to derive probabilities of capsize.

2.2 Current Helicopter Ditching Certification Requirements

BMT has reviewed the current certification requirements with regard to emergency alighting on water as defined in BCAR Paper G779 (1985) [4] and reported its findings in Ref [7]. The main conclusions of the study were as follows:

2.2.1 That the current helicopter certification requirements in respect of ditching and afloat stability are ambiguous and incomplete in some respects.

2.2.2 That the ambiguity lies mainly in terms of the definition of the waves in which a stable floating attitude must be demonstrated, whether more severe conditions should be selected in some circumstances, whether the helicopter should be considered to have sustained any damage, and in the results required from model tests intended to demonstrate compliance.

2.2.3 That historical interpretation of these requirements seems to have concentrated on the regular wave steepness requirements (none of the helicopters types examined seemed to comply with the irregular wave requirements).

Consequently, the main recommendations were:

2.2.4 That the certification requirements should be amended to remove the ambiguities.

2.2.5 That there was a choice in terms of how this amendment should be made. One approach would be to keep the existing structure of the requirement, but to define the wave conditions in which stability was to be demonstrated more rigorously. An alternative approach would be to leave the selection of sea-states to the designer and require him to demonstrate an adequately low risk of capsize in the intended operational area.

2.2.6 That model tests in regular waves against a specific steepness criterion should be discouraged as, owing to the fact that capsize only normally occurs in breaking waves, the results are likely to depend more on the wave basin properties than the helicopter properties.

2.3 Practicality of Imposing a New Probability-Based Methodology

The current helicopter ditching certification requirements have been contrasted with a probabilistic or risk-based method having some similarities with the current 'safety case' approach being adopted in the certification of offshore installations. The main conclusions of this part of the study are:

2.3.1 That the current individual risk experienced by a typical offshore worker associated with being killed as a result of a helicopter capsize following a controlled ditching is probably less than 3×10^{-5} per year (or about once every 30,000 man years).

2.3.2 That a probabilistic or risk-based certification approach would make the certification dependent on the intended area of operation of the helicopter, and would therefore give due design benefit to those helicopters which were only intended to operate in benign areas.

2.3.3 That it would also set the certification requirements in context with other CAA safety or risk level objectives.

2.3.4 That the ease with which such a new certification approach could be implemented depends on the extent to which CAA already has, or could develop, appropriate risk targets.

Consequently the main recommendations are:

2.3.5 CAA should review internal safety and risk criteria and consider how these can form the basis of certification for ditching.

2.3.6 CAA should consider the implications of following such a policy on other wider aspects of aircraft certification.

2.3.7 That it may be appropriate to perform a detailed risk analysis of helicopter incidents in order to set the overall safety and risk targets into context, and to permit apportionment of risk target components to specific incidents such as ditching.

2.3.8 Providing such targets can be arrived at, there should be comparatively little difficulty in modifying the ditching certification requirements to place the onus on the designer to demonstrate that target capsize risk levels have been achieved in the helicopter operating area.

3 Helicopter Ditching Performance - Current Understanding

BMT conducted a review [6] of current understanding of helicopter ditching. This review studied a number of theoretical and experimental research reports commissioned by the CAA in recent years, and also performed a literature search of available information in the public domain. The study was confined to consider helicopters that are floating upright and intact, having alighted on the water in a reasonably controlled manner.

The study carefully re-analysed and re-presented the results of numerous model tests made on a number of different helicopter types, floating in various conditions and with various novel configurations including; raised floats ('wet floor'), with added float scoops, and in one case with engine cowl floats.

One of the objectives of this analysis was to try to identify what the main controlling physical influences are on helicopter capsize in waves, and to this end, attempts were made to correlate the data with various non-dimensional helicopter parameters in order to discern trends that followed across all types. The results of this analysis were quite disappointing with hardly any trends being seen with the physical helicopter dimensions or static stability parameters. There were also considerable difference between results obtained in regular waves and irregular waves.

It was noted that the capsize of an intact helicopter only occurred in breaking waves, and consideration of the physical processes involved in riding a breaking wave indicated that the following should be important in resisting capsize:

- high roll inertia;
- large range of static stability;
- large range of peak righting moment;.
- low lateral resistance to movement through the water;
- low above water profile.

There was some evidence in the results of the model tests to confirm the influence of the first three factors, but this evidence was not strong.

It was noted that free floating model tests in waves are very difficult to conduct in an accurate and repeatable way. There are particular difficulties associated with wave generation, with keeping the model in a zone where the wave quality is satisfactory, and in performing long enough runs. These difficulties were almost certainly a factor in the inability to demonstrate clear trends between model tests on different helicopter types.

The ideal output from a model test on a helicopter in waves would be a quantitative measure of the probability of capsize in a given period of exposure to a given sea-state. This can only be derived from many repetitions of relatively long runs in realistic irregular waves.

Unfortunately most model testing for certification purposes seems to have been performed in regular waves. The certification criterion in regular waves is simply framed in terms of a wave steepness, and if capsize is mainly caused by breaking waves, there is a real risk that pass or failure of the certification criterion is more a function of the model scale and tank wave quality than it is a function of the helicopter design.

However, an important message from the model test results was the benefit that float scoops can provide in raising the capsize boundary to higher sea-states. In almost all helicopter types tested and all weight conditions the floats provided a significant benefit. It was not clear, however, whether this benefit was coming primarily from the effect the scoops have on static stability or from dynamic (damping and inertia) effects.

Work on the development of float scoops seems to have been halted in recent times, possibly due to difficulties in predicting the increased forces on the floats. This does not seem to be an insurmountable problem, although some of the previous theoretical analysis work studied on the subject was flawed. The work should be continued, and particular attention should be given to the relative importance of static and dynamic factors in case this can lead to significant scoop design improvements.

Model tests on helicopters with raised floats (the so-called 'wet floor' approach) have provided a very mixed performance, with significant improvements to resistance to capsize in some conditions and significant degradation in others. It seems that the new raised float locations must be chosen very carefully in order to obtain any beneficial effect.

Other theoretical work [11] has combined wave analysis and measured wave data to present estimates of probabilities of experiencing a breaking wave over a certain height and probability of capsize within a given period of exposure (in this case 10 minutes). The methods used seem to be sound, although the results suggest probabilities of capsize that are lower than suggested by historical data. Any discrepancy could be due to the choice of breaking wave height for the capsize criterion which unfortunately is not substantiated by any of the other research reports.

Helicopters have a very high centre of gravity when floating on the water (due to the substantial weight of engines and gearbox located on the top of the fuselage) and, in view of the comparatively high risk of capsize of helicopters that are unlucky enough to ditch in relatively severe sea-states, it is surprising that more consideration has not been given to measures that will prevent a helicopter from overturning into a completely inverted position. One model test was conducted with floats added at the engine cowling level in order to try and ensure that the helicopter found a more stable location on its side. This was not wholly successful, as the helicopter involved performed a 270° roll before finding this stable position. In addition, later reports seem to have given the wrong impression that the helicopter then continued to roll over in the waves, and this seems to have contributed to the shelving of any further development of this interesting idea. Investigation of devices of this type should be pursued further.

4 Current Certification Requirements

BMT conducted a review [7] of current CAA helicopter ditching certification requirements. The current requirements have their origin in Chapter G410 of the British Civil Airworthiness Requirements issued in January 1976, which were amended by Paper BCAR G779 in October 1985. [1]

The main provisions of the requirements are as follows:

> Section 2 requires that the craft should **remain afloat for the time required for everybody to escape**, and further indicates that this time should **not be less than 5 minutes in severe seas**. (Note that `severe seas' are not defined here, but from later sections we may assume that their definition is to be found in G4-10 Appendix which implies that a severe sea is therefore sea-state 6). This section also mentions that **allowance for damage to the helicopter should be made**, although the nature or extent of this damage is not defined in any way.
>
> Section 4 requires that satisfactory flotation and trim characteristics shall be **demonstrated by investigation** and **model tests conducted** so that the results would be valid in the declared conditions. (Note that the conduct of a model test is compulsory.)
>
> Section 5.2 defines the declared conditions as **those in which compliance with the requirements have been demonstrated**, and that if these are less than the conditions given in the Appendix (i.e. sea-states 0-6), then these **limitations shall be included in the flight manual**. Furthermore it indicates that in particular geographical areas **more severe criteria will be applicable**.

The main potential ambiguity in G779 lies in the definition of the sea-state conditions in the G410 Appendix. Whilst 1.2(a) makes it clear that the compliance must be investigated in sea-states 0 - 6, the second part 1.2(b) says that it should be in **individual waves** with height/length ratios with given requirements in all sea-states of (a). It is not at all clear what is required here. If the requirement were just 1.2(a), then we would understand that we must test in the range of sea-states listed 0 to 6. There might be some question about how we were to choose the spectrum shape (or the steepness of the irregular sea-state) but otherwise the meaning would be clear. The addition of 1.2(b) which refers to individual waves of particular steepness, and links these in some way to the irregular sea-states is, however, confusing.

It could potentially mean:

a) You must test in regular waves of this steepness, and choose the height of these regular waves to be consistent with the heights of the irregular sea-states.

b) You must test in irregular waves and ensure that your irregular waves include individual waves of the steepnesses stated (i.e. an implied constraint on the spectrum shape and wave time series).

---

[1] **Note added in 2005:** This report was written in 1993, at a time when all helicopters operating in the UK North Sea were certificated according to BCAR. BCAR ditching certification requirements have since been superseded by JAR/FAR requirements 27 and 29.801. JAR requirement 29.801 was reviewed and compared with BCAR G779 in a follow-up BMT report 44035r32 dated November 1995. Both sets of requirements were found to suffer from similar ambiguities.

c) You must do both (a) and (b).

d) You may test in irregular waves and ignore any capsizes which might occur caused by individual waves steeper than the given values.

Further interpretations are possible.

It would seem to be a prime requirement that one should consider realistic sea conditions in which to determine the limiting conditions in which capsize occurs. This implies that such tests should be performed in irregular waves characteristic of the spectrum shapes and mean periods anticipated in the area of operation.

The key issue is the probability that the helicopter will be capsized in a given period of time (5 minutes) in any given limiting sea-state, and the probability of meeting such a limiting sea-state (or worse) in a random ditching incident in the area of operation. The latter component is not really addressed in the BCAR G779 at all, except to the extent of stating that more severe criteria **will be applicable in certain areas**.

From the above we might deduce:

- Model testing should be in irregular waves.
- The wave spectra used should be typical of the operational area.
- The objectives of the model test should be to demonstrate an adequately low probability of capsize in a 5 minute period of exposure.
- A wave climate analysis for the operational area should be performed to demonstrate that the overall risk of capsize in a randomly occurring ditching event is adequately low.

It is worth considering in more detail here the consequences of model testing helicopters in steep regular waves, if the capsize of the helicopter is only likely to occur in breaking waves [6]. Theoretically regular waves break at a steepness (wave height / wavelength) $H/\lambda \approx 1/7$. However, in practice in model basins waves often break at lower steepnesses. Indeed it is not uncommon for breaking to be seen at the face of the wavemaker for steepness greater than 1/10. Other factors that influence breaking in a model basin include; the purity of the original wavemaker motion, the distance travelled by the waves along the model basin, the height of the waves and the presence of other spurious waves in the basin. If the helicopter certification requirement is to remain upright in a regular wave of a given steepness, and helicopter capsize is only caused by breaking regular waves, then a model basin which can produce the **steepest non-breaking waves** will be able to demonstrate the best wave steepness performance for each helicopter type. In other words, this regular wave steepness criterion is perhaps more a test of the wave quality in the basin than it is a measure of the helicopter resistance to capsize.

It is possible to draw some tentative conclusions about historical interpretation of the certification requirements from the model test results contained in the BHC research model test reports for the CAA.

These indicate that all the helicopter types tested had little difficulty in complying with the wave steepness requirements of BCAR G779, but none remain stable in irregular waves of sea-state 6 (many capsized in sea-state 4 and the remainder capsized in sea-state 5).

Furthermore it is understood that no currently certified helicopters contain any stated limitations in their flight manuals.

From the above it can be deduced that the regular wave steepness criterion is being applied in isolation, and the results of any irregular sea-state tests ignored.

5 A Probabilistic Methodology

5.1 General Considerations

The motivation behind aircraft certification requirements is obviously primarily to ensure that all aircraft achieve a certain minimum standard of safety. This is true of the requirements pertaining to helicopters following ditching. The requirements are intended to ensure that, following an initial failure which has led to the necessity to land the helicopter on the surface of the sea, the helicopter remains in a reasonably safe condition so that the occupants have the opportunity to escape to life-rafts to await rescue.

It is generally acknowledged that it is not possible or practical to achieve perfect safety in all circumstances. Consequently the degree of safety that has been achieved in any given situation is normally measured in terms of the probability or 'risk' that an undesirable event will occur, and in terms of the seriousness of the consequences of this event if it does occur. In the context of risk, the concept of risk being **As Low as Reasonably Practical (ALARP)** is often quoted as an objective.

These concepts have been used increasingly in recent years to drive safety in a number of industries where failures can potentially lead to serious life-threatening or asset-threatening situations. In the current context of offshore helicopter operations, it is particularly relevant that the UK offshore regulatory environment was changed dramatically as a result of the Piper Alpha disaster of July 1988, and the recommendations of the Enquiry conducted by Lord Cullen. Lord Cullen's report [8] recommended a significant change in the regulatory environment, moving away from the prescriptive rule-based design and operation of offshore structures, and towards a 'safety-case' based approach which had been successfully pioneered in the nuclear and chemical industries.

The safety case approach considers safety at all stages during the design and operation of an offshore installation. It places the onus on the operator to ensure that appropriate studies are performed at the concept and detailed design stage to consider the various implications of failure (of equipment or of operating personnel) and the consequences to the installation and those on board. Where the risks of such failure are unacceptably high, or where the consequences of such failure are unacceptably serious, the operator must take steps that preferably remove or reduce the risk at source, or alternatively ameliorate the consequences. The safety case approach places great importance in the development of a Safety Management System (SMS) which is used to ensure that the installation is always operated in a safe manner, and that unsafe incidents are reported and actions taken to ensure that they are not repeated. Thus the regime effectively integrates issues of design and day-to-day operation.

There are no absolutes in terms of safety, and the Health and Safety Executive (responsible for offshore safety as a result of another recommendation of the Cullen Report) have not, for example, specified numeric levels of individual risk that must be demonstrated for an installation to be termed 'safe'. The ALARP concept implies that there is a continuous striving for practical means to reduce risk to lower levels. However, it is often considered that an 'unacceptable risk' for an individual to be exposed to in the course of his normal employment is a total probability of suffering a fatality as a direct result of his job of more than 1×10^{-3} per year (i.e. one fatality per 1000 man years of exposure).

When considering the risks associated with helicopter transportation to offshore platforms it obviously makes sense to ensure that the overall risks to the individual who rely on such transportation are consistent with the other risks they are exposed to in the course of their job. It would be unacceptable if the risks associated with transportation were significantly higher than others that they are exposed to. By the same token it would be pointless to expend a great deal of effort in reducing the risk associated with this one element of their job-related activity to extremely low levels, if this would not significantly lower the overall risk to the individual. A balanced approach is therefore required.

When the nature of the job changes, although the underlying basic elements of risk may remain the same, the total risk exposure experienced by the individual can change dramatically. This has been highlighted by the tendency for offshore platforms to be converted to unmanned operation (a further recommendation of Lord Cullen). This tendency is obviously attractive, as it means that exposure of personnel to the 24 hour risk of living in close proximity to a potentially dangerous hydrocarbons plant is considerably reduced. However, maintenance staff who visit the unmanned platforms regularly will travel on many helicopter flights, and it turns out that the risk experienced by these individuals can now be dominated by helicopter transportation risks [9].

The work of the current study has focused on helicopter ditching and the ability of helicopters to remain floating in a stable attitude following such a ditching. It can be seen that the risks associated with helicopter ditching, and the consequences of a ditching in bad weather, and of helicopter capsize, must be considered in the overall context of the other risks associated with helicopter transportation and the other risks that helicopter passengers are exposed to. There would be very little point in expending much effort in reducing the probability of a helicopter capsize following ditching if the likelihood of a ditching occurrence was itself extremely low. But the reason why ditching performance is in fact an issue in transport helicopter design is that ditching occurrences are not as rare as (say) equivalent incidents on fixed wing aircraft.

It has not been part of this study to perform a risk analysis of helicopter transportation in general, or of helicopter ditching in particular. Perhaps such a study should be conducted. However, on the basis of certain published historical data it is possible to draw some conclusions about the various components of risk associated with ditching.

We can break the overall risk to the individual associated with a helicopter capsize following a ditching into the following components:

a) The risk that a helicopter in which the individual is travelling suffers a failure that forces the pilot to land the helicopter on the sea.

b) The risk that the helicopter capsizes following the ditching before the individual has had time to escape to the relative safety of a life-raft.

c) The risk that the individual will not be able to escape from the capsized helicopter.

This is a simplified representation of just one set of circumstances which could lead to a helicopter passenger fatality. Obviously there are many other different circumstances that could lead to a fatality. Furthermore, this simplified representation ignores 'branches' with their own associated risks (e.g. the failure of the pilot to achieve a satisfactory landing on the water at step 1, or the failure to successfully deploy a life-raft at step 2). A full risk analysis would consider all these aspects.

However, this simple representation does permit us to consider three key elements in the risk and compare them. Risks can be estimated in two main ways: (a) by analysis of appropriate historical data, (b) by theoretical analysis of detailed failure mechanisms.

5.1.1 Risk of a Ditching Incident

This has been estimated from historical data [10] to be about 1×10^{-5} per flying hour for transport helicopters. If we assume that, on average, an individual worker on an offshore rig makes 12 round trip helicopter flights per year of average 2.5 hour total duration, then he will experience about 30 helicopter flying hours per year, which means that his probability of being involved in a ditching incident is about $3 \text{x} 10^{-4}$ per year, or about once every 3000 years.

Obviously this is only part of the helicopter transportation risk (his risk of being involved in a crash is about the same again), and the actual helicopter risk exposure for a particular individual will depend on his particular travel profile, but this does indicate the approximate level of risk of being involved in a ditching.

5.1.2 Risk of a Capsize

This is the aspect of helicopter performance that this BMT study has concentrated on. However, the study has mainly focused on the mechanisms of capsize and how to prevent it, rather than specifically on the risk of such capsize.

The crucial issue for the individual passenger in a ditched helicopter is whether capsize occurs before or after he has managed to escape to the relative safety of a life-raft. Unfortunately, historical records on ditchings that have occurred are not always specific on this point, but interpretation of the historical data on civil helicopters [10] and [5] indicates that about 30% of ditched helicopters have capsized within a quite short time of landing on the water.

Theoretical estimates made of the probability of capsize within 10 minutes [11] have yielded a probability of about 5%.

The CAA stated objective for the probability of capsize within 5 minutes is 1% [10].

It is not possible to draw any meaningful conclusions about the propensity to capsize of different helicopter types from the historical data. As pointed out in [6], although all the capsizes that have occurred to intact ditched helicopters in the North Sea were S61 type helicopters, all these incidents occurred in sea-state 4 or worse, whilst all incidents to other types happened to occur in benign conditions (sea-state 2 or better). All one can say therefore is that these results are broadly consistent with the results of model tests in irregular waves also summarised in [6].

Furthermore [6] has indicated that a very simple analysis of sea-state capsize limits as indicated by the model tests, and North Sea weather data, would indicate a probability of capsize of about 30%, which is consistent with the historical incident data.

On the basis of the above, therefore, it is reasonable to assume that about 30% of currently certified helicopters which ditch in the North Sea will capsize within a short period of time.

5.1.3 Risk of Not Being Able to Escape from a Capsized Helicopter

This aspect of the risk is almost impossible to estimate by any theoretical means. It is therefore only possible to examine historical data and draw conclusions from them.

The somewhat surprising result, in view of the large percentage of capsizes experienced by ditched helicopters, is that to-date **not one fatality has occurred** as a result of the capsize of an intact ditched civil transport helicopter. Thus, on the basis of this historic data, the risk of failing to escape is zero. Obviously with relatively few (11) incidents to analyse, this may not be a good estimate of the true mean individual risk.

In order to broaden the number of incidents analysed it is possible to include those experienced by military helicopters. However, this experience is difficult to apply with any confidence because of a number of key differences. The most important being; the different helicopters types flown, the different operational missions flown, the different conditions in which flying is conducted, and the different training, personal equipment and age profiles of crew and passengers.

The recent military experience is described in detail in [12], and covers some 94 accidents which resulted in helicopters crashing into, or landing on, the sea[1]. Some 243 occupants were involved in these incidents and 58 fatalities resulted. However, if one studies the list of accidents, no fatalities seem to have occurred as a result of a helicopter capsize or sinking following a controlled landing on the water. This despite the fact that a significant proportion capsized immediately. However, according to [12] a number of the fatalities in other incidents (uncontrolled descents into the sea) could have been avoided if the flotation systems fitted to the helicopters had prevented immediate inversion and/or sinking. The report states that there is "... considerable risk to survival when immediate inversion occurs ...", but that "... even an inverted helicopter floating with significant freeboard would permit survival for most."

It is difficult to interpret these data in quantitative terms for the risk of not being able to escape a capsized ditched helicopter, except perhaps to say that the risk most probably lies somewhere in the range of zero (because there were no fatalities in any of the civil or military 'controlled ditching' helicopter capsizes) and 58/176 = 0.33 (the total military fatalities divided by all the occupants of all the helicopters that capsized).

5.1.4 Combining the Risks

If one combines the risks estimated in the above sections one arrives at a rough estimate of an upper limit for the risk of an individual offshore worker suffering a fatality as a result of a helicopter capsize following a ditching of:

$3{\times}10^{-4} \times 0.30 \times 0.33 \approx 3{\times}10^{-5}$ per year

or about once every 30,000 man years.

Clearly there are many other risks associated with helicopter travel (e.g. being involved in a helicopter crash) and other risks associated with being an offshore worker which are probably higher than this value.

5.2 A Probabilistic or Risk-Based Approach

If the CAA were to set a total individual risk level as a target value for passengers on transport helicopters, then this risk level could be broken down and interpreted in terms of the proportion of risk to be associated with helicopter ditching. Furthermore, within ditching, this risk could be broken into various components such as the three outlined in 5.1.1 - 5.1.3 above.

This would result in the derivation of a target risk level for the occurrence of a capsize prior to passenger escape, and ditching studies on helicopters could then focus on demonstrating that an adequately low probability of capsize has been achieved for a given design.

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[1] The term 'ditching' is used in reference [12] to cover all crashes or landings on the sea. However, in the context of the current CAA work the term 'ditching' is limited to controlled landings on the sea.

If the risk targets for 5.1.2 and 5.1.3 were combined into one value, then this would give freedom to the designer to choose whether to concentrate effort on preventing capsize, or on ensuring a means of escape from a capsized helicopter (for example by introducing measures that ensure that a total inversion does not occur, and/or that ensure that there is always an escape hatch above the water surface).

It is believed, however, that there would be significant difficulties in quantifying the risk associated with 5.1.3 for different helicopter designs, and in quantifying the benefit in terms of reduced risk of introducing some new provision for escape.

Consequently, probably a more realistic option in the foreseeable future would be to derive a probability of capsize target value. More than one level might be defined, depending perhaps on the helicopter type, number of escape hatches, and the presence of any device intended to prevent total inversion.

The objective of the certification process would then be to demonstrate compliance with this risk of capsize target by: (a) estimating risk of capsize in individual target sea-states, and (b) integrating these results with appropriate wave climate data to obtain an overall risk of capsize for a randomly occurring ditching event in the operational area.

The main advantage of this certification approach would be that it would make the certification dependent on the intended area of operation of the helicopter, and would therefore give due design benefit to those helicopters which were only intended to operate in benign areas, whilst ensuring that more onerous flotation requirements were placed on those intended to operate in severe areas. It would also set the certification requirements in context with other CAA safety or risk level objectives.

5.3 Application

5.3.1 Setting of Capsize Risk Targets

The application of this method would require the setting by the CAA of ditching capsize risk targets. It may be that sufficient individual passenger risk targets already exist within CAA for these to be set with relative ease, or it may be necessary to perform some significant overall helicopter safety and risk studies in order to arrive at a logical target for this element.

Once this target was set, the revised certification requirements would merely state this target, and would place the onus of the helicopter designer to present evidence to demonstrate that his design complied.

It is anticipated that the method used by the designer to demonstrate this would consist of:

5.3.2 Probability of Capsize in Various Sea-States

The designer would perform model tests and/or theoretical analysis to estimate the probability of capsize within 5 minutes for his helicopter design. These estimates would be established for a range of sea-states typical of the operating area (see next section).

5.3.3 The Operating Area

The designer would define the 'operating area' for the helicopter and the wind and wave conditions characteristic of that area.

He would demonstrate that, with the probabilities of capsize estimated in 5.3.2 above and the wind and wave climate of the operating area, the overall risk of experiencing a capsize within 5 minutes in a randomly occurring ditching incident is less than the CAA specified target value.

Presumably the certified helicopter would be required to include a definition of the operating area in the flight manual.

5.3.4 The Certification Process

The designer would submit the evidence obtained as a result of 5.3.2 and 5.3.3 above to the CAA in the form of appropriate technical reports. The CAA would review this evidence, make whatever checks it considered appropriate, and would determine whether the submitted evidence was sufficient to demonstrate that the required targets had been achieved.

6 Discussion and Concluding Remarks

This study has reviewed the current understanding of capsize of helicopters and the current certification requirements. It has considered these in the light of the historical experience of ditching incidents.

It has been seen that the mechanisms behind helicopter capsize are very complex, and are not well understood. The results of many model tests on different types have not resulted in much physical understanding of the controlling phenomena, but have demonstrated that certain measures (e.g. float scoops) can increase resistance to capsize. It is believed that physical understanding of the processes requires further theoretical simulation work backed up by appropriate good quality experimental validation.

It has been seen that the current CAA helicopter certification requirements regarding ditching seem to be deficient in a number of respects, most notably in the way in which limiting wave conditions are defined. It has been proposed that these could be improved, in particular by requiring capsize performance to be demonstrated in irregular waves which, whilst presenting some significant model testing difficulties, offer a much more realistic approach than using regular waves, which can potentially give a quite misleading impression.

A simple analysis of civil and military helicopter ditching occurrences has indicated that the risk to the individual offshore worker of suffering a fatality due to helicopter capsize following a controlled ditching is probably less than 3×10^{-5} per year (or about once very 30,000 man years).

Finally, a move away from a prescriptive wave condition requirement has been suggested. This would instead set 'risk of capsize' targets that the designer would be required to demonstrate are achieved by the helicopter in the defined 'operating area'.

The detailed conclusions and recommendations of this study are listed in Section 2 above.

7 References

[1] CAA Letter Ref 10MG/13/5 dated 1/10/92.

[2] BMT Proposal Q94004 Review of Helicopter Ditching Performance, dated 6th October 1992.

[3] CAA Contract No. 7D/S/1096 dated 16th December 1992.

[4] Civil Aviation Authority, BCAR Paper No G779, 7th October 1985

[5] Williams, D.L., Report DW/CAA/03, March 1993.

[6] BMT Report 44011r12 Review of Helicopter Ditching Performance, Release 2 dated 7th July 1993.

[7] BMT Report 44011r21 Review of Helicopter Ditching Performance, Release 1 dated 6th July 1993.

[8] The Hon. Lord Cullen The Public Enquiry into the Piper Alpha Disaster, HMSO Nov 1990.

[9] Harnett, J., Making Unmanned Platforms a Viable Safety Option, Conference on Achieving Topside Safety through Design and Modification, IIR Ltd., March 1992.

[10] CAA-SRG Internal Report ref 9/31/R50-11C-3, Sept 1989, Helicopter Ditching Survival Aspects.

[11] Carter, D.J.T., Brice, A.A., On Estimating the Probability that a Ditched Helicopter will be Capsized by Wave Action, IOS Report to CAA, Jan 1987.

[12] Reader, D.C., Helicopter Ditchings - British Military Experience 1972-88, RAF Institute of Aviation Medicine Report No. 677, March 1990.

Appendix D Helicopter Ditching Certification Requirements: Alternative Model Testing Cost Estimates

Executive Summary

In an earlier review BMT noted that the current BCAR and JAR certification requirements are ambiguous as regards the requirements for model tests to assess helicopter stability, and as regards the performance expected in regular waves and irregular waves. These requirements seem to have been interpreted in the past to mean that the helicopter may pass one or other of the criteria, but does not have to pass both. None of the existing helicopters considered in BMT's earlier review seemed to have passed the BCAR irregular sea-state criterion, but all seemed to have passed the regular wave steepness criterion. It was noted, however, that the JAR irregular sea state criterion is less stringent (survival in sea state 4) than the BCAR criterion (sea state 6).

The CAA have now requested BMT to make a comparative estimate of the costs of performing two alternative series of model tests that would be required to certificate a helicopter according to:

a) existing regular wave requirements, or

b) modified irregular sea requirements.

This report presents the two scopes of work for a conventional test programme, and for an alternative irregular-sea test programme, and summarises the two alternative sets of costs. The advantages and disadvantages of each approach are discussed, together with the data analysis requirements.

The cost of performing a conventional (Annex A) programme of model tests (four load conditions), then analysing and reporting the results, is estimated to be about £34,000. The cost of performing, analysing and reporting the alternative programme (Annex B), based on irregular sea requirements, is estimated to be about £30,000. These costs do not include model design, fabrication, instrumentation, preliminary balancing and static stability tests, or general project management costs, which would be common to both programmes.[1]

The overall difference in price between these two programmes of tests is not significant, and depends on the procedures and capabilities of the test basin. Of considerable greater significance is the relative reliability and statistical significance of the results obtained by the two methods. On these grounds the Annex B procedure is considered to be far superior.

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[1] **Note added in 2005:** Model testing prices may well have changed since 1996, when this comparison was made. In relative terms, however, the price for carrying out a conventional test programme based mainly on regular waves is still likely to be similar to the price for carrying out an alternative test programme based entirely on irregular waves. The arguments for carrying out the irregular wave test programme remain valid.

1 Introduction

The Civil Aviation Authority (CAA), Safety Regulation Group, have requested BMT Fluid Mechanics Limited (BMT) to make a comparative estimate of the costs of performing two alternative series of model tests that would be required to certificate a helicopter according to:

a) existing regular wave requirements, or

b) modified irregular sea requirements.

BMT had previously carried out a review of helicopter ditching performance and certification requirements on behalf of the CAA [1, 2]. BMT noted [1] that the current CAA certification requirements [3, 4] are ambiguous as regards requirements for model tests to assess helicopter stability, and as regards the performance expected in regular waves and irregular waves. These requirements seem to have been interpreted in the past to mean that the helicopter may pass one or other of the criteria, but does not have to pass both. None of the existing helicopters considered in BMT's review seemed to have passed the BCAR irregular sea-state criterion, but all seemed to have passed the regular wave steepness criterion.

BMT's second report [2] reviewed differences between the British Civil Airworthiness Requirements (BCAR) and the Joint Airworthiness Requirements (JAR) on helicopter ditching. This review found an important difference in required survival conditions (sea state 4 specified in the JAR [5, 6], but sea state 6 in the BCAR [3, 4]), although both imply that higher sea states might be appropriate. Both the BCAR and JAR requirements were considered to be ambiguous about the steepness of the waves to be considered.

BMT considered [1] that the results of regular wave tests may be misleading, and that an irregular wave criterion is a more realistic measure of the likely actual performance of the helicopter ditched in the sea. It was further suggested that a minimum model testing standard should be considered.

The present report represents the first stage in developing such a standard. It aims to identify minimum requirements and costs for a programme of helicopter model tests in irregular waves, and compares these with the requirements and costs for a conventional programme of tests performed mainly in regular waves.

1.1 Terms of Reference

BMT's response to CAA's request for a proposal for this work was contained in BMT letter, ref. q94384/sjr/l1, dated 29 April 1996. BMT's scope of work was defined to be as follows:

a) Prepare a specification for a traditional regular wave certification model test.

b) Prepare a specification for an irregular wave certification test to demonstrate an 80% probability of remaining upright in sea state 4.

c) Prepare cost estimates for the performance of the two different tests.

d) Prepare a short report summarising the cost elements, and explaining the reasons for the main differences (and including the specifications as annexes).

2 BCAR and JAR Model Testing Requirements

Current CAA requirements for model testing are mainly defined in British Civil Airworthiness Requirement (BCAR) Paper G779 [3]. BMT carried out a detailed review of these requirements in [1]. The following points are relevant to the present study:

- The craft should remain afloat for the time required for everybody to escape. This time should be not less than 5 minutes in severe seas, and an allowance for damage to the helicopter should be made.
- Satisfactory flotation and trim characteristics are to be demonstrated by investigation and model tests, conducted so that the results are valid in the 'declared conditions'. Model testing is considered to be compulsory.
- The 'declared conditions' are defined to be those in which compliance with the requirements has been demonstrated. If these are less than those described in the Appendix of [3], they have to be included in the Flight Manual as limitations.
- The standard conditions are defined in the Appendix of [3] as follows:
  a) Sea states should cover the range 0 to 6, but with a maximum wave height (usually 1.6 times the significant wave height) of 9.15m. Sea state codes are listed in Table 1.
  b) Individual waves should have height/ length ratios in the range 1:8 for rotorcraft in Group B, and 1:10 for rotorcraft in Group A, for all sea states in (a). The wave height/ length ratio may be varied with the declared time interval, up to a maximum of 1:12.5 when there is no limit on the declared time interval.

The JAR [6] requires the craft to cope with 'reasonably probable water conditions', and states that sea state 4 may be regarded as representative of reasonably probable water conditions. Sea state 4 is defined as a moderate sea with significant wave heights of 4 to 8 feet, with a height-to-length ratio of:

- 1:12.5 for Category A rotorcraft,
- 1:10 for Category B rotorcraft, with Category A engine isolation,
- 1:8 for Category B rotorcraft.

As noted in [1, 2], there are a number of ambiguities in both sets of requirements, although a fairly standard interpretation seems to have emerged over the years. This forms the basis for the conventional model testing programme described below.

It should be noted that several alternative definitions of sea state codes are in common use. These definitions differ in terms of the range of significant wave heights contained within each sea state. Defining a wave condition by sea state is therefore ambiguous, and thus not recommended. In order to define a wave condition unambiguously, the significant wave height, modal (peak) wave period and spectrum shape (e.g. JONSWAP, Pierson Moskowitz) should be defined.

Table 1 Sea State Codes (World Meteorological Organisation [7])

Sea State Code	Description of Sea	Significant Wave Height	
		Metres	Feet
0	Calm (Glassy)	0	0
1	Calm (Rippled)	0 to 0.1	0 to $^1/_3$
2	Smooth (Wavelets)	to 0.5	$^2/_3$ to $1^2/_3$
3	Slight	0.5 to 1.25	$1^2/_3$ to 4
4	Moderate	to 2.5	4 to 8
5	Rough	2.5 to 4	8 to 13
6	Very Rough	4 to 6	13 to 20
7	High	6 to 9	20 to 30
8	Very High	9 to 14	30 to 45
9	Phenomenal	Over 14	Over 45

3 A Conventional Programme of Model Tests to Meet Current Certification Requirements

Annex A contains a specification for a typical conventional programme of model tests that might be undertaken to assess the stability of a helicopter before certification. This specification is based on a series of model tests that was undertaken to evaluate the performance of 'scoops' [8].

It appears that three different types of model tests would typically be performed on a helicopter before certification:

- static stability tests, to measure the hydrostatic righting moment as a function of heel angle,
- tests in regular waves, probably without wind, to identify the craft's stability boundaries relative to the wave steepness,
- tests in irregular waves, both with and without wind, to provide information of a more qualitative nature about the behaviour of the craft in severe seas.

It seems that certification is almost entirely based on the results from the regular wave model tests, and the results from irregular wave tests seem to be largely ignored during the certification process. Past model tests have demonstrated that helicopters do not generally comply with the stated BCAR requirement to survive in sea state 6, and generally capsize in sea state 5, or even 4.

In order to make the cost comparison meaningful, the costings for the conventional test programme include a number of irregular wave tests, as well as a systematic series of regular wave tests. They therefore represent a typical range of model tests that would currently be performed before certification.

3.1 Model

Dynamic similarity is required between the model and full-scale craft. This requires the external hull form of the model, together with all significant attached sources of buoyancy (e.g. flotation bags) to be geometrically similar to the full-scale helicopter. Any floodable spaces must also have the same scaled internal volume and location.

The total structure mass, centre of gravity and radii of gyration of the model also have to be dynamically similar to those of the full-scale aircraft.

The model scale has to be chosen in relation to the wave generation capabilities of the test basin. The tests are conducted and analysed according to Froude scaling laws. The model has to be large enough to allow its physical properties to be represented reasonably accurately, but small enough to allow the largest sea states to be generated.

It seems to be common practice to build and test two models: a large model at about 1:10 scale, tested in moderate sea states, and a small model at about 1:25 scale, tested in very severe sea states. The large model seems to be built mainly for ditching tests, whereas the smaller model is built specifically for stability tests in higher sea states.

There seems to be little obvious need for testing two models, and no obvious need to test in quite such severe conditions. It is therefore assumed for present purposes that only one model will be built, at about 1:15 scale. Model-scale waves of significant height 0.27m then represent full-scale waves with a significant height of 4m (the upper limit for sea state 5), and this should be well within the capability of most modern wave basins.

It is assumed that the helicopter will be tested in four conditions: both fully and lightly loaded, with the helicopter's centre of gravity at both forward and aft positions.

3.2 Static Stability Tests

The helicopter model should first be balanced to obtain the correct mass properties in air: the correct total mass, the correct centre of gravity position (x, y and z), and the correct radii of gyration in roll, pitch and yaw. Measured and required values should then be tabulated. Normal practice is to balance the model for one load condition and one centre of gravity position, and ballast requirements for the other load condition and centre of gravity position will then be obtained by calculation.

The helicopter model should then be mounted in a frame, which holds the model statically at a range of known heel angles, between the upright and inverted positions, while the hydrostatic righting moment is measured. The model has to be able to trim and heave naturally at every stage during this entire process, so that it remains in hydrostatic equilibrium in these two modes. The heel axis should pass through the craft's centre of gravity, and the dynamometer must be able to measure both positive and negative righting moments.

A typical range of tests would cover a range of about 40 heel angles between 0° and 360°, for each of two craft loading conditions. The tests may be limited to heel angles in the range 0° to 180° if the craft is laterally symmetric. All tests should be performed in still water.

The total number of such measurements is therefore 80 (i.e. 40 angles × 2 load conditions).

3.2.1 Analysis

The results should be presented in the form of a curve of righting moment against heel angle, for each load condition.

3.3 Regular Wave Tests

Regular wave tests are usually performed in order to establish the helicopter's stability boundaries, with respect to limiting values of the wave steepness. BMT had earlier [1] expressed reservations about whether the results from such tests are likely to be meaningful. The problem with such tests is that helicopter models normally only capsize in breaking waves, and the results from such tests are likely to depend more on wave basin properties (how quickly waves break as they travel along the tank, and where the model is located in the tank) than on the helicopter model's properties.

The present proposal is concerned with comparing established practice, based on regular wave testing, with a possible new procedure based on irregular wave testing. No special precautions will therefore be taken to ensure that the regular waves are made to break in any particular way, or that relevant physical processes are represented.

For present purposes it is assumed that a traditional model test programme would cover the following range of conditions:

- about 20 separate regular wave conditions, covering a range of wave heights, with wave steepness values (height/ length) between about 0.08 and 0.13 (assuming a Category B craft),
- four loading conditions (heavily and lightly loaded, centre of gravity located forward and aft).

As noted earlier, a small model is often built for testing in very severe sea states. If the requirement is limited to sea state number 5, then the significant wave height will be at most 4m, and the highest individual wave in this sea state will be less than about 6.5m. It is proposed, therefore, that the above 20 tests should cover a range of regular wave heights between about 4m and 7m. This again should be within the capability of most modern wave-makers at 1:15 scale, although the range of steepness values may be limited either by the wave-maker software or hardware, or by the hydrodynamic limitations of the basin.

Each test starts with the model floating freely, beam-on to the waves. The model is not constrained in any way, and is free to turn naturally.

The total number of regular wave tests is therefore 80 (20 wave conditions × 4 load conditions).

3.3.1 Analysis

A steep regular wave train tends to break down, becoming more irregular and eventually breaking as it travels along the tank. It is not obvious how to characterise the 'height' of such a breaking wave train, and the relevant height is assumed to be that of the 1/3 highest waves in the sequence. An average wavelength also has to be defined, based on the mean zero up-crossing period.

The results should then be presented in the form of a scatter plot, showing the wave height against wave length for each test, with different symbols used to denote whether the model remained upright or capsized during a particular test. Constant wave steepness curves (height-to-length ratios 1:8 and 1:10) should be over-plotted, together with stability boundaries separating tests in which the model remained upright and capsized.

3.4 Irregular Wave Tests

Current practice is to include a certain number of irregular wave model tests. These tests generally seem to be regarded as qualitative in nature: mainly to confirm the helicopter's behaviour in severe seas. The results are typically presented in descriptive terms, with accompanying photographs, rather than in quantitative terms. It is not obvious how many such tests are performed, and the results seem to be largely ignored in the certification process. Most helicopter models capsize in sea states 5, or even 4, despite current BCAR requirements that they should survive in sea states up to 6, unless lower sea states are declared as limitations in the operations manual. It is understood that no currently certified helicopters contain any such stated limitations in their operations manuals. Most craft seem to comply, however, with the lower JAR requirement of survival in sea state 4.

For the purpose of the present comparative study, it will be assumed that the following tests would typically be performed in irregular waves:

- four different steep wave conditions representing sea states 4 and 5 (different combinations of significant wave height and zero-crossing period),
- four load conditions (heavily and lightly loaded, centre of gravity located forward and aft),
- both with and without collinear wind.

The model is initially released beam-on to the wind and waves. It is unconstrained, and can therefore turn until head-on to waves, when it is likely to be more stable.

The waves are chosen from the same range used in the irregular wave test programme (Section 4.3 below).

Each test should be of at least 5 minutes (full scale) duration.

The wind speed will be scaled according to Froude's law, in order to ensure the correct ratio between wind and wave forces. The physical processes involved in wind loading are not correctly represented by Froude's law, however, and the standard approach adopted in wave basin model tests is to vary the wind speed until the 'correct' wind force is applied to the model. The 'correct' forces have to be established by comparison with earlier wind tunnel tests. Assuming that wind tunnel test data for the helicopter are not available, the unmodified Froude-scaled wind speed will be used. It seems likely that this same approach has been used in previous capsize model studies.

The total number of irregular wave tests is 32 (4 wave conditions × 4 load conditions × 2 wind conditions).

3.4.1 Analysis

Minimal analysis will be performed on the results from these tests. Each test is observed to see whether the model capsizes, and to record its general behaviour. The test is also recorded on video and still photographs.

4 An Alternative Programme of Testing Based on Irregular Waves

Annex B contains a specification for a model testing programme, based on irregular waves, that might be undertaken as an alternative to the conventional programme described in Section 3. The objectives of the new test programme would be generally the same as the conventional programme, but the changes are intended to meet the criticisms in [1, 2].

As noted above, current certification seems to be based mainly on the results from regular wave model tests. BMT had earlier [1, 2] observed that, in general, helicopter models only capsize when these regular waves break, and expressed the view that the capsize boundaries measured in such tests may be more a measure of the wave breaking limits of the test basin than a meaningful measure of the helicopter's stability.

BMT sees no role for any regular wave model tests in the following alternative test programme. This test programme is based entirely on irregular wave tests, and should be regarded as the minimum necessary to gain certification under requirements consistent with BMT's recommendations [1, 2].

4.1 Improvements Suggested in Earlier BMT Report

BMT's earlier report [1] first asked whether the helicopter should be assumed to be damaged during the ditching process. This is clearly only a matter of model design and construction, and does not affect the way in which the tests are conducted. For present purposes, therefore, it is assumed that the model is in the same condition as for conventional tests (either intact or damaged, as considered appropriate).

BMT's report [1] put forward two alternative options:

- **Option 1*:*** retain current definitions of limiting conditions, but frame these in a less ambiguous way,
- **Option 2*:*** move to a risk-based approach, where the requirement is to demonstrate an adequately low overall risk of capsize.

Option 2 would have many implications for other areas of CAA certification, and may be considered appropriate in the longer term. Option 1 could be adopted much more quickly, and would be less controversial. Option 1 has therefore been chosen as the basis for the present proposed work programme.

BMT then proposed [1] the following changes to the criteria:

a) To base the criteria on irregular wave model tests.

b) To define the irregular wave sea states in terms of their significant wave heights, mean zero up-crossing (or peak) spectral wave periods and spectrum shapes.

c) To define an adequately low risk of capsize in the five-minute exposure period.

d) To provide a list of limiting sea states in which the designer must demonstrate an adequately low risk of capsize.

The following test programme is based exclusively on tests in irregular waves, and is based on achieving at least 80% probability of survival in sea state 4 (see Table 1) for at least five minutes, with additional tests to determine whether the craft will also survive in sea state 5. These sea states are defined in terms of ranges of significant wave height, spectral peak period and spectral shape.

There is no longer any requirement to demonstrate survival in steep individual waves. It is sufficient to achieve a sufficiently low risk of capsize in sea state 4, which should contain a realistic number of steep and breaking individual waves.

Different model testing establishments have different procedures for generating irregular wave sequences and spectra. Some of these procedures are likely to be more appropriate for helicopter stability tests than others. Considerations affecting the choice of test procedure have already been reviewed in an earlier BMT report [9], and are reproduced below in Annex C.

4.2 Model and Static Stability Tests

The tests would be performed on a model at approximately 1:15 scale. The model would be balanced, and measurements would start with a programme of static stability tests. The model preparation, balancing and static stability tests would be the same as under current practice, and as outlined in Sections 3.1 and 3.2 above.

4.3 Irregular Wave Model Tests

The main difference between the two alternative test programmes is that the conventional programme of regular and irregular wave tests, outlined above, is replaced by a more systematic and quantitative series of irregular wave tests, discussed below. No regular wave tests are proposed.

No helicopter currently seems to comply with the current BCAR requirement to survive in sea state 6. All seem to capsize in sea states number 4 or 5. It therefore seems more practical to apply the JAR requirement: that the helicopter should survive a sea state that is generally not less than 4. A limited number of additional tests will also be performed in sea state 5.

Sea state number does not define the wave conditions uniquely. It defines a range of significant wave heights, but does not specify either the associated range of wave periods or the spectral shape. The period and spectral shape parameters will now be considered.

Scatter diagrams for real sea conditions typically show a wide spread of zero-crossing periods T_Z associated with each wave height H_S, especially in low to moderate sea conditions. Recent offshore data sources and the HSE's Background to Guidance [10] suggest that it is reasonable to cover values of significant wave steepness, S, between about 1:18 and 1:12, where:

$$S = \frac{2\pi H_s}{g{T_z}^2}$$

Most engineering design work for the UK North Sea uses the JONSWAP wave spectrum, which also seems to have been used in previous model test programmes. The JONSWAP spectral formula will be used once again, with mean peakedness parameter $\gamma = 3.3$. The waves are assumed to be uni-directional (long-crested).

Wind generally seems to improve the stability of helicopter models, by turning them head-on to the environment, thus making them less likely to capsize. The relationship between wind and waves is not straightforward, however, and it would seem prudent to test models both with and without wind, and possibly to consider the need for extra tests with wind at a heading angle to the waves. At this stage, however, the proposed new programme is limited to one set of tests without wind, and a repeated set of tests with collinear wind and waves.

The proposed new test programme has the following aims:

- to show that the helicopter has at least an 80% probability of surviving for at least 5 minutes in sea conditions up to sea state 4, and to provide additional information about survival in sea state 5,
- to cover a range of significant wave steepness values S, up to the steepest conditions considered realistic,
- to demonstrate survival with the craft fully and lightly loaded, with the centre of gravity located both forward and aft,
- to demonstrate survival both with and without wind.

The test programme therefore covers the following range of conditions:

- a matrix of about twelve sea conditions (four significant wave heights and three significant wave steepness values), representing sea states 4 and 5,
- four helicopter load conditions (fully and lightly loaded, centre of gravity located forward and aft),
- tests repeated both with and without wind, from the same direction as the waves.

The wind speed will once again be scaled according to Froude's law, noting the reservations expressed in Section 3.4.

There are a number of ways in which the tests might be performed in order to achieve a target of 80% probability of survival for at least 5 minutes, and several possible ways in which this requirement might be interpreted.

4.3.1 Approach A: Separate Five-Minute Tests

The most obvious approach would be to carry out individual five-minute tests, and repeat these several times. Different combinations of randomly-selected wave phase angles would be selected for each repeat test, in order to ensure independent samples from the distribution of all possible realisations of the sea state.

The probability of capsize P_{c5} in a five-minute period may then be estimated very simply from the ratio:

$$P_{c5} = \frac{\text{number of capsizes}}{\text{total number of tests}}$$

This ratio can be estimated more accurately as the number of repeat tests is increased. It seems likely that a minimum of about ten such repeat tests will be needed in order to obtain a reasonably reliable estimate of the 80% exceedance value.

4.3.2 Approach B: Single Continuous Test

The total time in the test basin can be reduced significantly if the test runs are joined together. Waves are then run continuously, only stopping when the level of 'noise' in the basin reaches an unacceptable level, or when a capsize occurs. Each successive five-minute (full scale) segment from the record is then treated as if it is a separate model test. The test run has to be re-started every time a capsize occurs, with a different random realisation of the sea state, until the required total number of five-minute test runs has been completed.

This raises an important question about the way in which the tests are conducted: whether the model should be left entirely free, or restrained in order to prevent it turning into the wind and waves. Previous model test results suggest that wind often has a stabilising influence, turning the model head into the waves. Current practice is therefore to test a freely-floating model, which is initially placed beam-on to the waves, but is then allowed to turn naturally in the wind and waves.

If several individual five-minute (full scale) tests are replaced by a single extended test, a free-floating model would quickly turn into the weather, and would be relatively stable for the remainder of the test period, thus giving an **optimistic** view of the helicopter's stability. If, on the other hand, the model is constrained by lines, so that it remains beam-on to the waves, this will prevent it taking up its more stable heading, and will therefore give a **pessimistic** view of its stability. The advantages of this approach, however, are that the test can be extended as long as necessary, thus minimising tank time, and the results are likely to be more repeatable and steady-state in character.

BMT's present view is that the benefits of testing with a constrained model outweigh the disadvantages, and these tests will still give a fair view of the craft's stability in wind and waves. The results are likely to be slightly more conservative, however, than under current testing regimes. The following test programme is therefore based on using a constrained model, that is kept permanently beam-on to the waves.

A test of five minutes duration at full scale will take about 77 seconds at 1:15 model scale. The present costing is based on Approach B, where all ten repeat tests take place during a single extended run, except in cases where the run has to be re-started after a capsize. It should be possible to complete about ten such tests in a single run lasting about 15 minutes.

The total number of extended irregular wave runs is therefore assumed to be 96 (12 sea states × 4 load conditions × 2 wind conditions), with re-starts as necessary in cases where the model capsizes.

4.3.3 Analysis

Results will be presented in the form of capsize boundaries on the (H_s, T_z) scatter diagram. The results from each extended test run will provide a single estimate of the probability of capsize P_{c5}, and this will be used to identify a single point on the scatter plot of H_s against T_z. Different symbols will be used to denote conditions in which P_{c5} is less than or greater than 0.8. (Different symbols may also be used to denote conditions in which P_{c5} exceeds other values, such as 0.7 or 0.9, if these are also of interest.). Curves of constant values of significant steepness should be over-plotted, and a boundary curve inserted between points which lie above and below the 80% exceedance data.

5 Comparative Costs

The following costs are intended for guidance, and are for comparative purposes only. The costs of testing a particular model will vary according to individual circumstances, detailed test requirements, and on the pricing policy of the individual test basin. The following costs and comments are based on information provided by the Haslar Hydrodynamic Test Centre, Gosport, Hampshire, UK.

The following costs cover model test set-up, the model tests themselves, data analysis and reporting only. They do not cover model design, fabrication and instrumentation, model balancing, initial static stability tests or general project management costs, because these items would be common to both types of test programme.

5.1 Tests According to Existing Standard Procedures

The scope of work for this conventional programme of model tests is summarised in Annex A, and includes the following items:

- Set-up on facility, with video and two wave gauges. Calibrate waves. Set up wind fans, and calibrate the required conditions.
- Conduct regular wave tests, light and heavy load conditions, centre of gravity located forward and aft. Model free to drift. Total of 80 runs of 5 minutes (full scale) duration.
- Conduct irregular wave tests, light and heavy load conditions, centre of gravity located forward and aft, with and without wind. Model free to drift. Total of 32 runs of 5 minutes (full scale) duration.

- Data analysis and reporting.

Total cost for tests as per Annex A: £34,000

5.2 Tests According to Modified Procedures

The scope of work for this modified programme of model tests is summarised in Annex B, and includes the following items:

- Set-up on facility, with video and two wave gauges. Calibrate waves. Set up wind fans, and calibrate the required conditions. Set up mooring system.
- Conduct irregular wave tests, light and heavy load conditions, centre of gravity located forward and aft, with and without wind. Model restrained in beam seas. Total of 96 runs of 15 minutes (model scale) duration.
- Data analysis and reporting.

Total cost for tests as per Annex B: £30,000

5.3 Discussion

It is estimated that both test programmes will involve the same number of actual days of testing (i.e. about 10). The man-power requirements under the Annex B procedure are lower, however, because the model is restrained by lines. This means that the carriage does not have to move, and there is no need to provide for fending the model off the tank wall.

It should be noted that a significant part of the total set-up cost relates to the installation and calibration of wind fans. The costs of providing wind fans are somewhat uncertain, because precise requirements will depend on circumstances. It has been assumed that the test basin has enough existing fans to cover the required test area, and that the fans are capable of achieving the required maximum wind speed. The model is restrained under the Annex B procedure, and so the fans will not have to cover such a wide area of the tank. This factor has slightly reduced the set-up costs compared to the Annex A procedure, offsetting the extra cost of setting up the mooring system.

The analysis of results from the Annex B tests is more complex, and will take marginally longer (although a bespoke analysis program could be written to minimise these costs). Reporting effort will be similar in both cases.

6 Conclusions

BMT have made comparative estimates of the costs of performing two alternative series of model tests that would be required to certificate a helicopter according to:

a) existing regular wave requirements, or

b) modified irregular sea requirements.

Scopes of work for a conventional test programme and an alternative irregular-sea test programme have been developed, and the corresponding costs have been summarised.

The cost of performing a conventional (Annex A) programme of model tests (four load conditions), then analysing and reporting the results, is estimated to be about £34,000. The cost of performing, analysing and reporting the alternative programme

(Annex B), based on irregular sea requirements, is estimated to be about £30,000. These costs do not include model design, fabrication, instrumentation, preliminary balancing and static stability tests, or general project management costs, which would be common to both programmes.

The overall difference in price between these two programmes of tests is not significant, and depends on the procedures and capabilities of the test basin. Of considerable greater significance is the relative reliability and statistical significance of the results obtained by the two methods. On these grounds the Annex B procedure is considered to be far superior.

7 References

[1] BMT Offshore Limited, Review of helicopter ditching certification requirements, Report 2, Project no. 44011/00, 1993.

[2] BMT Offshore Limited, Helicopter ditching: JAR certification requirements, Report 3, Project no. 44035/00, 1995.

[3] Civil Aviation Authority, British Civil Airworthiness Requirements, Paper no. G779, 7 October 1985.

[4] Civil Aviation Authority, British Civil Airworthiness Requirements, Sub-section G4 - Design and Construction, Chapter G4-10, Emergency Alighting on Water, 20 January 1975.

[5] JAR 29.801 from Joint Aviation Requirements JAR-29 Large Rotorcraft, Civil Aviation Authority (on behalf of the Joint Aviation Authorities Committee), 5 November 1993.

[6] Advisory Circular No. 29-2A, Change 2, Certification of Transport Category Rotorcraft, Federal Aviation Administration, 24 September 1991.

[7] Meteorological Office, Ships' Code and Decode Book, ref. Met.O. 509, HMSO, 1968.

[8] British Hovercraft Corporation Limited, Helicopter flotation stability - an investigation into the effect of fitting water scoops onto emergency floats, Report no. X/O/3257, 1986.

[9] BMT Offshore Limited, Review of helicopter ditching performance, Report 1, Project no. 44011/00, 1993.

[10] Institute of Oceanographic Sciences, Estimating wave climate parameters for engineering applications, Department of Energy report no. OTH 86 228, HMSO, 1986.

Annex A Specification for a Conventional Programme of Model Tests

The following is intended to represent a conventional programme of model tests to assess the stability of a helicopter after ditching in waves, and is considered to be typical of tests currently undertaken to achieve certification of a helicopter. Programme costs exclude model design, construction, instrumentation, together with preliminary balancing and static stability tests, which would be common to both programmes of work.

The model will be of a typical large civil helicopter, such as the EH101, at approximately 1:15 scale. The actual scale will be chosen to suit the capabilities of the wave maker but the model should be as large as possible to aid model manufacture. The model will have the correct mass properties, and will be designed to flood in a realistic manner when in the water, so that it has realistic righting moment properties.

Regular Wave Tests:

The following tests will be performed:

- Heavy and light load conditions.
- Centre of gravity located forward and aft.
- 4 wave heights: H = 4m, 5m, 6m, 7m.
- 5 wave steepness values (e.g. 0.08, 0.10, 0.11, 0.12, 0.13).

Each test will have a duration of 5 minutes (full scale), or less if capsize occurs. The behaviour of the model will be recorded with still and video photography. The wave elevation will also be recorded at a minimum of two locations within the model tank. Each test will start with the model floating freely, beam-on to the waves. The model will not be constrained in any way, and will be free to turn naturally.

This makes a total of 80 regular wave tests.

Irregular Wave Tests:

The following tests will be performed:

- Heavy and light load conditions.
- Centre of gravity located forward and aft.
- Four irregular wave conditions (e.g. JONSWAP spectra), representing sea states 4 and 5 with varying significant heights and peak spectral periods.
- With and without wind.

Each test will have a duration of 5 minutes (full scale), or less if capsize occurs. The behaviour of the model will be recorded with still and video photography. The wave elevation will also be recorded at a minimum of two locations in the model tank.

Each test will start with the model floating freely, beam-on to the waves. The model will not be constrained in any way, and will be free to turn naturally. Wind speed will be scaled according to Froude's law.

This makes a total of 32 irregular wave tests.

Analysis

Results from the regular wave tests will be presented in the form of individual points, which identify whether capsize occurred, together with capsize boundaries, on a plotting of wave height against wavelength (or wave period).

Each irregular wave test will be observed to see whether capsize occurs, and to record the model's general behaviour. The test will be recorded using still and video photography.

Annex B Specification for an Alternative Programme of Model Tests

The following alternative programme of model tests is intended to assess the stability of a helicopter after ditching in waves, on the basis of a programme of systematic irregular-wave model tests only. Programme costs exclude model design, construction, instrumentation, together with preliminary balancing and static stability tests, which would be common to both programmes of work.

The model will be of a typical large civil helicopter, such as the EH101, at approximately 1:15 scale. The actual scale will be chosen to suit the capabilities of the wave maker but the model should be as large as possible to aid model manufacture. The model will have the correct mass properties, and will be designed to flood in a realistic manner when in the water, so that it has realistic righting moment properties.

Irregular Wave Tests:

The following tests will be performed:

- Heavy and light load conditions.
- Centre of gravity located forward and aft.
- Twelve irregular wave conditions (e.g. JONSWAP spectra) representing sea states 4 and 5 with varying significant heights and peak spectral periods.
- With and without wind.

Each test will have a minimum duration of 15 minutes (model scale). It therefore meets the requirements for the single long continuous test described in Section 4.3.2: Approach B, with about ten different short realisations of the sea state run in continuous succession. When capsize occurs, the run will be halted, the model returned to the upright condition, and the run continued. The behaviour of the model will be recorded with still and video photography. The wave elevation will be recorded at a minimum of two locations in the model tank.

Each test will start with the model floating beam-on to the waves. The model will be constrained by light lines, so that it remains permanently beam-on to the waves. Wind speed will be scaled according to Froude's law.

This makes at total of 96 extended irregular wave tests, with re-starts as necessary.

Analysis

The probability of capsize in each sea state within each five-minute period will be calculated by taking the ratio of the total number of observed capsizes divided by the total number of five-minute (full scale) segments represented in each extended test run. The results will then be presented graphically as points on a scatter diagram of significant wave height and peak spectral period, using different symbols to denote different capsize probability ranges. Capsize boundaries will also be shown.

Records will also be made using still and video photography.

Annex C Model Testing Considerations

The following text is reproduced from BMT's report [9].

1 Introduction

Physical model tests are often the only way of handling complicated dynamic problems such as the capsize of helicopters in waves. Models constructed with due regard to the necessary physical similarity and mass/inertia properties can give a realistic qualitative and quantitative impression of the way in which the full scale helicopter will behave. The tests can be particularly impressive to the layman who sees what appears to be a true representation of reality (particularly when filmed, and slowed down to simulated 'real-time').

However, such tests do present a number of real difficulties which must be considered when such tests are designed or the results from them interpreted.

The main difficulties when considered in the context of helicopters are:

- The construction of accurate models (accurate in terms of shape, floodability, mass, inertia, etc).
- The generation of appropriate and repeatable wave conditions.
- The conduct of tests in these waves in a controlled and repeatable manner.

2 Model Construction

It is important that models used in this type of testing are statically and dynamically similar to the full scale helicopter.

Static similarity involves ensuring that the external shape and dimensions are accurately represented on the model. When the model is going to be permitted to flood through open doors it is also necessary to ensure that the internal voids are properly modelled. This latter can be quite difficult to do precisely owing to the need for very thin walls, and the many internal details (passenger seats etc.).

The model must also have the correct weight and centre of gravity location. This can be quite difficult to arrange (particularly for small models when it is sometimes difficult to make the model light enough). Obtaining the appropriate centre of gravity location involves balancing the model and adding ballast weights until the correct CG location is achieved.

Dynamic similarity involves ensuring that the inertia of the models in the three rotational axes is correct. The most important in the context of capsize is obviously the roll inertia or radius of gyration.

It is usual in wave model test reports to list all the static and dynamic properties of the model both as 'desired' and 'obtained' so that the reader can judge the accuracy of the modelling. In the case of the BHC model test reports [C1] and [C2], information on the means of balancing the model and achieving the desired properties is rather sketchy, and tables showing full scale and model properties do not seem to be 'as measured' properties of the model, but rather just desired values scaled down from full scale.

In the context of helicopters there are some specific modelling problems:

- How to model the interior spaces when water is permitted to flood in and wash through the cabin.
- How to model the rotor. The prototype rotor assemblies are quite flexible, and it is not immediately clear how the inertia of the rotor influences the total inertia of the helicopter at wave frequencies. The rotor tips are also likely to touch the water surface in extreme conditions and it is not clear how this should be modelled. (It is noticeable that most of the helicopter models tested by BHC did not have rotors fitted, but in some cases used a mast with a weight on the top to help obtain the required total CG and inertias.)

3 Wave Conditions

3.1 Regular Waves

'Regular' waves (the reason for the quote marks will become apparent later) are intended to be regular in terms of the wave amplitude and frequency, the wavemaker paddle normally moving with a sinusoidal movement.

Until the late 60's almost all wave model tests were performed in regular waves because this was the only wave generation technology available. All realised that these regular waves were a very poor model of the real waves experienced in the ocean, but if one was able to assume linearity of response, harmonic or Fourier analysis provided ways of interpreting this information to predict the behaviour in irregular seas.

In addition to not being representative of real ocean waves the apparent simplicity of sinusoidal regular waves is, to some extent, illusory. Only the least steep (small wave height compared with wave length) approximate to sinusoidal shape. The steeper these waves become, the less sinusoidal they are - the peaks get more sharp and the troughs flatten. Somewhere between a wave length/wave height of 10 - 7 these waves also break.

In longer model basins it also becomes apparent that such 'regular' waves do not propagate unchanged down the tank. Depending on their steepness, and the distance they have travelled, and the purity of the initial wave form, these waves degrade and change shape as they propagate. Eventually they become quite irregular and break. This means that the shape and properties of the wave are different in different parts of the tank, and also tend to change with time as reflections and other 'noise' build-up in the tank accelerate the degradation process.

Furthermore, waves steeper than 1:10 will often break as they are generated at the wavemaker paddle.

Once breaking is occurring in a 'regular' wave train, an energy conversion process is occurring that ensures that the wave cannot continue to propagate with the same shape and regular properties. It can no longer be a regular wave.

It is clear from the above that tests performed in steep regular waves are fraught with difficulties. The wave shape changes with position in the tank and with elapsed time, and one run will usually be different from the next. This presents particular problems for the testing of a free-drifting model as the helicopter model will tend to drift down the tank from a region of smooth regular waves into a region of steadily increasing irregularity and wave breaking. (The model cannot be constrained to remain in the same place, as these constraining forces would have a major effect on its behaviour.)

These factors were well-understood by those who performed the helicopter model tests in steep 'regular' waves. It is clear from the work reported that no capsizes occur unless the vehicle is hit by a breaking wave. Thus 'regular' waves in this context have really been used as a way of making breaking waves - which are inevitably irregular by nature.

It is understood that the wave height, wavelength and steepness were estimated as best as possible for an individual wave that capsized (or failed to capsize) the model. This was in itself very difficult in practice as the model was not necessarily alongside a wave probe at the moment of interest.

3.2 Irregular Waves

The use of 'more realistic' irregular waves has been on the increase since the 60's. Understanding of the ocean environment was improving, and later the availability of cheap computer technology and servo-controlled wavemakers started to impact on the science, and permitted more sophisticated control of wavemakers.

Early irregular wavemakers were electro-mechanical, driven by a variable speed electric motor via an eccentric crank, where the speed of the motor was controlled by some kind of programming device (often a punched card). In these systems the irregular sequence was usually quite short (say 100 waves) before the program repeated, and this type of control made it difficult to produce waves with a spectrum shape and Gaussian randomness (or pseudo-randomness) that was representative of the real ocean.

Later wavemakers, actuated by hydraulic servo systems or linear electrical actuators and controlled by computer, solved these problems and made it possible to generate more or less infinite sequences of pseudo-random waves with the desired spectral and statistical properties. More recently this technology has been extended to multi-directional irregular waves in some tanks.

A good quality irregular wavemaker makes it possible to generate irregular waves in a closely controlled and repeatable fashion that is a good representation of a given sea-state. In fact wavemaker technology today is capable of generating waves to much closer tolerances than the ocean environment is generally understood.

The strategy adopted in the irregular wave test is rather different from a that used in a regular wave test. The usual policy is to set a given sea-state (usually defined in terms of a significant wave height, mean period and spectrum shape) and record the behaviour of the vessel under test for a long period of time (often about 3 hours full-scale time). The reason for the long run times is that the results of the test can only really be interpreted properly in a statistical fashion if there are a lot of waves. In principle, a helicopter ditching test could be run on many occasions in different time-history realisations of the same sea-state, and an accurate determination made of the probability of capsize in any period of time. In practice there are some difficulties with this approach.

The free drifting nature of the model means that eventually the model will drift down the tank and the run must be stopped. Also when capsize occurs, the test must obviously be halted and the model recovered.

In addition to this inherent difficulty it is unfortunate that the model tests conducted in irregular waves described in [1] and [2] have been performed using an electro-mechanical wavemaker of the early type. This has lead to very poor spectral shaping and very short run sequences.

All that is known from such a test is whether the helicopter capsized or not. If it did, then there is still no information about the probability of capsize in a given period of exposure. If the size of the wave that capsized the helicopter were known, then it might be possible to calculate the probability of this wave, but this has not been recorded.

Similarly, if a helicopter remained upright through a sequence of 100 waves (about 10 minutes full-scale time) then there is nothing to say that a 101st wave would not have capsized it. A detailed statistical analysis of the 100 wave heights experienced would reveal whether these 100 waves represented a typical distribution of heights, but again this information is not believed to be available for the tests concerned.

3.3 An Ideal Helicopter Capsize Model Test

Given that the requirement for a ditched helicopter is to remain upright long enough for crew and passengers to make a safe evacuation to the life rafts, the real requirement for a helicopter model test is to demonstrate that the probability of capsize within a given short period (say 5 or 10 minutes) is adequately low.

The only way of demonstrating this in a physical model test is to run a large series of realistic irregular wave conditions and record the mean frequency of capsizes that occur. This will enable the probability of capsize to be estimated. Alternatively, if the wave height and period characteristics which cause capsize can be recorded in each case (difficult because of the drifting position of the helicopter model), then the probability of meeting this wave can be estimated and the probability of capsize arrived at in this way.

This implies that a large number of long tests must be performed in a long tank with good wave generation properties.

4 Further References

[1] BHC Draft Report No X/O/3282, Nov 1985, Study of Float Positioning.

[2] BHC Report No X/O/3257, April 1986, Study of Fitting Scoops to Emergency Floats.

Appendix E1 Wave Height Probabilities on Helicopter Routes

Executive Summary

Research studies performed for the Civil Aviation Authority have considered the sea-states in which capsize of a ditched helicopter might occur. More recently there has been interest in the ability of helicopter emergency flotation systems to survive a crash into the sea, and thus keep the damaged helicopter afloat.

The risks associated with these occurrences are clearly dependent on the severity of the sea-state at the time of the incident, and the likelihood of any given sea-state is in turn dependent on the nature of the ocean wave climate. This climate varies considerably for different sea areas.

A study has been performed of the wave climate on helicopter routes used to serve the oil and gas industry in the North Sea and West of Shetlands. Six routes were selected to be representative of this traffic:

- Great Yarmouth to Murdoch (Block 44/22)
- Esbjerg to the Dan Field (55.5N, 4.9E)
- Aberdeen to Forties (Block 21/10)
- Aberdeen to Schiehallion (Block 204/20)
- Stavanger to Sleipner Field (58.5N,1.7E)
- Aberdeen to Hutton (Block 211/27)

The data has been interpreted in terms of the probability of exceeding particular sea-states which are referred to in the helicopter airworthiness certification requirements. Attention is drawn to the large difference in capsize risk, which is apparent from this data, between helicopters capable of withstanding sea-state 4 and those capable of withstanding sea-state 6.

The data can be used in other studies on particular helicopter types to assess risk of capsize following a ditching, and in order to assess the severity of wave impacts resulting from helicopter crashes in the sea.

1 Introduction

Research studies performed for the Civil Aviation Authority have considered the sea-states in which capsize of a ditched helicopter might occur [1]. More recently there has been interest in the ability of helicopter emergency flotation systems to survive a crash into the sea, and thus keep the damaged helicopter afloat [2].

The consequences of these occurrences are clearly dependent on the severity of the sea-state at the time of the incident, and the likelihood of any given sea-state is in turn dependent on the nature of the ocean wave climate. This climate varies considerably for different sea areas.

The objective of this study was to establish the wave climate along a representative selection of the main helicopter routes used to service the offshore oil and gas industry in the North Sea and West of Shetlands.

BMT Fluid Mechanics Limited (BMT) submitted a proposal [3] which suggested the use of archived data from the UK Meteorological Office wave forecasting model.[1] Six helicopter routes were chosen, and grid points were selected from the forecasting model which represented these routes. The work, was performed under the CAA contract [4].

Data was obtained from the forecasting model on the frequencies of occurrence of significant wave height, zero crossing period and wind speed, although the work of this present study considered only the significant wave height. The height frequency data was converted to probabilities of exceeding sea-states in the range 3 - 7.

These probabilities have been interpreted in terms of the risk of exceeding sea-states specified in airworthiness certification requirements.

2 Definitions

2.1 The Routes

It was considered that the main part of the population of helicopter flights in support of the oil and gas industry in the North Sea and West of Shetlands could be characterised by six routes as follows:

A	Aberdeen to Schiehallion (Block 204/20)
B	Aberdeen to Hutton (Block 211/27)
C	Aberdeen to Forties (Block 21/10)
D	Great Yarmouth to Murdoch (Block 44/22)
E	Stavanger to Sleipner Field (58.5N,1.7E)
F	Esbjerg to the Dan Field (55.5N, 4.9E)

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[1] **Note added in 2005:** This study was undertaken in 1997 using archived wave forecast data. If a similar study were to be performed today, the preferred wave data sources would be either satellite measurements or wave hindcast data sets such as *NEXT* or *NEXTRA*. Use of these later data sources would not significantly affect the outcome of the study, however.

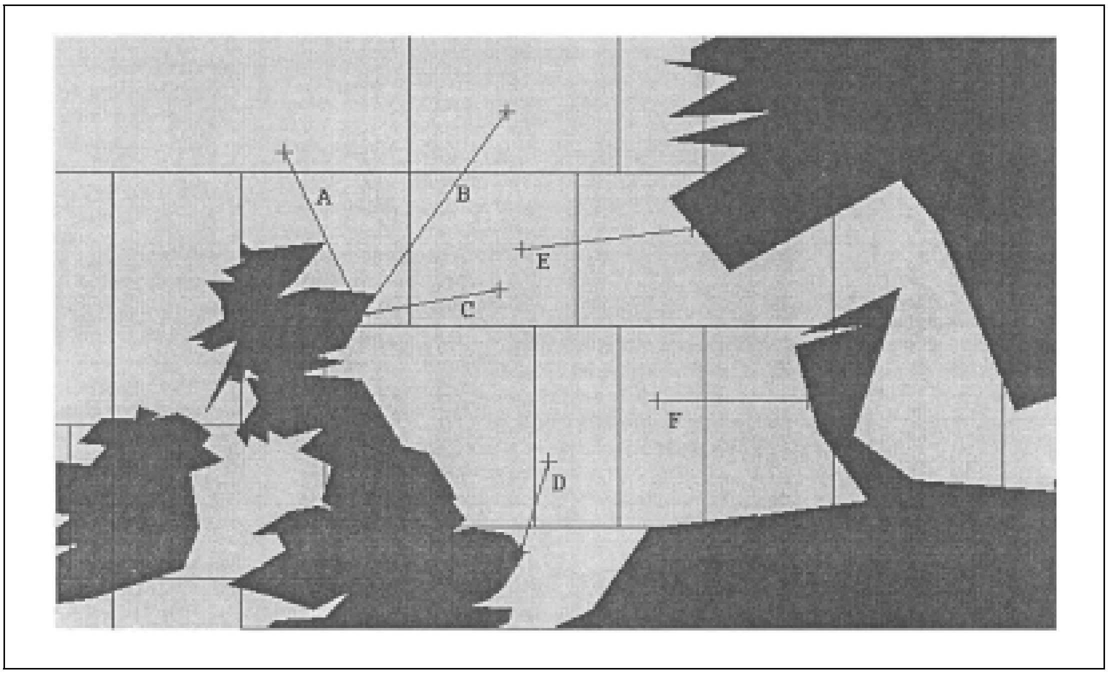

Figure 1 Helicopter Route Definition

2.2 Sea-states

The sea state definitions used in the study are listed in Table 1.

Table 1 Sea State Codes (World Meteorological Organisation [5)

Sea State Code	Description of Sea	Significant Wave Height	
		Metres	Feet
0	Calm (Glassy)	0	0
1	Calm (Rippled)	0 to 0.1	0 to $^{1}/_{3}$
2	Smooth (Wavelets)	0.1 to 0.5	$^{2}/_{3}$ to $1^{2}/_{3}$
3	Slight	0.5 to 1.25	$1^{2}/_{3}$ to 4
4	Moderate	1.25 to 2.5	4 to 8
5	Rough	2.5 to 4	8 to 13
6	Very Rough	4 to 6	13 to 20
7	High	6 to 9	20 to 30
8	Very High	9 to 14	30 to 45
9	Phenomenal	Over 14	Over 45

2.3 Meteorological Office Wave Model Data

The data used in the study was obtained from the UK Meteorological Office Wave Model Archive. This consists of the hindcast fields of winds and waves produced during the operation of the atmospheric and wave model forecast suite.

The model starts with all available reports of surface pressure, wind speed and direction (from ships, buoys, platforms and land stations), which are subjected to a range of consistency checks before being assimilated into the model's analysis. The resulting wind field is then used to modify the wave field derived from earlier model time steps. For each of the 16 directional and 13 frequency bands, the changes in wave energy are computed at each grid point, using the local wind as energy input, and allowing for propagation, dissipation and transfer between spectral bands.

The model is a so-called 'Second Generation' model, where the spectral shape is empirically defined, rather than being calculated at run time. Further details of the model's formulation may be found in [6] and [7]. There are two versions of the wave model, both in operation since 1986 - one covers the Global oceans, and the other European waters.

The Global Wave Model operates with an assumed fixed depth (200m) on a lat/long grid. The analysed fields of wind and one-dimensional spectra (i.e. energy within each spectral band, plus a mean direction for that band) have been archived, initially at 12-hour intervals and subsequently (since June 1988) at 6-hour intervals. The spatial resolution was initially approx. 150km (13.8k grid points); this was improved in June 1991, and is currently approx. 85km (37.3k grid points).

Nested within the Global Wave Model, and taking boundary conditions from it, is a European waters Wave Model. This is a depth-dependent second-generation model operating on a lat/long grid with spacing approx. 25km (8.5k grid points). The model covers West European waters to 14 deg W between 30.5N and 66.7N and also covers the Mediterranean and Baltic Seas; the Black Sea was added in 1993. Wind and wave hindcast values were archived initially at 6-hour intervals and since June 1988 at 3-hour intervals.

Output at each time step consists of wind speed and direction, plus either: 1-dimensional spectrum (energy and mean direction in each of the 13 spectral bands) or the conventional integrated variables derived from the spectrum i.e. significant wave height, period and direction for both wind sea and swell, together with resultant height and period).

Since the winds are taken from the lowest level of the Atmospheric Model, they represent conditions approximately 20m above mean sea level.

As with any operational model, there have been many small-scale improvements incorporated over the years. Most of these are introduced for computational reasons, to improve the efficiency of the calculations but some are more fundamental, the latest being the incorporation of wave height data from the ERS-1 satellite into the Global Wave model analysis with effect from June 1993 (see [8]).

Over the years there have been occasional interruptions to the operational routine due to mainframe malfunction. Consequently, there are some periods of missing data in the archive, most of them of 12 hours duration or less.

For the present study a total of 27 grid points were selected from the model. These were selected to be the closest to the helicopter routes and were taken to be representative of the six routes. Data provided was based on a total of 10 years (Oct 1986 - Oct 1996), which should provide a reasonably reliable climatic average.

The significant wave height statistics for each grid point along a route were summed and averaged in order to obtain a reasonable estimate of the wave statistics for each route as a whole.

3 Results

The results are presented as probabilities of exceedance of sea states. A sea-state is defined as a range of significant wave heights (see Table1), and the probabilities given in the results are the probability of exceeding the upper limit of this range.

Sea-state numbers are not an ideal way of referencing the size of waves for a number of reasons. They do not relate precisely to a particular wave height, and they do not contain any information on wave steepness or wave period. Furthermore the equivalent wave height definition of a sea-state has changed over the years, and this can cause confusion when referencing old documents and papers. However, much of the work on helicopter ditching and capsize has used this definition of wave height, and indeed the current ditching certification requirements are defined in terms of sea-state number. They are therefore used in this report.

The ability of a helicopter to remain upright in waves following a ditching is dependent on a number of factors including the design of the helicopter and its emergency flotation equipment and the severity of the waves it experiences, its heading to those waves, and so on. Although helicopters vary considerably from one type to another, most will capsize in sea-states in the range 4 - 6. However, the actual capsize event is invariably caused by a single large breaking wave. The occurrence of breaking waves of sufficient severity to cause the capsize is a function of the wave height, the wave steepness and the presence of wind.

It may be appropriate in a later follow-on study to analyse the wave periods and wind speeds in order to attempt to obtain a more direct measure of the incidence of breaking waves, and perhaps a more precise estimate of the probability of capsize. However, at this time knowledge of the helicopter capsize process, and the exact nature of the waves which cause it, is not sufficient to warrant such a sophisticated analysis.

The data was delivered as monthly frequency tables, but this was considered to be too detailed for the purposes of the current study, and so it was collected into four seasons of the year:

- December to February
- March to May
- June to August
- September to November

Data was also presented for the year as a whole.

Data from the Met. Office archived forecast model was received by BMT in the form of wave frequency tables which BMT converted into probability of exceedance, and plotted the result on Weibull axes. This involves plotting the ln (H_S) versus ln (-ln (P)) where H_S is the significant wave height in metres, and P is the probability of exceeding the significant wave height. This form of plot is commonly used for wave height data because the data will often approximate to the Weibull distribution shape, and will therefore appear on such a plot as a straight line. This makes it convenient to interpolate and extrapolate the data to find, for example, extreme values.

The upper limits of wave height corresponding to the various sea-state numbers, and the probabilities of exceeding these sea-states are listed in Table 2.

The Weibull plots are shown in Figures 2 - 6, where the statistics for each route are plotted. Data for the whole year is given in Figure 2, whilst the four seasons of the year are covered by Figures 3 - 6. Vertical lines drawn on these plots show the upper limit boundaries of the various sea-states.

Table 2 Probabilities of Exceedance of Sea State Limits

Season	**Route**	**Sea State Code and Upper limit (Hs)**				
		3	**4**	**5**	**6**	**7**
		1.25 m	**2.5 m**	**4 m**	**6 m**	**9 m**
		Probability of exceeding the sea state (%)				
All Year	A	62.6	31.5	11.9	2.7	0.2
	B	70.1	36.1	12.4	2.1	0.1
	C	61.3	25.7	6.6	0.7	0.0
	D	48.7	13.8	2.0	0.1	0.0
	E	68.7	34.9	12.1	2.1	0.1
	F	59.3	24.4	6.3	0.7	0.0
December February	A	79.8	51.0	24.3	6.8	0.6
	B	90.6	65.3	31.8	6.8	0.2
	C	83.0	50.6	19.3	3.0	0.1
	D	69.2	27.6	4.9	0.2	0.0
	E	89.5	63.6	30.9	6.9	0.2
	F	79.0	45.6	16.9	2.8	0.1
March May	A	64.6	31.4	10.6	1.9	0.1
	B	72.0	35.6	10.6	1.3	0.0
	C	61.6	24.2	5.3	0.4	0.0
	D	47.2	10.7	0.9	0.0	0.0
	E	68.0	31.6	8.9	1.0	0.0
	F	54.5	18.2	3.3	0.2	0.0
June August	A	41.0	8.2	0.7	0.0	0.0
	B	41.1	7.4	0.4	0.0	0.0
	C	31.5	5.2	0.4	0.0	0.0
	D	24.3	2.9	0.1	0.0	0.0
	E	41.6	8.1	0.6	0.0	0.0
	F	39.1	8.2	0.8	0.0	0.0
September November	A	66.8	33.2	11.2	1.9	0.1
	B	77.6	41.7	13.1	1.5	0.0
	C	67.7	29.1	6.8	0.5	0.0
	D	55.7	15.1	1.5	0.0	0.0
	E	76.3	39.8	12.1	1.3	0.0
	F	66.7	26.9	5.4	0.3	0.0

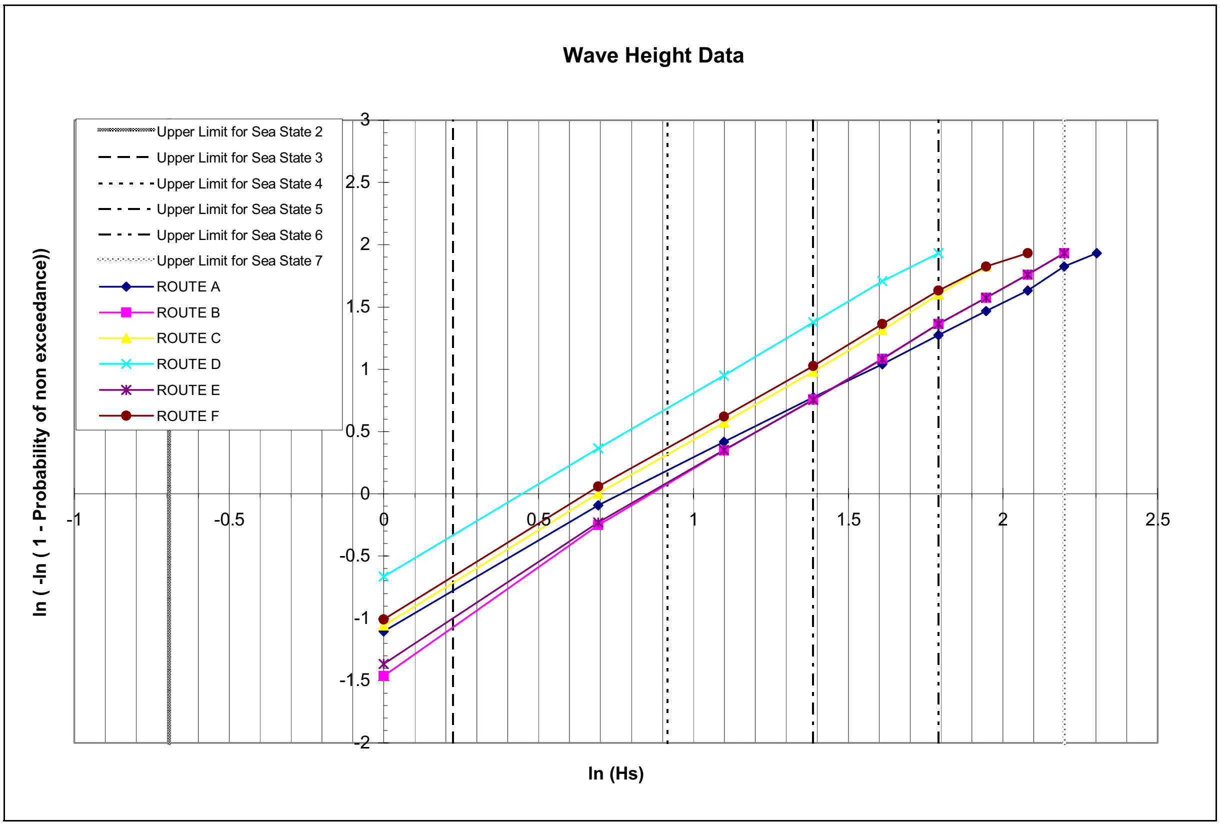

Figure 2 All Year Probabilities

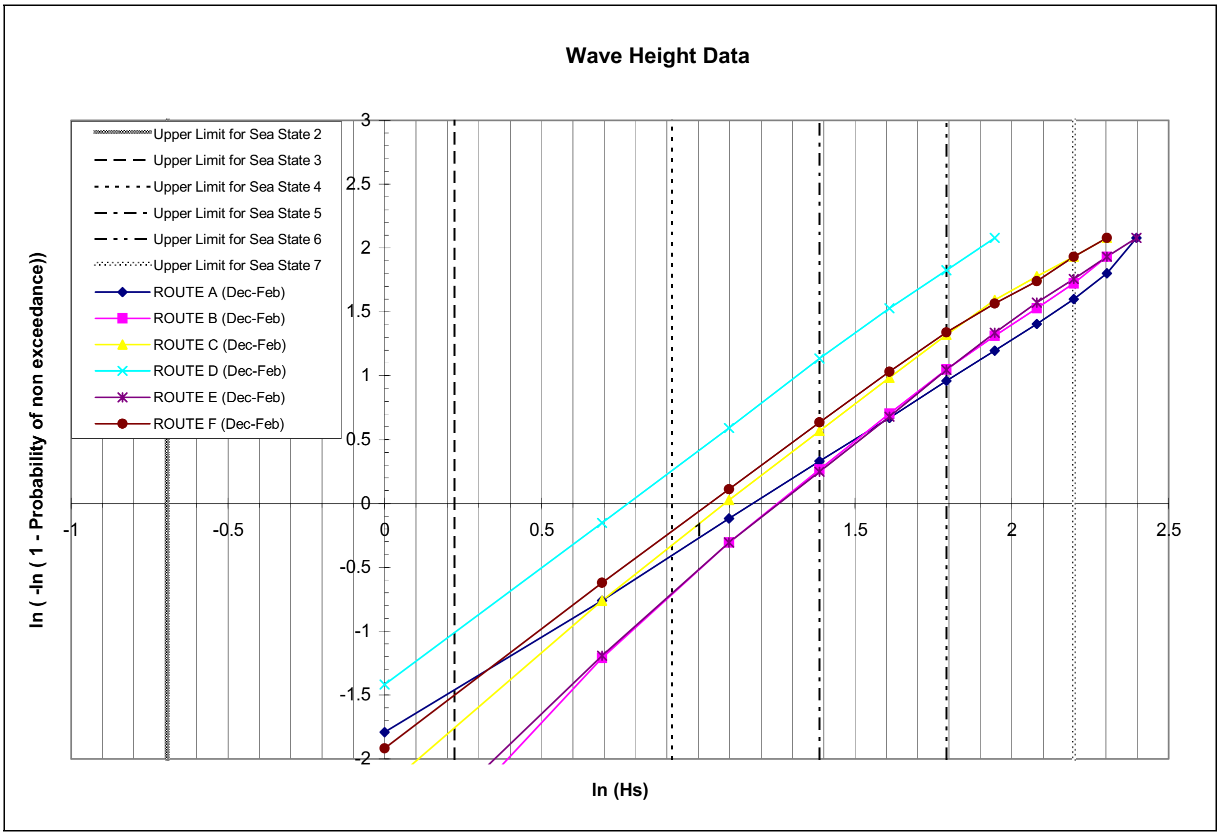

Figure 3 December-February Probabilities

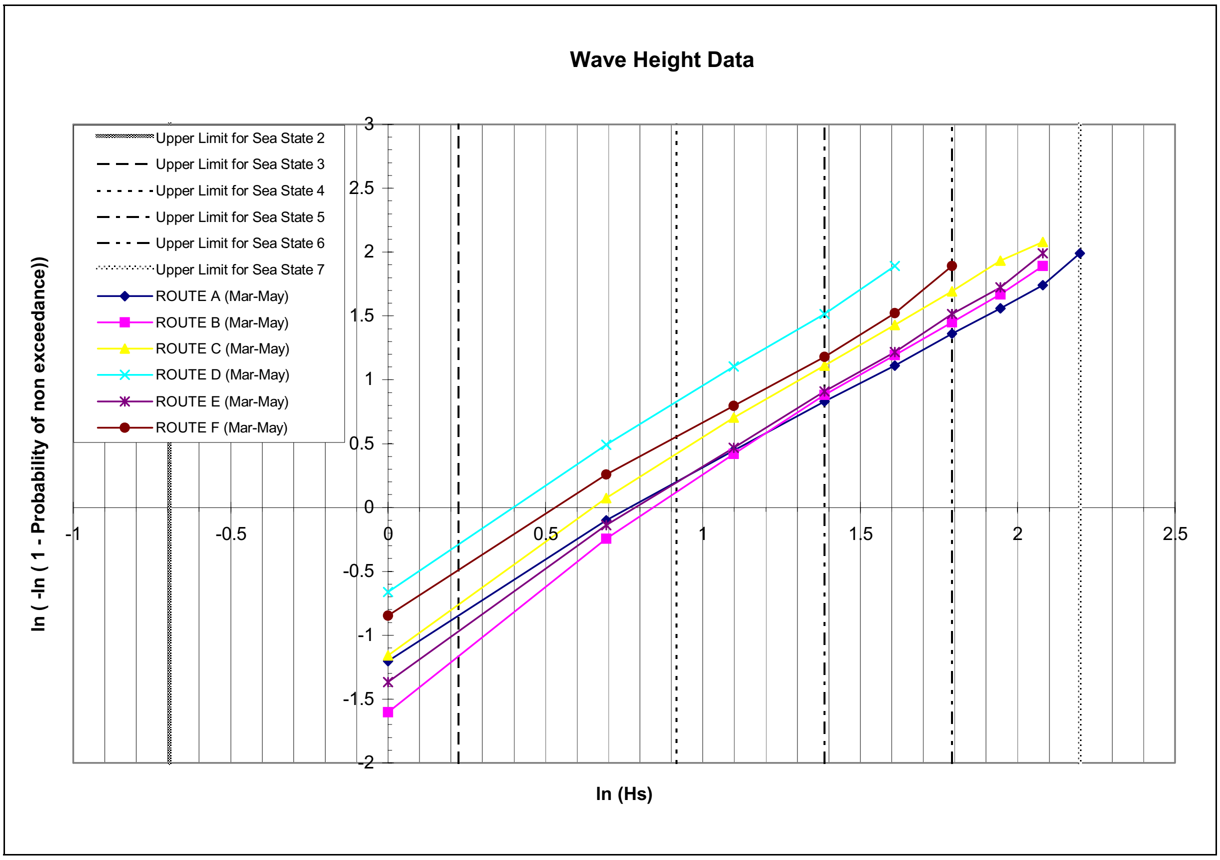

Figure 4 March-May Probabilities

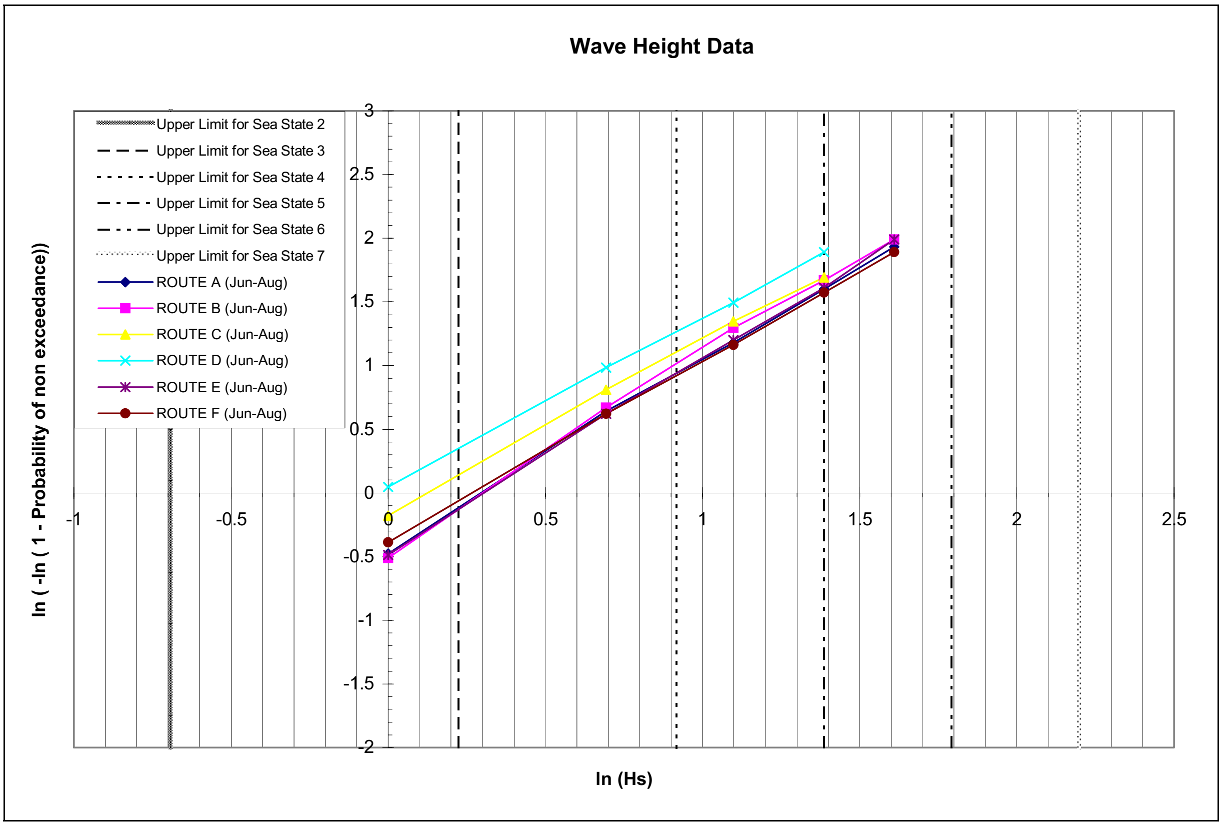

Figure 5 June-August Probabilities

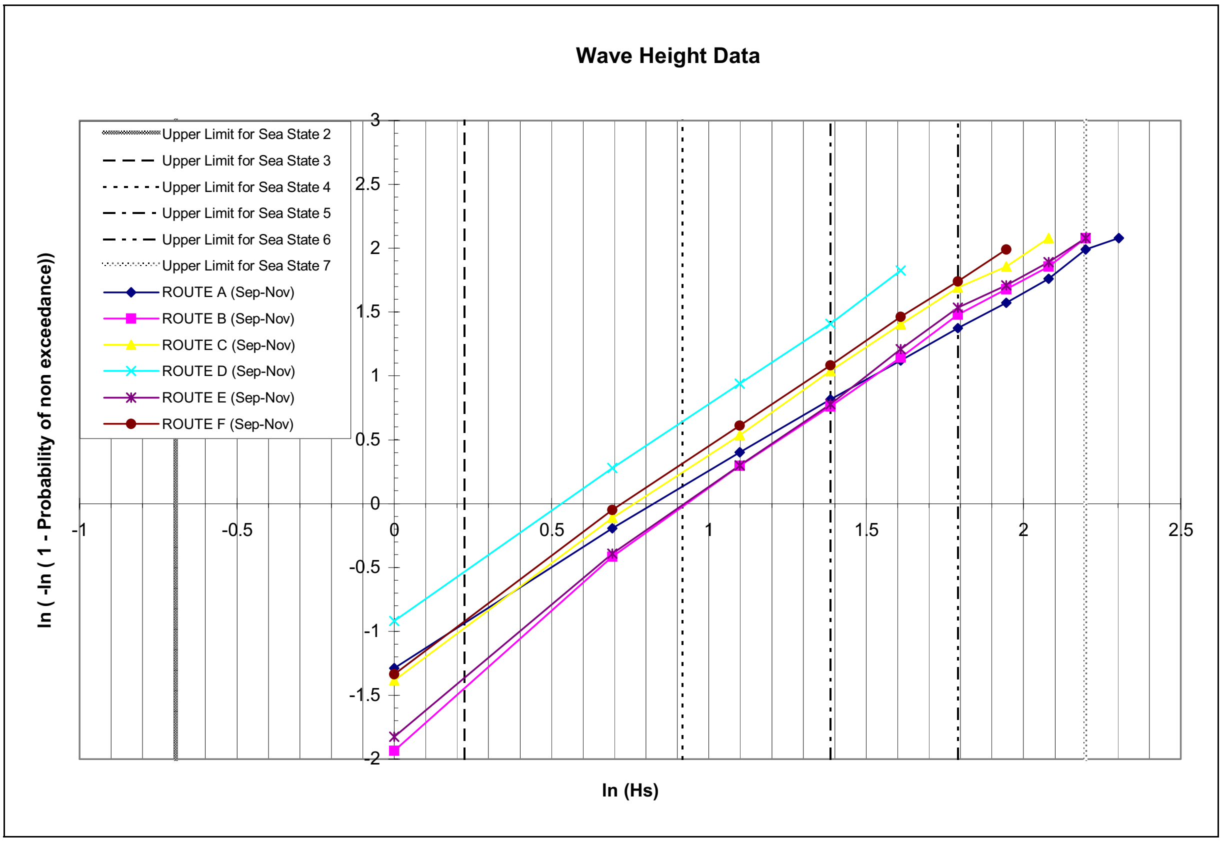

Figure 6 September-November Probabilities.

4 Discussion of Results

The probabilities of exceedance of the various sea-states for the routes needs to be considered in the light of the performance of the helicopter emergency flotation systems in resisting capsize.

This study has not considered any particular helicopter type, but a general appraisal can be made on the basis of the certification requirements on ditching. The two relevant requirements in this context are the BCAR [9] and the JAR [10]. Most helicopters in service in the North Sea today have been certified according to BCAR, but future new aircraft will be certified to JAR.

As noted in [11], the JAR is much less onerous than the BCAR in terms of remaining upright in particular sea-states. The BCAR requires investigation of flotation characteristics up to sea-state 6, whilst the JAR only requires sea-state 4. The probabilities of exceeding sea-state 4 and sea-state 6 can thus be usefully compared in Table 2.

It can be seen that overall there is a large difference in the probability of exceeding sea-state 4 and sea-state 6. If the whole year is considered, then the results for the six routes can be summarised as follows:

Probability of exceeding sea-state 6:

Route A - Aberdeen to Schiehallion (Block 204/20)	3%
Route B - Aberdeen to Hutton (Block 211/27)	2%
Route C - Aberdeen to Forties (Block 21/10)	1%

Route D - Great Yarmouth to Murdoch (Block 44/22)	>0%
Route E - Stavanger to Sleipner Field (58.5N,1.7E)	2%
Route F - Esbjerg to the Dan Field (55.5N, 4.9E)	1%

Probability of exceeding sea-state 4:

Route A - Aberdeen to Schiehallion (Block 204/20)	32%
Route B - Aberdeen to Hutton (Block 211/27)	36%
Route C - Aberdeen to Forties (Block 21/10)	26%
Route D - Great Yarmouth to Murdoch (Block 44/22)	14%
Route E - Stavanger to Sleipner Field (58.5N,1.7E)	35%
Route F - Esbjerg to the Dan Field (55.5N, 4.9E)	24%

In the northern North Sea (e.g. Route B) sea-state 4 is exceeded for 36% of the time. Thus a helicopter certified to sea-state 4 ditching on this route at a random time during the year would have a 1 in 3 chance of capsize. If, however, the helicopter was capable of fulfilling a more onerous requirement of sea-state 6, then there would only be a 2% (or 1 in 50 chance) of experiencing a capsize. This dramatically demonstrates the large difference in risk levels represented by different certification requirements.

The seasonal variations can also be seen from Table 2. Probabilities of Exceedance of Sea-state Limits. Taking route B as an example, the probability of exceedance of sea-state 4 varies from 65% in the winter months down to 7% in the summer months. Sea-state 6 is exceeded 7% of the time in the winter months and not at all in the summer months.

The climatic variation between the different routes is very much as expected. The most benign route is D from Great Yarmouth to the southern basin fields. The most severe are those in the North.

5 Summary and Conclusions

5.1 Summary

This project has established the wave climate along the main helicopter routes used to service the offshore oil and gas industry in the North Sea and West of Shetlands.

The results of this study provide information on the probability of experiencing or exceeding a range of significant wave heights or sea states on various helicopter routes in the North Sea and West of Shetlands.

These data can be interpreted in terms of risk of capsize of helicopters which have ditched on the surface of the sea.

They can also be used as part of studies of crashworthiness where the sea-state is one of the factors which may influence the severity of the wave impact, and hence the ability of the helicopter to remain afloat after the incident.

It was not part of the scope of the study to compare the risk of capsize for various individual helicopter types, but general conclusions may be drawn in relation to the certification requirements relating to ditching.

5.2 **Conclusions**

5.2.1 A helicopter able to remain upright in sea-state 6, will have the following probabilities of capsize on the routes considered (assuming that the ditching incident occurs at any random time throughout the year):

Route A - Aberdeen to Schiehallion (Block 204/20)	3%
Route B - Aberdeen to Hutton (Block 211/27)	2%
Route C - Aberdeen to Forties (Block 21/10)	1%
Route D - Great Yarmouth to Murdoch (Block 44/22)	>0%
Route E - Stavanger to Sleipner Field (58.5N,1.7E)	2%
Route F - Esbjerg to the Dan Field (55.5N, 4.9E)	1%

5.2.2 However, a helicopter only able to remain upright in sea-state 4 has the following, much higher probability of capsize:

Route A - Aberdeen to Schiehallion (Block 204/20)	32%
Route B - Aberdeen to Hutton (Block 211/27)	36%
Route C - Aberdeen to Forties (Block 21/10)	26%
Route D - Great Yarmouth to Murdoch (Block 44/22)	14%
Route E - Stavanger to Sleipner Field (58.5N,1.7E)	35%
Route F - Esbjerg to the Dan Field (55.5N, 4.9E)	24%

5.2.3 These results show the expected trends in risk between the southern North Sea, and the northern sector and West of Shetlands. The most benign route is route D from Great Yarmouth to the southern fields, whilst the most onerous are those in north from Aberdeen and Stavanger (routes A, B and E).

5.2.4 The difference in capsize risk represented by the difference between sea-state 6 and sea-state 4 is very marked. A sea-state 6 helicopter will have a 2% risk of capsize following a ditching on Route B (Aberdeen to Hutton), whilst a sea-state 4 helicopter will have a 36% risk of capsize on the same route. This is the difference between a 1 in 50 risk of capsize as compared with 1 in 3 risk of capsize.

5.2.5 The seasonal risk data presented in Table 2. Probabilities of Exceedance of Sea State Limits, offers the possibility to compare risk of capsize for different helicopter types throughout the seasons, and to consider the possibility that certain helicopter types should be used on certain routes only during the more benign seasons of the year. For example, the sea-state 4 compliant helicopter referred to in the previous paragraph will reduce its risk of capsize following ditching by about a factor of about 5 if only operated on Route B during the summer months.

5.2.6 Finally it should be noted that this study has only considered the wave climate in terms of significant wave height, but it is known that the capsize of helicopters is mainly caused by the presence of breaking waves, and these are in turn are a function of the wave steepness and the presence of wind. There is a need to improve understanding of the wave conditions causing capsize, and this information could then usefully be combined with the available data on wave period and wind speed in order to provide more reliable estimates of the capsize risk.

6 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] Report of the Review of Helicopter Offshore Safety and Survival, Civil Aviation Authority, CAP 641, February 1995.

[3] BMT Fluid Mechanics Limited Proposal No. Q94434_2, 1st October 1996,

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[11] Helicopter Ditching JAR Certification Requirements, BMT Fluid Mechanics Limited Report 44035 Report 3 Release 2, 28th November 1995.

Appendix E2 The Ditching of G-TIGK - 19/1/95

1 Introduction

The Aerospatiale AS332L Super Puma helicopter G-TIGK ditched in the North Sea at a location 6nm South West of the Brae Alpha oil production platform on the 19th January 1995. The circumstances of the ditching are fully reported in [1]. A photograph of the ditched helicopter is shown in Figure 1.

The sea conditions at the time of the ditching were rough (sea-state 5) but the emergency flotation systems worked well, and the helicopter did not capsize. The crew and passengers were able to escape to the life-rafts without injury. The helicopter eventually sank a few hours later when the flotation became damaged as attempts were made by a vessel to get alongside for salvage purposes.

The Civil Aviation Authority (CAA) requested BMT Fluid Mechanics Limited (BMT) to gather some further information on the weather conditions in order to help set the apparently good performance of the emergency flotation system into context with research work on helicopter ditching. The study was commissioned by CAA in [2].

2 Scope of Work

The work performed by BMT in this short study may be summarised as follows:

- Review of AAIB report [1].
- Commissioning of an “Assessment of Weather Conditions” from the Met Office [3].
- Commissioning of numerical results from the Met. Office's Wave Model [4].
- Analysis and presentation of the Wave Model data.
- Interpretation of the Met. Office Assessment and data in terms of the expected performance of the helicopter emergency flotation system.

3 Results

It was clear from [1] that the helicopter had behaved reasonably well in quite severe sea-states; “six to seven metre waves and a 30kt southerly wind”, and had “remained afloat for some 3 hours 30 minutes”.

The assessment in [3] indicated that the sea-state was “Rough” (or sea-state 5) from 0900 UTC to 1500 UTC, meaning a significant wave height H_s in the range 2.5 - 4.0m. Such a sea-state is likely to result in largest individual waves up to about 7m high, and so this information is quite consistent with that given in [1].

The weather assessment gave the general synoptic situation at the time as; “a frontal trough crossed the area from the west with a fresh to strong south to south-westerly airflow over the area”. An infrared satellite image timed at 1150 UTC on 19/1/95 (available on the Internet from the Dundee Receiving Station) is given in Figure 2.

It can be seen from the photograph in Figure 1 that the helicopter is riding quite rough seas containing some 'whitecaps'. The helicopter appears to be heading approximately into wind (the wind direction being judged on the basis of the whitecaps). It is not known at what time the photograph was taken.

Model test research on ditched helicopters [5] has generally indicated that many types may be expected to capsize at around sea-state 5 or 6, but this research has also emphasised the tremendous importance of wave steepness in the capsize process. Helicopter capsize is initiated by breaking waves and the occurrence of these breaking waves is largely dependent on the steepness.

In the random ocean wave environment the steepness is normally defined in terms of the Significant Steepness [6]:

$$S_s = \frac{2\pi H_s}{g{T_z}^2}$$

Where:

H_S = significant wave height

T_Z = zero-crossing period

Values of significant steepness less than 1/18 are generally regarded as not particularly steep waves, whilst a value in the region 1/15 would be regarded as quite steep. There is a theoretical limit to the steepness at about 1/12. Waves steeper than this cannot persist because of wave breaking and other wind/wave interaction processes.

In order to obtain some information on both the wave steepness and the likely wave spectrum shape at the time of the ditching, the data in [4] was commissioned and a slightly longer time period from 0900 UTC to 1800 UTC was requested. The results of BMT's analysis of this data are summarised versus time in Figure 3. The omni-directional (point) wave spectra are presented in Figure 4, and the directions of the wave frequency components are given in Figure 5.

It should be emphasised that the Met. Office data is from their Wave Model, and are **not** measurements made at the time. The Wave Model works as part of the general weather forecasting process, taking wind speed and direction predictions over a large area, and calculating the resulting wave conditions every 3 hours via a complex semi-empirical computer model. The model provides wind and wave estimates at grid points which cover the oceans, and their primary use is the provision of sea-state forecast information. The closest grid point to the location of the ditching is at 58°30'N 1°08'E which happens to be extremely close to the location of the ditching given in [1] as 58° 36'N 1° 10'E.

Figure 3 shows the Significant wave height Hs (m), the wind speed V_W (m/s), the 1/Significant steepness S_S and the wind direction V_{dir} (deg true from), as they vary with time over the period of interest. The wind speed was fairly constant from 0900 to 1500 at about 13 m/s, but the direction started backing at about 1200, going from 175 deg to 150 deg by 1800 UTC. It had also strengthened to 16 m/s by 1800 UTC.

The significant wave height was quite constant from 0900 to 1500 at 2.9m, but had increased to 3.6m by 1800. Figure 4 shows the virtually constant wave spectrum shapes from 0900 to 1500, but also shows that by 1800 additional energy had grown the spectrum peak considerably.

The significant steepness was calculated from the significant wave height and from the peak period of the spectrum given in the Met. Office data. The peak period was converted to an estimate of the zero-crossing period by dividing by the factor 1.4 for an ITTC spectrum shape. (It was not considered that the spectral shape information was sufficiently reliable or of wide enough bandwidth to warrant a determination of the zero crossing period by integration of the spectral moments.) Figure 3 shows that the significant steepness was constant at 1/21 from 0900 to 1500, but had increased to 1/17 by 1800 UTC.

4 Conclusions

Although detailed measurements of the wave conditions at the time of the ditching are not available, all the evidence points to the fact that the waves were not more severe than sea-state 5 (i.e $H_S > 4.0$m) at any time between 0900 UTC and 1800 UTC on 19th January 1995.

However, the conditions were getting worse in the latter stages of the helicopter ditching, and were reaching a value nearer the top of sea-state 5 by the time the helicopter sank.

The evidence is that the sinking occurred due to damage caused to the emergency flotation system, rather than as a result of worsening weather alone.

Although small spilling breakers (or 'whitecaps') can be seen in the photograph taken at the time, the sea-state, as evidenced by the data from the Met. Office wave model, was not particularly steep. Consequently it is considered that there would not have been breaking waves present of sufficient magnitude to cause capsize. Furthermore, the photograph shows the helicopter apparently floating with a heading into the wind and waves. If this was the case throughout, then this would also have been a major factor reducing the likelihood of capsize.

5 References

[1] Air Accident Investigation Branch, Air Accident Report No: 2/97 (EW/C95/1/1). (Also available on the AAIB web site at http://www.open.gov.uk/aaib/gtigk)

[2] CAA Contract 7D/S/1096/3 Amendment No 1, 28/7/97.

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[4] Met. Office Wave Model Data, grid point 58.5oN, 001.14oE for the period 0900 UTC 19th January 1995 - 1800 UTC 19th January 1995 (data received from the Met. Office on diskette).

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

[6] Offshore Installations, Guidance on their Design, Construction and Certification, The Health & Safety Executive, Fourth edition with amendments 1993.

Figure 1 G-TIGK Drifting After Evacuation of the Occupants.

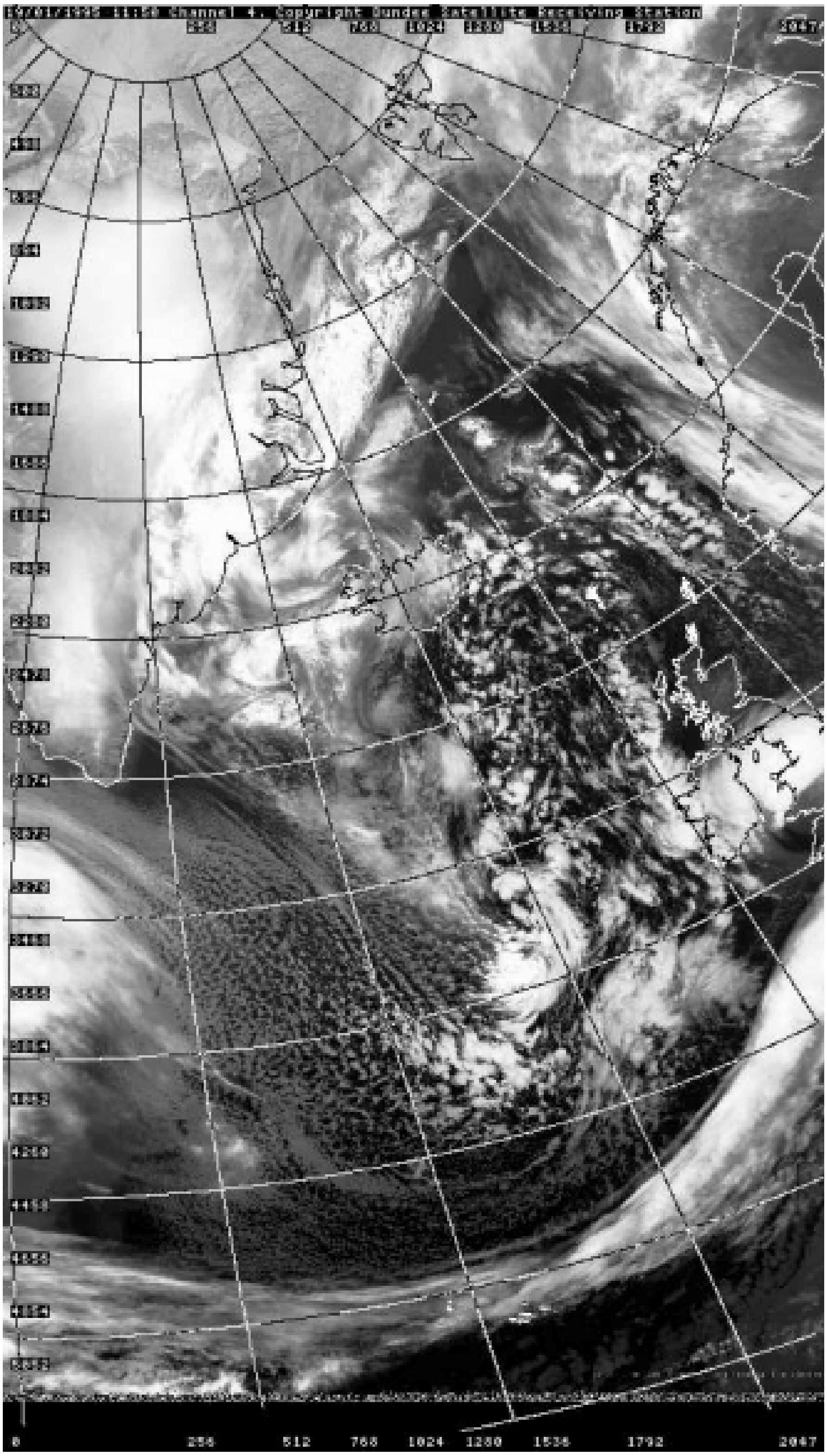

Figure 2 Infrared Satellite Image at About the Time of the Ditching.

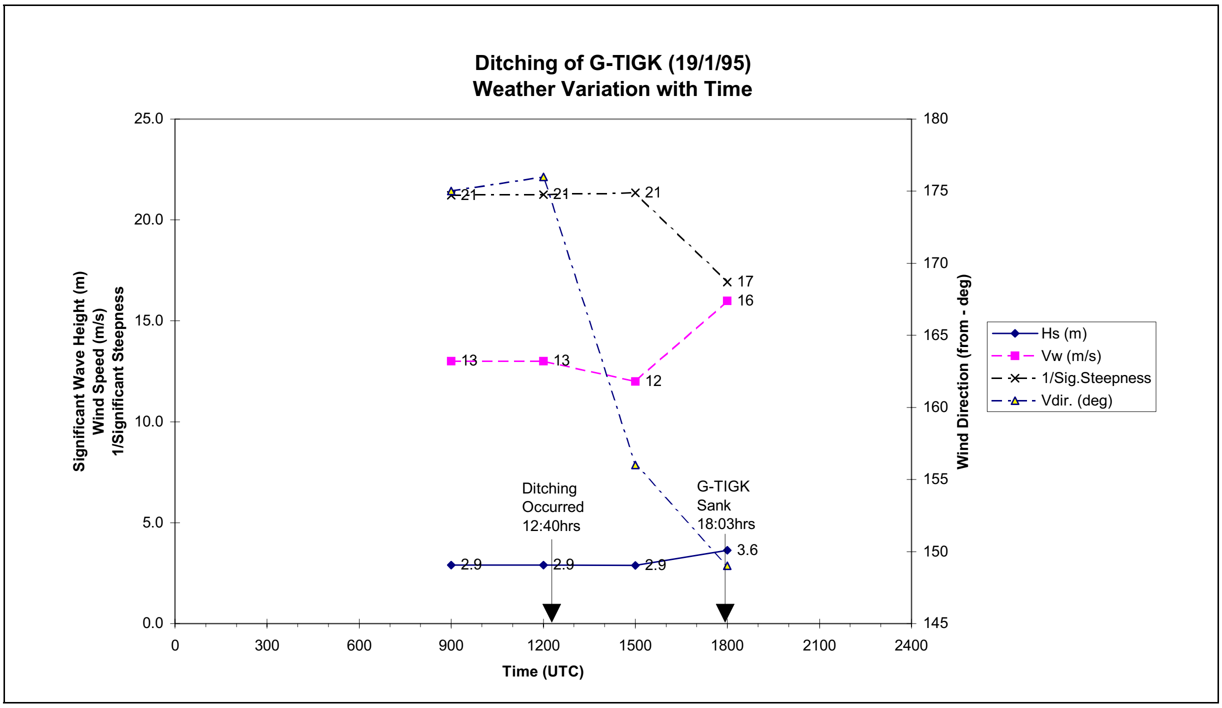

Figure 3 Weather Variation with Time

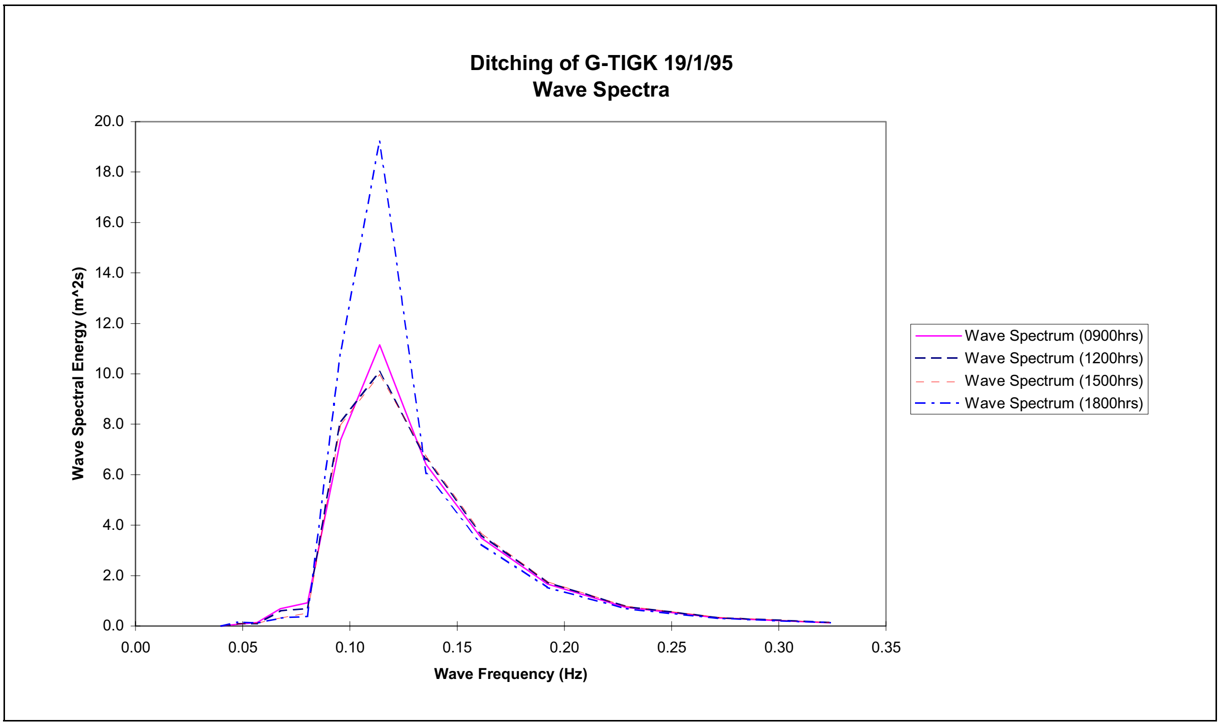

Figure 4 Wave Spectra

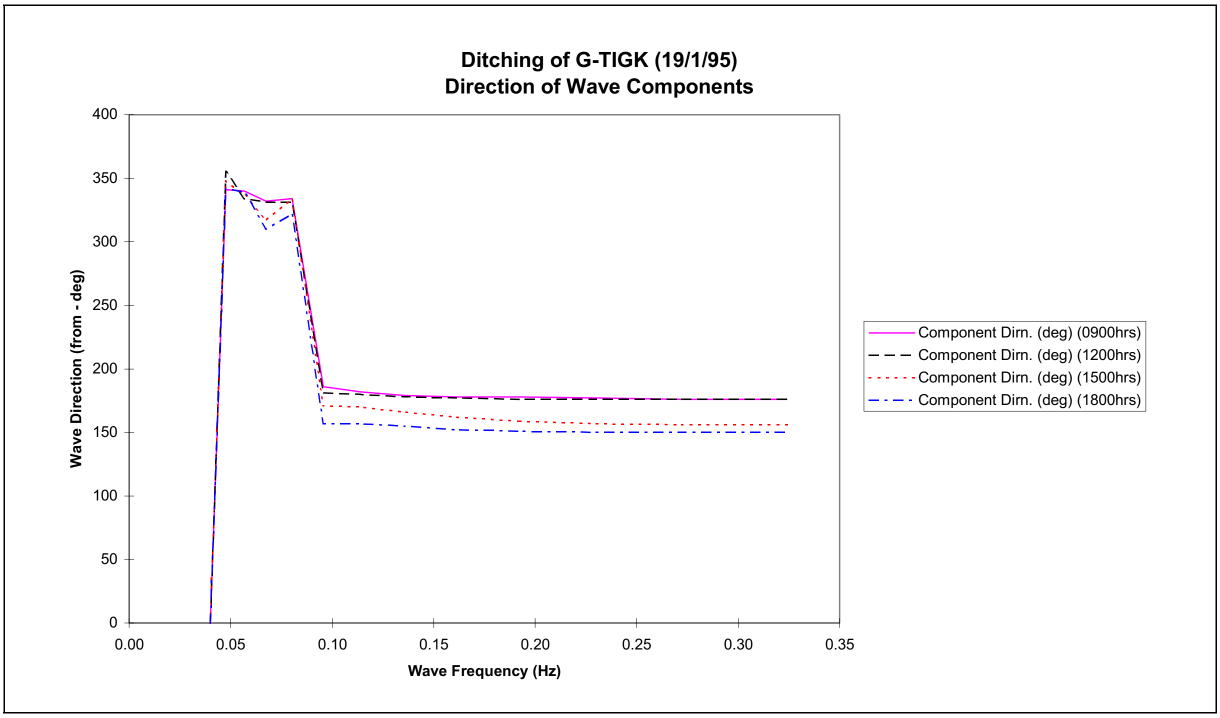

Figure 5 Direction of Wave Components

Appendix F HOSS Paper on Helicopter Safety and Occupant Survivability

Ref. HOSS/WP-99/8.5

OFFSHORE OPERATIONS - HELICOPTER SAFETY AND OCCUPANT SURVIVABILITY FOLLOWING DITCHING OR WATER IMPACT

1 Aim

The aim of this paper is to review the airworthiness standards currently associated with both intentional ditching and unintentional water impact in the light of service experience and ongoing research into occupant safety and survivability, and to recommend where improvements should be made.

Over-water helicopter operations are permitted in the knowledge that emergency situations may arise which require an immediate and forced landing. Accordingly, ICAO Annex 6 Part 3 paragraphs 2.2.11 and 4.5.1, and national operating rules specify those circumstances where approved flotation and safety equipment must be carried, and ICAO states that **Sea State shall be an integral part of ditching information**.

Currently, in both JAR and FAR rotorcraft airworthiness requirements, there are two standards of flotation equipment which can be approved. The first, which is applicable to both JAR/FAR 27 and 29 is Ditching Equipment. The second, which is only applicable to JAR/FAR 27 is referred to as Emergency Flotation Equipment. The airworthiness requirements applicable to both are generally the same except that Emergency Flotation Equipment is not required to meet any prescribed standards for the water entry phase.

FAA Advisory Circulars AC 27-1 and 29-2 define Ditching as an emergency landing on the water, deliberately executed, with the intent of abandoning the rotorcraft as soon as practical. For the purposes of this paper, it is assumed that Emergency Flotation Equipment is intended to achieve the same aim as Ditching Equipment.

Following a ditching onto the surface of the water however, there are conditions which will cause a helicopter floating upright to capsize before abandonment has been completed. In these circumstances, evacuation will have to be carried out from an inverted and flooded cabin with the occupants probably suffering from severe disorientation and cold water shock. Service experience has brought about a number of design features which can significantly enhance occupant survivability in these circumstances. A number of these features are currently not required by the airworthiness codes.

Accident data indicates that unintentional water impact is also to be expected and, in otherwise survivable crashes, the major cause of fatalities is drowning. There are currently no crashworthiness certification requirements specific to water impact. Recent research into accident data has concluded that improvements in the crashworthiness of flotation equipment would significantly enhance post crash survivability.

2 Discussion

2.1 General

Both JAR and FAR rotorcraft airworthiness codes currently contain a number of requirements, some optional, appropriate to the potential need to carry out an emergency alighting on the water. FAR/JAR 27 and 29.801 Ditching requires that the rotorcraft must **under reasonably probable water conditions, be shown to be able to remain upright on the surface of the water for sufficient time to allow the occupants to leave the rotorcraft and enter the life-rafts**. It is recognised in the code however, that the rotorcraft may be capsized and that occupants may have to escape from an inverted and flooded hull. A review of operational experience in the Northern European offshore areas indicates that current JAR/FAR requirements do not adequately address all aspects of ditching and subsequent occupant safety and survivability. A summary of over-water accidents is provided at Annex A. The following requirement inadequacies have been identified.

2.2 Ditching Flotation Stability

2.2.1 Capsize Boundary

As previously stated FAR/JAR 27/29.801 Ditching requires under paragraph (d) that flotation and stability must be demonstrated in **reasonably probable** sea conditions. Paragraph (b) requires that measures **must be taken to minimise the probability that in an emergency landing on water, the behaviour of the rotorcraft would cause immediate injury to the occupants or would make it impossible for them to escape**. Experience suggests that the greatest risk to the occupants in a ditching is drowning due to inability to evacuate the aircraft following a capsize and subsequent flooding of the hull.

Taken on their own, the FAR/JAR would require the designer to select a reasonably severe wave condition for the area in which he expects the helicopter to operate and to demonstrate that the probability of a capsize has been minimised. FAA and JAA however, have adopted an interpretation (AC29-2A paragraph 337(a)(3)) which states that **Sea State 4 is considered to satisfy the reasonably probable requirement**.

Although sea keeping qualities vary from one helicopter type to another, most types currently in use will capsize in sea states in the range 4 to 5 and above. A recent study of wave climates along a representative selection of main helicopter routes in the northern North Sea and West of Shetland (regarded in JAR-OPS 3 as a Hostile environment), indicates that Sea State 4 will be exceeded on 26-36% of occasions over the whole year (Ref. 1). During the winter period between December-February, this increases to between 51-65%. If the certification requirement was raised to Sea State 6, the risk of exceedance would fall to a maximum of approximately 3% over the whole year and 3-7% in the winter months.

Research into the effects of fitting scoops to flotation equipment has demonstrated an improvement in the resistance to capsize of most helicopters (Ref. 2). This indicates that expectations of improvements in flotation stability of the order of one sea state are realistic. Installation of scoops does however increase loads on flotation equipment and the airframe. This will affect airframe weight and costs but these have been estimated to be quite modest, i.e. fitting scoops to a large helicopter would result in an overall increase in cost of the helicopter of about 0.3%. This is considered to be justifiable when compared with the significant reduction in the risk of capsize.

Whereas the proposal to require enhanced flotation stability is considered appropriate for operations in hostile environments such as the North Sea, it may not be appropriate for a number of other operating environments, e.g. the Gulf of Mexico.

Having regard to current FAA and JAA operating rules and Industry requirements for straightforward certification standards, the following is proposed:

a) **For Non-Hostile environment; Emergency Flotation Equipment should be the standard. The current interpretation of the JAR/FAR 27.801(d) requirement to demonstrate flotation stability in reasonably probable sea conditions as being Sea State 4, is considered to be appropriate for this class of flotation equipment.**

b) **For hostile environments; the flotation stability requirement of JAR/FAR 27 and 29 should be amended to require a higher standard of Sea State 6 for Ditching Equipment.**

NOTE: As Sea State codes are ambiguous, capsize boundary targets should be specified in terms of significant wave height, zero crossing period and wave spectrum.

2.2.2 Demonstration of Compliance

The traditional method of demonstrating compliance with 27/29.801(d) is to determine a capsize boundary by model testing in regular wave conditions of a given maximum height/length ratio. This methodology has been discredited by naval architects who state that results of such tests are likely to depend more on the properties of the wave basin at the test facility than of the helicopter model itself. This is because capsizes are caused by breaking waves and the breaking of a regular wave in a basin is largely a matter of wave quality. Consequently, the best helicopter performance will appear to be obtained in the basin that can generate the steepest *non-breaking* regular waves. Numerous wave basins are now available that can generate irregular waves which are significantly more representative of actual sea conditions. Investigation has shown that the cost of regular and irregular wave testing can be comparable.

If irregular wave testing is to be adopted, the immediate questions are what probability of capsize and what period of exposure should be regarded as acceptable. Historically, an exposure period of 5 minutes to allow for rotor run-down, life-raft deployment and egress of all occupants has been assumed and there appears to be no compelling reason to modify this figure.

As regards probability of capsize, one approach would be to set a safety target based on the likelihood of its occurrence, derived from service experience, and the consequences of the failure condition. This has the advantage of producing a rational methodology for determining a certification test plan. In the absence of any form of mitigation, a helicopter ditching which results in a capsize before the occupants can make good their escape could be expected to cause the death of a number of them through drowning; there is known to be an incompatibility between breath hold capability in typical North Sea temperatures and escape times from a capsized helicopter despite the use of immersion suits (Ref. 7). Efforts should therefore be made to determine the current ditching/capsize rate and define a safety target appropriate to the consequences of a capsize. A comparison of the two would determine the scope of certification effort required to meet the ditching requirement of 27 & 29.801, as previously stated.

In view of the above, it is proposed that:

a) **The AC material be amended to specify irregular wave testing with an appropriate exposure period and target probability of capsize.**

b) **A standard test protocol for demonstration of compliance using irregular wave testing be developed and adopted.**

NOTE: As Sea State codes are ambiguous, irregular wave test conditions should be specified in terms of significant wave height, zero crossing period and wave spectrum shape.

2.3 life-raft Installation

Following the successful ditching of a Sikorsky S61N in 1983 (Annex A Event 5), problems were encountered during deployment of both life-rafts. The rear life-raft was successfully deployed and inflated but was found to have deflated some minutes later. It had been punctured after coming into contact with part of the aircraft's structure, believed to be the VOR aerial. The forward life-raft was subsequently deployed but was itself punctured after coming into contact with the cargo door rail. Both life-rafts were thus rendered unusable by damage sustained after coming into contact with the aircraft's structure.

In May 1986, a Bell 214ST (Annex A Event 6) was forced to ditch onto a calm sea following partial loss of collective control. The aircraft was fitted with two life-rafts mounted externally in the forward fairing on top of the cabin roof. The rafts are normally launched by the crew pulling a 'D' ring mounted in the cockpit overhead console. As a back-up, manual deployment is possible by opening the external cabin roof stowages by rotating individual emergency latch handles on the rear lower face of the fairing. The decals indicating life-raft stowages and instructions for manual deployment were located adjacent to the handles in approximately ¼ inch lettering. Upon safely alighting onto the water, the crew activated the cockpit 'D' rings but the life-rafts failed to deploy. Subsequently, one life-raft was quickly deployed using the manual release but the other was not. Because a crew member was unable to reach the operating mechanism, he directed a passenger to release the life-raft. Difficulties were encountered and it was considered (by the accident investigator) that the external identification of the stowage and the explanatory legend on operation of the release handle were inadequate both in size and colour (Ref. 3). Had the helicopter overturned, it is unlikely that either life-raft would have been available.

Following inadvertent impact with the sea during an inter-rig transfer at night in poor weather in March 1992 (Annex A Event 10), an AS332L capsized and flooded. Of the two life-rafts carried, only one was deployed. The other, which was installed in a box structure beneath two seats, was not. Following a Fatal Accident Inquiry in Scotland and a UK Air Accident Investigation Branch investigation, the UK CAA commissioned a review of safety and survival aspects of offshore helicopter flights. This was carried out by a group consisting of government agencies, medical institutions, research organisations and offshore operators. The group was known as the Review of Helicopter Offshore Safety and Survival (RHOSS) and after a detailed investigation recommended, inter alia, that CAA should determine the best method of life-raft carriage and release (Ref. 4). In doing so, they should take account of the RHOSS findings that:

- primary deployment should be by a single action by the crew in their normal positions, and
- secondary deployment should be from the passenger compartment with the rotorcraft in an upright attitude, and
- deployment should also be possible from outside the rotorcraft when in an upright or inverted attitude.

A small specialist group was set up in the UK who developed a draft of a technical standard for life-raft installations taking into account these recommendations.

In Jan 1995 an AS332L (Annex A Event 11) was forced to ditch after having been struck by lightning. The ditching was successful and all occupants transferred to life-rafts after jettisoning the cabin doors. The life-raft lower chamber was however, punctured when it came into contact with the edge of a floating door. On older helicopter types, jettisonable doors were usually made from metal and could be expected to sink. Use of composite material may, as in this case, produce doors skins separated by a low density core which will float for a period after being jettisoned. As in the case of this accident, the buoyancy is thought to have prevented the door from falling away from its retention mechanism. The rolling motion of the helicopter is thought to have induced a torsional load on the door attachments which failed. The broken edges are believed to have punctured the life-raft. It is proposed that:

a) **FAR/JAR be amended to require design of life-raft installations incorporating the following principles:**
   - **primary deployment by single action from normal crew positions,**
   - **secondary deployment from passenger compartment with the cabin in an upright attitude, and**
   - **deployment possible from outside the helicopter when in either an upright or inverted attitude.**

b) **FAR/JAR advisory material be revised to indicate that 'delethalisation' of the fuselage area in proximity to the installation is necessary to prevent life-raft damage.**

2.4 Post Ditching Capsize

The current ditching requirements do not preclude the helicopter encountering a wave which causes capsize. FAR/JAR 29.811 for example, requires that emergency exit markings must remain visible in the event of a capsize and submerged cabin. Service experience has indicated that other measures are necessary to ensure a reasonable chance of evacuation from a capsized helicopter.

2.4.1 Cabin 'Push-out' Windows, Emergency Lighting and Seating Layout

Following unusual in-flight noise and vibration and subsequent loss of transmission oil pressure, the pilot of an S61N in November 1988 (Annex A Event 8) was forced to carry out a ditching at very short notice. The conditions were Sea State 6 and the helicopter immediately inverted. The 2 crew and 11 passengers all managed to evacuate the hull but none used the normal exits. The helicopter had been fitted with 'push-out' windows in the cabin and all passengers and one of the crew members used these to escape. In the accident investigation, push-out windows were acknowledged as having made a fundamental contribution to occupant survivability (Ref. 5). On a number of underwater escape trials however, it was noticed that difficulty was sometimes experienced in physically removing the window once the release mechanism had been operated. Hand holds sited close to the windows would help the occupants to apply enough force to ensure release.

For large rotorcraft, FAR/JAR 29.811 requires that **each passenger emergency exit, its means of access, and its means of opening must be conspicuously marked for the guidance of occupants using the exits in daylight or in the dark. Such markings must be designed to remain visible for rotorcraft equipped for over-water flights if the rotorcraft is capsized and the cabin submerged**. In December 1997, a Sikorsky S76 inadvertently impacted the water during a night approach to a helideck (Annex A Event 14). The flotation equipment was not activated and the helicopter inverted immediately. The emergency lighting in the cabin illuminated just after impact and was reported to have been of great help during the evacuation (Ref. 6). Where the method of marking requires illumination from a power source, it is considered that the system should be automatically activated following flooding of the cabin. This requirement should be extended to apply also to 'push-out' windows. In addition, a minimum standard of conspicuity should required.

Given the high risk of disorientation to be expected following a capsize and flooding of the cabin, successful location and use of a push-out window is more probable if seat rows are located in-line with windows. Optimising the seating configuration in such a way will reduce the need for occupants to have to move from their seats in order to locate an escape opening with the subsequent reduction in the required breath-hold time.

In view of the above it is proposed that:

a) **FAR/JAR 27.807 and 29.809 be amended to require that all apertures in passenger compartments suitable for the purpose of underwater escape shall be made openable in such an emergency, and hand holds should be provided adjacent to such apertures to assist their location and operation. Associated advisory material should be developed to indicate what constitutes a 'suitable' aperture.**

b) **Emergency exit marking systems should also be required on 'push-out' windows and be automatically activated following flooding of the cabin.**

c) **Seat rows should be aligned with windows.**

2.4.2 Mitigation of Breath Hold Difficulties

The difficulties of escape from an inverted and submerged helicopter have long been recognised and a number of lessons learnt, as discussed in Section 2.4.1. Even with the adoption of all these measures, there is the potential for the occupants of an inverted helicopter not be able to hold their breath long enough to escape to the surface. Research has shown that maximum breath hold time in cold (10 deg C) water during simulated helicopter underwater escapes can be as low as 13.5 seconds (17.2 +/- 3.7 sec) despite wearing of warm clothing and immersion dry suits (Ref. 7). Underwater escape, however, typically takes between 16.5 and 47 seconds (even with push-out windows). Optimisation of cabin layouts and other measures can minimise escape times, but times of around 30 seconds are nevertheless to be expected for occupants who have to await the escape of a neighbour prior to making their own exit. A disparity between breath hold capability and escape time will thus continue to exist unless further measures are taken.

2.4.2.1 Side Floating Helicopters

As part of its ongoing investigation of the stability of ditched helicopters, the UK CAA instigated research into novel emergency flotation devices intended to prevent total inversion following capsize. The intended function of such devices is to ensure that following capsize, an air space is maintained within the cabin and some of the cabin doors and windows remain above the water level, thus affording a less hazardous escape route for the occupants. The work was carried out by BMT Fluid Mechanics Limited with assistance from GKN-Westland Helicopters Limited (Ref. 8). Following consideration of a number of design solutions which included model testing of the three most highly ranked, it was established that the concept of additional emergency flotation equipment could be effective in preventing total inversion. The two most promising solutions were considered to be buoyant cowling panels in areas close to the main rotor and additional flotation units high up on the side of the fuselage. The effect of a side floating attitude (say 150° from the vertical) would be to provide an accessible air gap within the cabin and a number of push-out windows and ditching emergency exits above the waterline. This would significantly reduce the risks associated with an escape from a capsized helicopter.

Follow-up research into the human factors aspects of this concept has demonstrated a significant reduction in required breath hold time and has indicated that escape from a side floating helicopter is easier than from a fully inverted cabin. Nevertheless, it is realised that more work on the overall costs/benefits still needs to be done. It is therefore proposed that:

- **The potential benefits of the side floating helicopter concept in respect of post ditching capsize be recognised and support for its further development be given.**

2.4.2.2 Emergency Breathing Systems (EBS)

There are currently available a number of systems which provide the wearer with a limited supply of air, specifically with the aim of escaping from a submerged helicopter. There are two basic systems, one of which provides a supply of pressurised air and another which uses air exhaled by the wearer. There is also a third system available which uses a combination of both features.

The provision of such an underwater air supply could solve the breath hold problem, provided it was always available to the wearer in the circumstances associated with a capsize, and did not unduly hinder his escape. In this respect there are a number potential difficulties associated with all systems which require further investigation. It is therefore proposed that:

- **Research be carried out into the use of EBS in order that all aspects of its use can be properly considered.**

2.5 Water Impact Crashworthiness

Whereas ditching certification is intended to ensure safe water entry, flotation stability and occupant evacuation in **reasonably probable water conditions**, helicopters frequently operate over seas which are outside of the ditching envelope. Attempts to alight on such water conditions, or impact with water at speeds in excess of the ditching envelope, will not necessarily benefit from ditching provisions. Once again, service experience has indicated that other measures can enhance survivability in such conditions.

2.5.1 Automatic Deployment of Flotation Equipment

There have been a number of accidents where aircraft have impacted the water in an uncontrolled manner, the flotation equipment has survived the impact but has not been manually activated by the crew. Research carried out by Westland Helicopters in the UK (Ref. 9) and independently in the USA on behalf of the FAA (Ref. 10) has identified drowning to be the major cause of loss of life. Aircraft occupants having survived the initial impact then failed to safely escape from the hull.

In March 1992, an AS332L (Appendix 1 Event 10) crashed into Sea State 7 conditions during an offshore night flight. Only 6 of the 17 occupants survived. Although the impact was severe, post crash investigation indicated that the flotation system may have survived and been at least partially available, had it been activated. The crew did not have time to manually activate it and there was no automatic means. The accident investigators considered that inflated flotation bags would have prevented the hull from rapidly sinking and assisted passenger evacuation from the inverted cabin by allowing it to float higher in the water.

In September 1996, an AS350B1 (Annex A Event 12) was carrying out low level over-water filming with 2 persons on board. For reasons unknown, but suspected to be inadvertent closure of the fuel control lever, rotor rpm dropped and the aircraft descended into the sea. Although the pilot attempted to, he did not have enough time to manually activate the emergency flotation equipment. The helicopter impacted the sea, inverted with the subsequent loss of the passenger.

Provision of a means to automatically inflate both ditching and emergency floatation equipment could have prevented loss of life in the above accidents. It is therefore proposed that:

- **FAR/JAR 27 and 29.1415 be amended to require the provision of means to automatically inflate both ditching and emergency flotation equipment following water entry.**

NOTE: For helicopters where is not possible for the emergency flotation system to remain armed throughout the flight, automatic disarming/rearming should be required.

2.5.2 Flotation System Crashworthiness

As previously mentioned, the FAA and Westland Helicopters Limited accident review studies both came to the conclusion that a significant cause of death in helicopter water impacts was through drowning. They went on to further conclude that, had the helicopter's emergency flotation system been more crashworthy, the risk of drowning could be significantly reduced. Follow-on studies were carried out by W S Atkins and BMT Fluid Mechanics Limited on behalf of the UK CAA. Their aim was initially, to determine if it would be possible to define enhanced structural requirements for emergency flotation systems based on loading cases experienced during survivable water impacts. Whilst this work found that it was not practical to define such requirements, it did identify the benefits of a number of measures.

In the event of a survivable water impact, the risk of drowning will be greatest if the helicopter rapidly sinks. To some degree, automatic deployment of the emergency flotation system will reduce this risk but will not address the structural aspects of the system's survivability. The results of the BMT and WS Atkins research indicate that provision of redundant flotation at bag level rather than at compartment (within a bag) level, and relocation of flotation equipment away from primary impact sites could provide significant improvements in crashworthiness. It is therefore concluded that enhancing crashworthiness could be combined with the possible future requirement for means to prevent total inversion following post-ditching capsize (see paragraph 2.4.2.1). Locating additional flotation on the upper part of the airframe would increase flotation redundancy and minimise the effects of crash damage on the overall performance of the flotation system.

Other measures were identified which, although not mentioned in the requirements or advisory material, are considered to be standard practice within the industry. These measures included:

- Use of flexible hoses on flow distribution lines.
- Routing of hoses/wiring to avoid areas likely to be severely deformed in an impact.
- System deployment after impact with water.
- The flow distribution system should be designed to ensure equal float deployment (timing as well as volume) even with system/bag damage.
- Bags should be divided into multiple cells to limit the effects of minor bag ruptures.

In view of the above, it is recommended that:

a) **The potential benefits of the side floating helicopter concept in respect of flotation system crashworthiness be recognised and support for its further development be given.**

b) **Appropriate requirements/advisory material be generated and adopted to reflect current practice in terms of emergency flotation system crashworthiness.**

3 Conclusions

A review of current ditching and other certification requirements associated with the possibility of a forced landing on or impact with water, clearly indicates that occupant survivability considerations do not take account of service experience. In addition, the accepted method of compliance for determining flotation stability is no longer considered to be acceptable.

Through service experience and associated research, a number of design features have been identified which would enhance occupant survivability following a water landing/impact. In some instances these features are already accepted as representing a minimum standard for over-water operations in hostile areas. It is considered that certification requirements should urgently be reviewed and amended to reflect an improved airworthiness standard.

4 Recommendations

It is recommended that JAA, FAA and Industry urgently carry out a review of JAR/FAR 27 and 29 airworthiness requirements with a view to update those associated with ditching and water impact crashworthiness. This effort should address both short and longer term aims as indicated below:

4.1 Recommended Changes to Requirements

Research and service experience indicates that the following proposals are justified;

a) Revision of FAR/JAR 27 and 29.801 advisory material to indicate that **reasonably probable water conditions** for Ditching Equipment certification should be equivalent to Sea State 6, and Sea State 4 for Emergency Flotation Equipment (capsize boundary targets to be specified in terms of significant wave height, zero crossing period and wave spectrum). See paragraph 2.2.1.

b) Revision of FAR/JAR 27 and 29.801 advisory material to indicate that flotation stability substantiation should be based on representative (model) testing in irregular waves, and that an associated standard test protocol should be developed and adopted. See paragraph 2.2.2.

c) Revision of FAR/JAR 29.1411 and associated advisory material to require design of life-raft installation and methods of deployment to take account of the ditching envelope w.r.t. sea conditions, and to be operable and accessible when the helicopter is both upright and capsized. Furthermore, projections on the exterior of the rotorcraft which may damage a deployed life-raft must be either moved or delethalised. See paragraph 2.3.

d) Revision of FAR/JAR 29.809 to add a new requirement that all apertures in passenger compartments suitable for the purpose of underwater escape shall be openable in an emergency, and that hand holds should be provided adjacent to such apertures to assist their location and operation. Additionally, guidance should indicate that passenger seating should be arranged so that each seat row is aligned with a 'push-out' window, and that emergency exit marking systems should be automatically activated following flooding of the cabin. See paragraph 2.4.1.

e) Revision of FAR/JAR 29.1415 to require that any flotation system installed to meet ditching requirements, should be designed so as to automatically inflate upon water entry (to include automatic arming where appropriate). See paragraph 2.5.1.

f) Addition of new material to FAR/JAR to reflect current best practice in terms of emergency flotation system crashworthiness. See paragraph 2.5.2.

4.2 Recommended Future Work

a) As a matter of urgency, establish the regulatory need and expected benefits/ disbenefits of emergency breathing systems carried to enhance the prospects of successful egress from an inverted and flooded cabin.

b) Establish the costs and expected benefits/disbenefits of redundant flotation units configured so as to produce a 'side floating' helicopter following capsize.

5 References

[1] BMT Fluid Mechanics Project No. 44140/00 - Wave Height Probabilities on Helicopter Routes (17 July, 1997).

[2] CAA Paper 95010 - Helicopter Float Scoops (December 1995).

[3] UK AAIB Accident Report 9/87.

[4] UK CAA CAP 641 - Review of Helicopter Offshore Safety and Survivability.

[5] UK AAIB Accident Report 1/90.

[6] Dutch Transport Safety Board Accident Report on Sikorsky S76-B (PH-KHB).

[7] Tipton, M.J. The Relationship Between Maximum Breath Hold Time in Air and the Ventilatory Responses to Immersion in Cold Water. Eur. J. Appl. Physiol. (1992) 64: 426-429.

[8] CAA Paper 97010 - Devices to Prevent Helicopter Total Inversion Following a Ditching.

[9] CAA Paper 96005 - Helicopter Crashworthiness.

[10] FAA Reports DOT/FAA/CT-92/13 & 14 - Rotorcraft Ditchings and Water Related Impacts that Occurred from 1982-1989.

Annex A Summary of Over-Water Accidents

Table 1 Summary of Over-Water Accidents

	Aircraft	Ditching/ Crash	Cause	Capsize	Sea State	Occupants	Post Crash/Ditching Difficulties
1	S61N G-ASNM15 Nov 1970AAIB Report 11/71	Ditching	Loss of transmission oil pressure.	Yes	4-5	2 crew, 1 pax.	i) Deployment of sea anchor difficult. ii) life-raft punctured by aircraft structure.
2	S61N G-BBHN 1 Oct 1977.AAIB Report 8/78	Ditching	Severe vibration & control feedback.	Yes	8	2 crew, 1 pax	i) life-raft could not be extracted from cabin. ii) Cargo door could not be restrained in open position to allow retrieval of life-raft. iii) Upturned cabin difficult to locate because its light colouring blended with breaking waves
3	S61N G-BEID31 July 1980AAIB Bulletin 14/80	Ditching	Loss of gearbox cooling. High temperature and low pressure.	No	3	2 crew, 13 pax.	i) Slight problems keeping the life-raft close to aircraft during boarding.
4	Bell 212 G-BIJF12 Aug 1981AAIB Report 10/82	Crash	Pilot disorientation in poor visibility. Loss of control followed by vertical impact.	Yes	?	1crew, 12 pax.1 fatality.	i) Flexible pipe to right hand floats damaged by fuselage distortion. Subsequent gas leak prevented inflation. ii) Only 1 life-raft installed. It was not deployed by survivors and was considered to be inaccessible. Two life-rafts recommended.
5	S61N G-ASNL11 March 1983AAIB Report 4/85	Ditching	Main gearbox failure	No	1-2	2 crew, 15 pax.	i) Both life-rafts punctured by contact with sharp fuselage obstructions on or close to waterline.
6	Bell 214 ST G-BKFN15 May 1986AAIB Report 9/87	Ditching	Partial loss of collective control	No	1-2	2 crew, 18 Pax	i) Automatic deployment of life-rafts failed. Manual deployment difficult. ii) Fwd compartment of both side floats failed due to abrasion on fuselage members. iii) Difficulty in pushing out 'secondary' windows. Note - not designated as 'push-outs'

Table 1 Summary of Over-Water Accidents

	Aircraft	Ditching/ Crash	Cause	Capsize	Sea State	Occupants	Post Crash/Ditching Difficulties
7	S61N G-BDII17 Oct 1988AAIB Report 3/89	Crash	SAR a/c loss of control at night in hover.	Yes	?	4 crew	i) Release of rear port emergency exit by survivor inside inverted and submerged cabin not found possible. Lighting not adequate to locate mechanism.
8	S61N G-BDES10 Nov 1988AAIB Report 1/90	Ditching	Failure of main transmission combiner gear.	Yes	6	2 crew, 11 pax.	i) Pax could not hear PA above aircraft noise with ear protectors.Note. Push-out windows acknowledge as making a fundamental contribution to survival.
9	S61N G-BEID13 July 1988AAIB Report 3/90	Ditching	Uncontrolled fire in main transmission bay.	No	2-3	2 crew, 19 pax.	i) Port rear Emergency Exit/life-raft difficult to release in rapidly thickening noxious smoke.
10	AS332LG-TIGH14 March 1992AAIB Report 2/93	Crash	Inadvertent controlled flight into sea.	Yes	7	2 crew, 15 pax11 fatalities	i) Flotation equipment survived impact but was not deployed. Automatic deployment could have improved occupant survivability. ii) life-raft stowed in cabin inaccessible to survivors following capsize and flooding.
11	AS332L G-TIGK19 Jan 1995AAIB Report 2/97	Ditching	Lightning strike resulted in loss of tail rotor gearbox.	No	6	2 crew, 16 pax.	iii) life-raft damaged by aircraft structure.
12	AS350 OY-HEC13 Sept 1996HCL No 62/96	Crash	Power loss. Crash onto water.	Yes	Calm	1 crew, 1 pax	i) Not enough time to manually activate flotation gear.
13	Bell 212 OY-HMC2 Jan 1984Danish Accident Report 3/86	Crash	Loss of tail rotor drive	Yes	6	2 crew, 1 pax	i) Heavy impact at night. Floats inflated manually but damaged on impact. ii) Co-pilot's life-jacket not properly fitted.
14	S76-B PH-KHB20 Dec 1997Dutch Accident Report	Crash	Inadvertent controlled flight into sea.	Yes	4	2 crew, 6 pax	i) Flotation system not armed. ii) The two internally mounted life-rafts could not be deployed.

Appendix G Water Impact, Ditching Design and Crashworthiness Working Group Recommendations

Water Impact/Ditching – Working Group

The Water Impact, Ditching Design, and Crashworthiness Working Group (WIDDCWG) was tasked by the Joint Harmonization Working Group (JHWG) to review the current regulatory requirements and advisory guidance pertaining to rotorcraft water impact and ditching, and review existing research data associated with rotorcraft survivable water impact and ditching scenarios. Based upon this review, the WIDDCWG was to survey effective intervention strategies and present recommendations to the JHWG for changes or additions to the current regulatory requirements and/or advisory guidance.

The WIDDCWG was comprised of representatives for the Federal Aviation Administration (FAA), Joint Aviation Authorities (JAA), Civil Aviation Authority (CAA), US and European Industry. Over a period of approximately fifteen months, the WIDDCWG met on three separate occasions. The kick-off (first) meeting was held October 27 through 28, 1998 at the FAA Rotorcraft Directorate in Fort Worth, Texas. At this meeting, numerous research documents were distributed to each of the team members for self-study and review. Based on this self-study and review, each team member was tasked with developing recommendations for intervention strategies and determining areas of concern pertaining to the current regulatory requirements and/or advisory guidance.

The second meeting was held June 7 through 8, 1999 at Eurocopter in Marignane, France. During this meeting, briefings were presented on two research programs being conducted for the CAA. The FAA discussed the current research activities that are being conducted by the U.S. Army, the U.S. Navy, and the FAA.

The third meeting was held January 18-20, 2000 in Las Vegas, Nevada, prior to the HAI Heli-Expo 2000. During this meeting, the final recommendations for changes/additions to regulatory and/or advisory guidance were discussed with a consensus vote on the recommendations for changes to address water impact/ditching for rotorcraft.

The following recommendations represent the cumulative efforts of the WIDDCWG and are presented for the consideration and action of the JHWG. They are grouped under three headings: **Water Impact, Ditching, and Post Ditching Egress/Survivability**.

1 Water Impact.

1.1 Water Impact Crashworthiness.

Recommendation:

Structural ditching requirements should not be expanded to consider crashworthiness due to:

a) high variability of the impact loads, and

b) impact loads in survivable accidents can be too high to design for in a practical manner.

Structural ditching requirements are currently defined in terms of the horizontal and vertical velocities of the rotorcraft at the time of impact with the water. Research indicates that, although impact velocity greatly affects impact loads, other impact parameters also have a significant effect. In particular, the attitude of the rotorcraft fuselage skin relative to the surface of the water at impact has a large effect on local impact loads; it is not considered practical to define an impact attitude envelope as this depends on the condition of the water surface at the point of impact as well as the attitude of the itself, and is therefore highly variable.

Research into the range and variability of impact loads indicates that extremely high local impact loads can be generated in moderate (survivable) impacts. In the example studied, doubling the design strength was found to provide only a 15% improvement in crash resistance.

1.2 Automatic Activation of Flotation System.

Recommendation:

The activation flotation system should be automatically activated (either primary or secondary means) upon sensing water immersion.

Analysis of accident data indicates that, in a significant number of impacts, the emergency flotation system did not deploy because it was not activated. Current systems typically require pilot activation of a manual switch for deployment. It is considered unreasonable to rely on manual activation in the event of an impact due to the high risk of excessive pilot workload and/or pilot incapacitation.

1.3 Flotation System Arming/Disarming.

Recommendation:

During any flight over water, the possibility of the automatic float activation feature being disabled e.g. deactivation of the system should be minimized.

Analysis of accident data indicates that, in a significant number of impacts, the emergency flotation system did not deploy because it was not armed. Many current systems require the pilot to manually arm the system prior to take-off, and then disarm at a particular airspeed. In the event of an impact, the pilot is often unable to re-arm the system due to excessive workload and/or incapacitation. An automatic disarming function, e.g. based on an airspeed switch, would eliminate this problem. Automatic activation by means of immersion sensing (Recommendation 2) is ineffective if the system is not armed. The inclusion of an altitude sensing element should also be considered to cater for high speed, shallow descent impacts.

For rotorcraft for which inadvertent deployment could be hazardous, it is considered undesirable for the emergency flotation to be armed unnecessarily, i.e., when not operating over water.

1.4 Containment of Float Compartment Damage.

Recommendation:

Float bag design should provide a means to minimize the likelihood of tear propagation between compartments.

1.5 External Handholds/Life Lines

Recommendation:

Handhold/life lines should be installed where practical and feasible to allow person to hold on to an upright or inverted rotorcraft. (for AC)

Accidents have occurred where survivors have escaped from the cabin but have not been able to board a life-raft and have had difficulties finding anything to grasp in order to stay afloat.

2 Ditching

2.1 Ditching Flotation Stability

Recommendation:

The current interpretation of 27/29.801 (d) 'reasonably probable water conditions' should be amended to address a broader consideration of regional climatic sea conditions.

Current AC material for 27/20.801 Ditching, interprets "reasonable probable water conditions" as Sea State 4. A review conducted by the UK CAA indicated that in some rotorcraft operating areas, there is significant exposure over the year to sea conditions which exceed those modelled during ditching certification. A study of North Sea wave climate data along six representative rotorcraft routes has established that the probability of exceeding Sea State 4, the current design target in the AC material, is 28% averaged over the whole year. This rises to 51% during the winter months. In view of the ditching rate and the likely consequences of a capsize, a higher design target for the certification of ditching flotation systems is considered necessary. Given this and the practicality of achieving better roll stability by the incorporation of features such as float scoops (see paragraph 2.3), higher standards for ditching certification should be considered. It was noted however, that the predominant use of single engine rotorcraft in non hostile sea area could allow retention of existing sea state requirements for rotorcraft fitted with Emergency Flotation Equipment (see paragraph 2.2)

2.2 Emergency Flotation Equipment Stability Requirements

Recommendation:

Maintain present Sea State 4 for emergency flotation systems and a higher Sea State for ditching flotation systems.

It is recommended that the reference to Sea State 4 in the AC material be replaced by two sets of wave conditions corresponding to emergency flotation systems and ditching flotation systems. The rotorcraft equipped with emergency flotation systems generally operate in less severe environments than rotorcraft that are certificated for ditching and equipped with ditching flotation systems. The current AC guidance does not differentiate between the two flotation systems in terms of flotation stability requirements; consequently the ditching certificated rotorcraft operating in these more severe environments have no more safety benefit than the rotorcraft certificated to lesser requirements and operating in the more benign environment (see paragraph 2.1).

2.3 Float Bag Scoops

Recommendation:

The benefits of flotation stability of fitting scoops to flotation bags should be identified in guidance material.

Model tests in a wave basin of a number of different rotorcraft types have indicated that an improvement in sea keeping performance of approximately one sea state can consistently be achieved by fitting float scoops. Although float attachments would need to be designed to accommodate the additional flotation loads generated by the scoops, the associated costs are estimated to be modest.

2.4 Irregular Wave Spectra Model Testing

Recommendation:

For certification purposes model testing should use irregular waves and suitable guidance material should be developed that provides a specific test procedure with pass/fail criteria and defined test conditions.

This would provide clear, non-ambiguous design guidance. Experience has shown that regular wave testing results in over-predicting the sea state capability in real waves. It also allows the model to assume the natural sea-keeping attitude. The testing should be performed with wind and removal of dry floor criteria should also be strongly considered. The current length-to-height ratio requirements as defined by the World Meteorological Organization (WMO) should be eliminated from the AC guidance and replaced by the sea state conditions defined in terms of significant wave height, zero crossing period and spectrum (e.g. the Joint North Sea Wave Program (JONSWAP).

It is known that rotorcraft are essentially only capsized by breaking waves; by definition regular waves do not break and therefore no rotorcraft model should, in theory, ever fail regular wave tests. In practice however, wave tanks are unable to produce perfect regular waves and breaking waves do occur causing capsizes. The steepness at which regular waves break is largely dependent on the characteristics of the wave basin and the location of the model relative to the wave maker. It is therefore possible to generate a wide range of capsize boundaries for a single rotorcraft model using regular wave tests. The results of regular wave tests are therefore considered to provide a poor indication of the actual sea keeping performance of ditched rotorcraft. Irregular wave testing, properly defined and carried out, address these deficiencies.

2.5 Use of Fuel Jettison

Recommendation:

Fuel jettison aspects should be removed from regulations.

The design operational weight and center of gravity conditions cover the entire spectrum for which certification is requested. Buoyancy must be provided for all design conditions and is independent of the amount of fuel in the tanks. For rotorcraft with underfloor fuel tanks (the majority), jettisoning of fuel will not alter the buoyancy of the aircraft but will reduce its weight and raise its center of gravity. This is likely to degrade the stability of the ditched rotorcraft.

2.6 Flight Manual Limitations.

Recommendation:

Explicitly state in flight manual supplement, the capability and limitations of the flotation system installed on the aircraft.

The current AC guidance addresses the ditching certification and the approval of emergency flotation systems. The accepted practice and guidance for installing floats on rotorcraft that are not certificated for ditching have evolved over a long period of time and has caused some confusion over the operational capabilities of such equipment. Prior to changes in FAR 27/29.563, there was not a significant regulatory difference between the approval for ditching and emergency flotation systems. Under the current approval process, there could be a situation when emergency floats are installed on a rotorcraft that was originally ditching certificated which may be a safety concern. Therefore, the certification standard of flotation equipment should be specifically addressed in the rotorcraft manual and any limitations defined.

3 Post Ditching Egress/Survivability

3.1 Means to Prevent Total Inversion

Recommendation:

HASG/JHWG should consider incorporating this concept in the requirements once research has been completed and if shown to be technically feasible and economically viable.

Research to date has indicated side-floating concept has potential for significant improvement in survivability in water impacts and post ditching capsizes. However, further work in the following areas of concern is needed which include:

- Air drag.
- Weight.
- Handling qualities in normal flight.
- Handling qualities with inadvertent deployment in all flight phases.
- Other effects of inadvertent deployment.
- Costs.
- Structural effects.
- Egress.
- Different effects on different rotorcraft sizes (large, medium, and small).

Research and helicopter underwater escape trainer (HUET) trials have established an incompatibility between the time taken to escape from an inverted rotorcraft and human breath hold capability in cold water. The principal design aim of the side-floating concept is to ensure that, following capsize, an air gap is retained within the cabin. HUET trials have established that the time taken for occupants to surface into the air gap of a side-floating rotorcraft is compatible with breath holding ability. A further benefit of the side-floating concept is the provision of above-water escape routes (via push out windows). In addition, water impact modelling studies have show that the flotation unit redundancy inherent in the side-floating concept should significantly reduce the chances of a rotorcraft sinking or floating in a fully inverted attitude following water impact.

3.2 Push-out Windows

Recommendation:

All apertures in the passenger compartment suitable for the purposes of underwater escape shall be equipped so as to be usable in an emergency.

There are specific regulatory requirements for emergency exits for rotorcraft ditching certification but these requirements are still only concerned with the required emergency exits located above the water line. Research and accident experience have shown that more opportunity for emergency egress improves occupant survivability in a ditching or water emergency landing. Currently, many rotorcraft are equipped with push-out windows at each occupant station but are not considered emergency exits due to being smaller than the required size. A rule change to require push-out windows of appropriate size for all rotorcraft performing over water operations would allow appropriate emergency exit markings and improve occupant safety.

3.3 life-raft Deployment

Recommendation:

life-raft should be externally deployable regardless of whether the aircraft is upright or inverted.

Accident experience indicates that rotorcraft usually invert following water impact. Post egress survivability is significantly enhanced by the availability of life-rafts.

4 Definitions

a) Ditching – an emergency landing on the water, deliberately executed, with the intent of abandoning the rotorcraft as soon as practical. The rotorcraft is assumed to be intact prior to water entry with all controls and essential systems, except engines, functioning properly.

b) Water Impact- Any impact with water, in which the pilot may have had varying degrees of mechanical control of the aircraft.

c) Ditching Floats – floats that are installed on rotorcraft certificated to the ditching requirements.

d) Emergency Floats – floats that are installed on rotorcraft that are not certificated to the ditching requirements, but are approved for an emergency landing on water.

e) Hostile Environment – for over-water operations, the open sea areas North of 45N and South of 45S designated by the State concerned.

f) Emergency Landing on Water – a controlled but enforced landing on to water

g) Side Floating – usually due to asymmetrical float inflation, causing the Rotorcraft to roll over on one side and maintain flotation from the properly functioning float. A floating attitude that maintains an adequate air gap within the cabin for occupant survivability.

h) Amphibian - rotorcraft capable of water operations as part of their normal operating environment.

i) Limited Amphibian – a rotorcraft capable of performing an emergency landing on the water, deliberately executed, with the intent of abandoning the rotorcraft as necessary. If it is determined that the emergency is not flight critical, the rotorcraft is capable for take off from the water with floats inflated and continue flight to maintenance facility for appropriate action.

j) Survivable Accident – The acceleration environment was within the limits of human tolerance and a sufficient occupiable volume remained for properly restrained occupants, with the effects of fire or drowning not considered.