THE DERBYSHIRE RE-OPENED FORMAL INVESTIGATION

A TECHNICAL DETECTIVE STORY

BY

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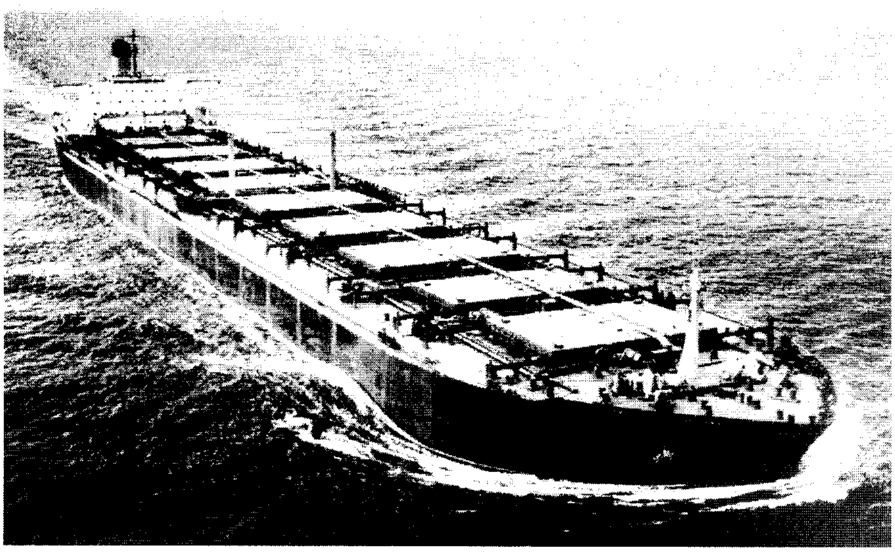
ABSTRACT

In the 20 years since she sank in a typhoon south of Japan in 1980, the loss of the bulk carrier MV *Derbyshire* has been the subject of numerous reports, surveys, papers, assessments and formal legal investigations. This culminated in November 2000 with the publication of the report on the Re-opened Formal Investigation which was held in the High Court over 54 days between April and July 2000.

This article gives a summary of the investigation and outlines the legal proceedings of a major marine investigation, the first ever held in the High Court. It also provides insight into how underwater survey results, coupled with model tests and technical analysis enabled the cause of the loss to be established in what proved to be a technical detective story. The article concludes by looking at the steps currently being taken to improve the future safety of bulk carriers.



MV DERBYSHIRE LADEN WITH CARGO

Introduction

In the 20 years since she sank in a typhoon south of Japan in 1980, the loss of the bulk carrier MV *Derbyshire* has been the subject of numerous reports, surveys, papers, assessments and formal legal investigations. This culminated in November 2000 with the publication of the report on the Re-opened Formal Investigation (RFI) (reference.1) which was held in the High Court over 54 days between April and July 2000 before a senior judge of the Admiralty and Commercial Division, Mr. Justice COLMAN.

This article gives a summary of the main findings of the report. It also aims to provide some insight into the technical issues and the analysis methods used in the investigation, and to explain some of the procedural aspects of the first major marine accident investigation held before the High Court[1] It is not intended to give a comprehensive summary of all aspects of the official report.

History of Derbyshire Inquiries and setting up of the RFI

The *Derbyshire*, British flagged, owned and crewed, disappeared virtually without trace when the vessel was caught in Typhoon ORCHID, south of Japan, during the night of 9-10 September 1980. All on board – 42 crew members and two wives were lost. At the time, the *Derbyshire* was only 4 years old, a fully equipped and well-managed Ore-Bulk-Oil (OBO) combination carrier. At over 90,000 GRT[2] she was, and remains, the largest UK ship ever to have been lost at sea.

Despite pressure from the families of those who died, the UK Government at the time resisted the setting up of a Formal Investigation due to the total absence of material evidence. This view changed in 1986 when one of the *Derbyshire*'s sister ships the *Kowloon Bridge* went aground and subsequently broke up off the south east coast of Ireland. Before going aground, the ship had reported a growing crack in the vicinity of a point just forward of the rear superstructure block (Frame 65).[3] This was not the first incident involving Frame 65. In 1982, an older sister ship, the *Tyne Bridge,* had suffered a brittle crack in severe cold weather at Frame 65. This repetition of cracking gave strong credence to a theory developed earlier in various reports and learned journal papers (e.g. those by the late PROFESSOR R.E.D. BISHOP (reference 2),[4] that primary hull girder failure near the stern due to fatigue was a possible cause of the loss. As a result, a first Formal Investigation was ordered into the loss of the ship. In the event the report of the Formal Investigation, which was published in 1989 (reference.3), concluded that brittle fracture and separation of the hull at Frame 65 was an improbable cause of the loss given the loads and prevailing high temperature. Instead, it took the view that the evidence supported no stronger conclusion than that:

> "The forces of nature probably overwhelmed the ship, possibly after getting beam on to the seas".

The families of those who died were naturally disappointed by this inconclusive result and pressed for further investigations to be carried out. The major breakthrough came in June 1994 when the wreckage of the ship was found two and a half miles (4,200m) under the Pacific, south east of Japan, during a search sponsored by the International Transport Workers' Federation.

In March 1995 the then UK Secretary of State responsible for transport asked LORD DONALDSON to carry out an assessment of what further work needed to be undertaken to identify the cause of the sinking of the *Derbyshire*, in the light of the discovery of the wreck. LORD DONALDSON with the support of 2 technical assessors, PROFESSOR D. FAULKNER and MR R. WILLIAMS, recommended that there should be a more comprehensive and final re-examination of the wreck (reference.4). This piece of work was technically notable for its use of safety risk assessment methods to define a list of loss scenarios (Table 1) and to categorize their risk (i.e. probability and consequence). In particular it highlighted the scenario of hatch cover failure under green sea wave loading as the most likely

1. The author acted as 1 of 2 technical advisors to the Judge and Attorney General's Team.
2. Gross Registered Tons.
3. Subsequent underwater inspection showed that the ship had fractured at 2 positions – at the bow where she had run aground and at the stern near Frame 65.
4. This paper which was published after the first Formal Investigation, following rejection of any particular cause, contains a list of references to earlier work dating back to 1984.

cause of the loss. (This had been considered in the original Formal Investigation but not given particular credence in the report).

TABLE 1 - *List of Scenarios*

SCENARIO		INITIATING EVENT	IMMEDIATE CONSEQUENCES	POSSIBLE END CONSEQUENCE
C1	Deck cracking at Frame 65.	Crack initiated brittle fracture.	Hull Separation then Foundering.	–
C2	Deck cracking near amidships.	Fatigue progression.	Hull separation then Foundering.	–
C3	Torsional weakness.	Fatigue cracking and hatch cover leaks.	Slow liquefaction/cargo shift.	Capsize.
C4	Hatch cover structural failure.	Collapse of forward hatch covers.	Rapid flooding of forward holds followed by foundering.	–
C5	Hatch cover slow leakage.	Loss of watertight integrity of hatch covers.	Slow flooding of forward holds and cargo liquefaction.	Foundering or capsize.
C6	Failure of fore deck plating.	Punching through of corroded plating.	Flooding of local spaces leading to loss of freeboard.	Initiates C4 resulting in foundering.
C7	Flooding of Fore Peak spaces.	Damage to side plating/vents & air pipes.	Flooding of Fore-Peak spaces leading to loss of freeboard.	Initiates C4 resulting in foundering.
C8	Cargo liquefaction.	Water entrained at time of loading.	Liquefaction of cargo leading to cargo shift with heavy rolling.	Capsize
C9	Propulsion loss.	Engine shutdown or propeller loss.	Ship falls beam-on causing large rolling.	Capsize
C10	Rudder loss/steering failure.	Rudder falls off or Steering Gear fails.	Ship falls beam-on causing large rolling.	Capsize
C11	Engine Room Fire/Explosion.	Fuel line failure.	Fuel supply shut down leading to C9 and C10.	Capsize
C12	Pooping from forward.	Waves sweep deck from forward	Water ingress into Fuel tanks leading to C9 and C10.	Capsize
C13	Pooping from aft.	Waves sweep deck from aft following master's action	Water ingress into Fuel tanks leading to C9 and C10.	Capsize

Following the recommendation by LORD DONALDSON, the Government announced that a return expedition would take place in two phases using the services of the United States Woods Hole Oceanographic Institution which had been notable for discovery of the wreck of the *Titanic* some years earlier. Phase 1, a preliminary survey, took place in July 1996, and succeeded in locating the stern of the vessel. Phase 2, the main expedition, was undertaken in March/May 1997. It returned with some 137,000 photographs and 200 hours of prime video imagery – a stunning operational and technical achievement. The UK Government (DETR) and the European Commission jointly funded the survey.

The UK/EC Assessors' report[5] was published on 12 March 1998 (reference.5).[6] It confirmed the cause of the sinking as the collapse of the main cargo hatch covers but concluded controversially (as the issue became more debated) that this had been triggered by the loss of freeboard due to flooding of the bow section whilst the ship was on the surface. This conclusion was driven by the fact that whereas the majority of the ship's structure had imploded/exploded into many separate items of wreckage, suggesting an intact state on sinking, the bow section was largely intact. More controversially still, they concluded that the flooding of the bow section was due to failure of the crew to secure a small 1.1m^2 access hatch to the forward Bosun's Store Flat where the hawsers were stowed.

The Assessors report received considerable press coverage and at the time was seen by the DETR and the media as the final word on the matter. However in the background, the Derbyshire Families Association (DFA) dissented strongly with the assertion of crew negligence and in the specialist technical press the conclusion concerning the degree and significance of prior bow flooding was also strongly debated. In particular FAULKNER issued his own view of the matter in a joint paper to SNAME and RINA (reference.6) in addition to many earlier general papers by himself and others on design for abnormal conditions and the inadequacy of bulk carrier hatch cover strength. (e.g. references 7 and 8).

Following the publication of the Assessors' report and in the light of the fact that the survey material on which it was based represented new and important evidence, the Government ordered in December 1998 that the Formal Investigation be re-opened. Furthermore, after consultation with interested parties and given the continuing degree of controversy and public interest, the unusual step was taken to hold the re-hearing in the High Court.

RFI procedure in High Court

A Formal Investigation is not a form of civil litigation or criminal trial with plaintiff and defendant, or prosecution and defence, but as the name implies a formalized legal investigation. It proceeds through the presentation of evidence by a number of recognized parties to the Court, who in this instance were:

- The Attorney General (responsible for leading the investigation).
- DFA.
- Bibby Tankers Ltd. (the ship owners).
- SHSEGL Realisations Ltd. (the successor company of Swan Hunter the shipbuilder).
- Lloyds Register of Shipping (LRS) (the Classification Society).
- The DETR (the then UK department of State which sponsors the Merchant Shipping Act and is signatory to international shipping regulations which governed some aspects of the design of the ship). Since June 2001 this is now the DTLR.

Each of the parties was represented in court by counsel, a QC with typically the support of 1 junior barrister (although the Attorney General had 2). Before the hearing (up to 1 year in this case) each of the parties assembles expert evidence in written submissions, which is then available to be commented upon by the other parties, or indeed other experts retained by their own party. By this process of 'truth triangulation', the resilience of certain pieces of evidence over others

5. 3 Assessors were appointed: D. FAULKNER and R. WILLIAMS for DETR and R. TORCHIO for European Commission. However, FAULKNER subsequently resigned before publication.

6. A summary of the report was given in 'The Loss of the Derbyshire' by D.K. BROWN in the *Journal of Naval Engineering*, June 1998. Volume 37 No.3. pp431-438.

becomes evident to the lawyers.[7] At the court hearing each of the parties 'adduces' the most important of this evidence orally by leading their expert witnesses through the salient points in their written submissions so that it becomes part of the official transcript. It is only this evidence which has formal weight. The counsel of the other parties are then free to cross-examine the expert witness and, of course to call their own experts. In order to prevent too much unnecessary divergence, an important procedural feature, which was new to the RFI, was the system of 'experts' meetings' whereby the experts of the different parties agreed joint statements (as far as this was possible).

To structure the investigation logically, the hearing was divided into separate periods, each dealing with a different technical issue. Of the parties, the Attorney General had a particular responsibility to lead the investigation as 'counsel to the tribunal'. This meant he had the right to present the first evidence on a given area of the investigation, except where mutually agreed. However, the most valuable evidence (in retrospect) came from a number of key expert witnesses, not all of them affiliated to the Attorney General.

The judge presiding over the Court had the responsibility of preparing the final report. Although in some circumstances a judge can choose to be assisted by official assessors who sit with him/her and participate in the writing of the report, on this occasion there were 2 technical advisors[8] appointed to provide 'behind the scenes' briefing on request. In these circumstances, the judge takes sole formal responsibility for the report.

The High Court was set in modern surroundings in a specially prepared courtroom in a building situated in Chancery Lane, with facilities to show survey and other images on VDU terminals on the desks of each of the parties. The atmosphere was informal and robes were not worn. Daily transcripts[9] and significant 'image exhibits' presented by the parties during the course of each of the days hearings were posted on a special Internet site each evening.

Overall, one was left with the impression of a process which was 'inquisitorial', but with the potential to produce 'adversarial' hot-spots in some of the cross-examinations, particularly when issues that touched on blame for the loss were under examination.[10]

The ship and her last voyage

The *Derbyshire* was an OBO Carrier of 92,000 GRT, 294 m in length, 44m beam and a depth of about 25m. At the maximum permissible load (173,000 tonne deadweight and 204,000 tonne displacement) she had a summer draught of around 18.5m and therefore a freeboard to the upper deck of approximately 6.5m as permitted by the International Load Line Convention of 1966 (ILLC 66). Effective freeboard was increased at the forecastle by a bulwark and the holds had

7. Evidence and contributions from expert witnesses is assembled by each of the parties in numbered ring binders called 'bundles'. In this investigation, this amounted physically to 10m approx. of shelf space – but obviously multiplied by the number of parties. A majority of this is brought into the court.

8. In addition to the author the other advisor was DR. P.S.J. CROFTON of Imperial College London

9. One of the more impressive aspects of the technology used in the court was the taking of the transcript of the court proceedings, which was generated almost contemporaneously by a stenographer working in conjunction with a computer program called LIVENOTE. This allowed an almost perfect written transcript to appear on laptops of all the parties about 5 seconds after the words were spoken, and enabled people to check the clarity of cross-examination in real-time.

10. This was a major issue for the DFA relating to crew negligence over the Bosun's Stores hatch and for LRS on the issue of hatch-cover strength standards.

coamings that raised the cargo hatch cover above the main deck by 2m approx. The installed power was 24.2 MW, giving a maximum speed of approximately 12kt. Normal transit speed was 10kt.

The last voyage of the *Derbyshire* on 11 July 1980 was from Sept-Iles in Canada bound for Kawasaki in Japan, laden with a substantial cargo of 157,000 tonne of iron ore concentrate. She was well laden, but her mean draught was some 0.45m less than the ILLC regulations allowed (of which more on this later). Of the 9 holds, Holds 2 and 6 were left empty. In the laden holds, the cargo occupied only a third to a half of the available volume due to its high density. The vessel passed via Capetown, transited the Indian Ocean and by 3 September had reached the sea area to the south of the Philippines. At around this time the ship was first advised of tropical storm activity to the east.[11] An initial tropical depression petered out, the ship maintaining its direct course to Japan, although it had for some time increased speed as a precautionary measure to clear possible storm tracks. However during 6 September a further tropical depression developed, and by the 7th this had been denoted officially as Typhoon ORCHID. At this time, the typhoon was over 650 nm. to the east of the ship. Over the course of 8 September, the ship became affected by the sea state associated with the typhoon and had to reduce speed. By 0300Z of 9 September (midday local time) she reported that she was hove-to in 10m seas. During the 9th and into 10 September the ship came very close to and remained near the worst weather of the typhoon. The last automatic radio acknowledgement from the ship was sent at 1019Z, but did not give a position. The wreck of the ship was subsequently found some 35 miles from the earlier 0300Z position. The RFI came to the conclusion that the ship sank probably between 1700 Z and 2000 Z (i.e. between 0200 and 0600 during the course of the night of 9/10th local time)

The story of why the ship chose to maintain its course, and was eventually over-run by the typhoon has been pieced together in the official report, and is summarised below.

The evidence from the wreckage

The wreckage was found to be located within a relatively small area of about 1,400m by 1,000m at a depth of 4,200m, with the majority concentrated in a 600m x 250m area (FIG.1).

11. During the voyage the ship was being 'ocean routed' by a company called Oceanroutes, based in California. She was also in receipt of regular shipping weather information from Japan and Guam.

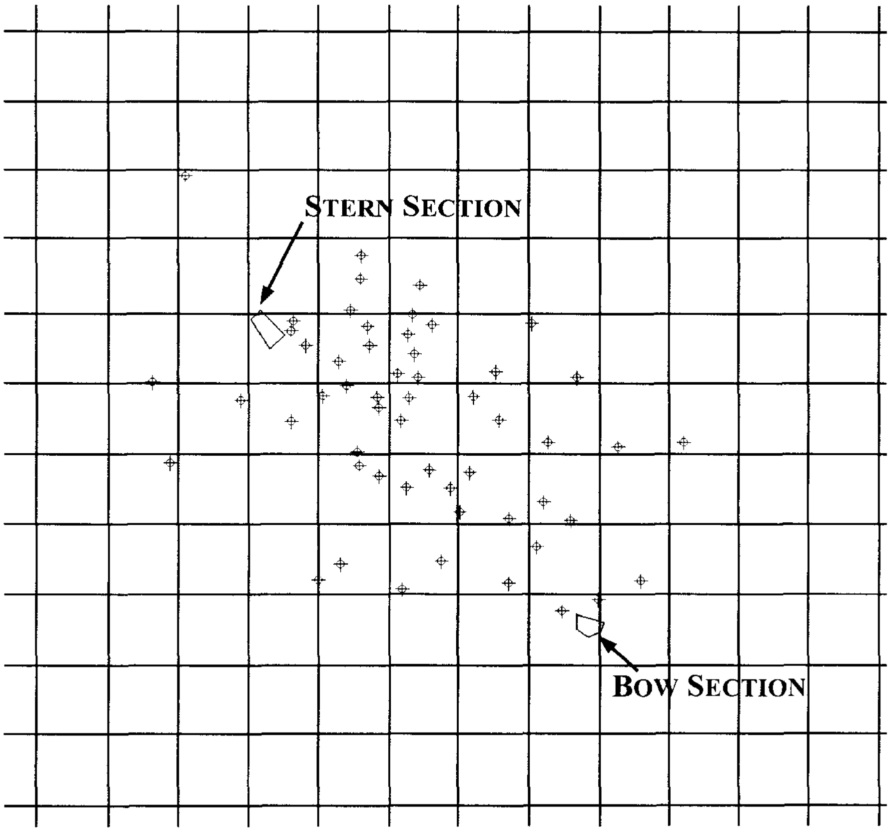


FIG.1 – WRECKAGE FIELD

By far the largest pieces were the relatively intact bow (FIG.2) and stern sections that were found separated by about 600m.

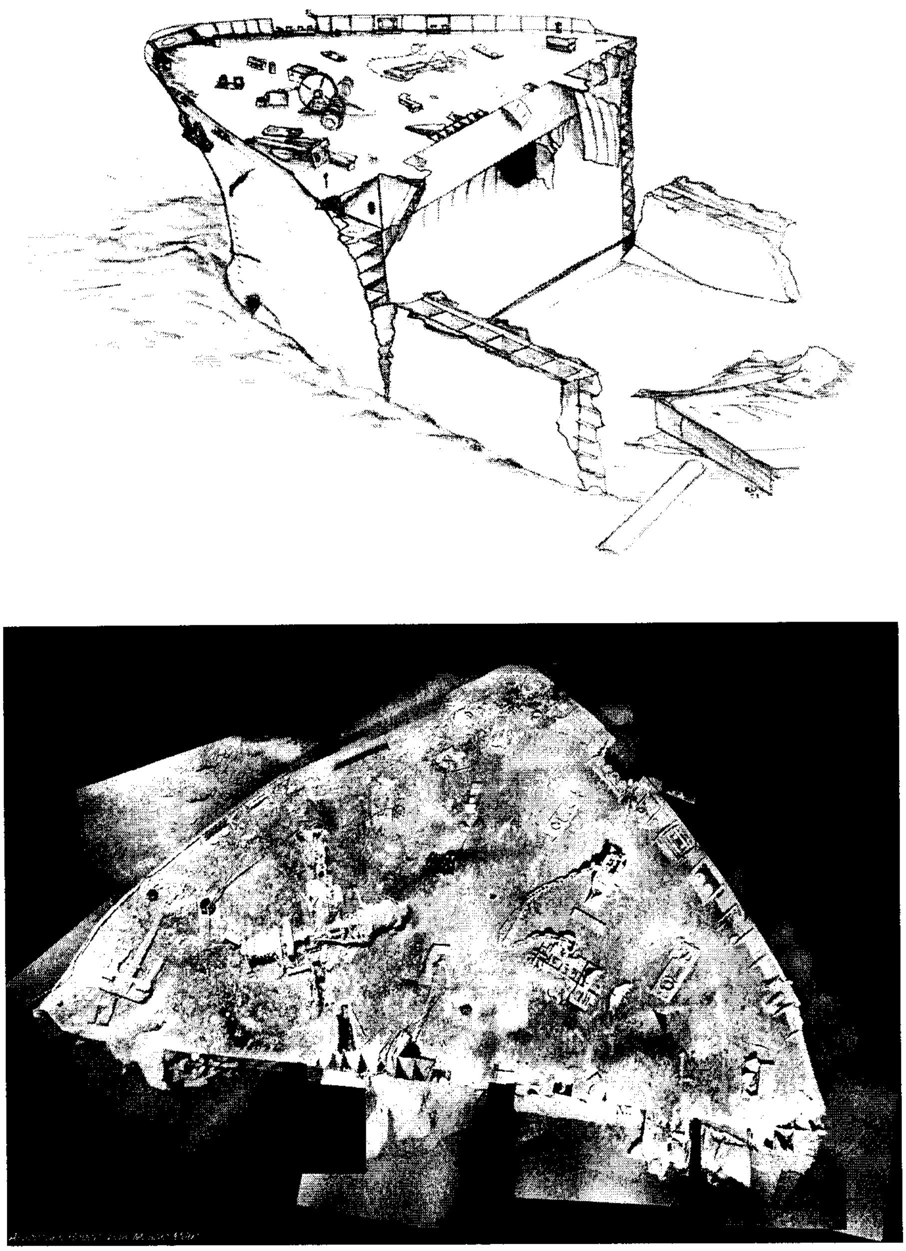


FIG.2 – SKETCH AND IMAGE OF BOW SECTION

The cargo hatch covers were all identified in the wreckage field showing evidence of failure from external pressure loading. The double-skin cellular structure composing the intermediate 9 holds – the double bottom, the hopper and saddle tank structure, and the double bulkheads (FIG.3) – was completely fragmented due to the 'implosion/explosion' mechanism.[12] In total, there were some 2,500 separate pieces of wreckage.

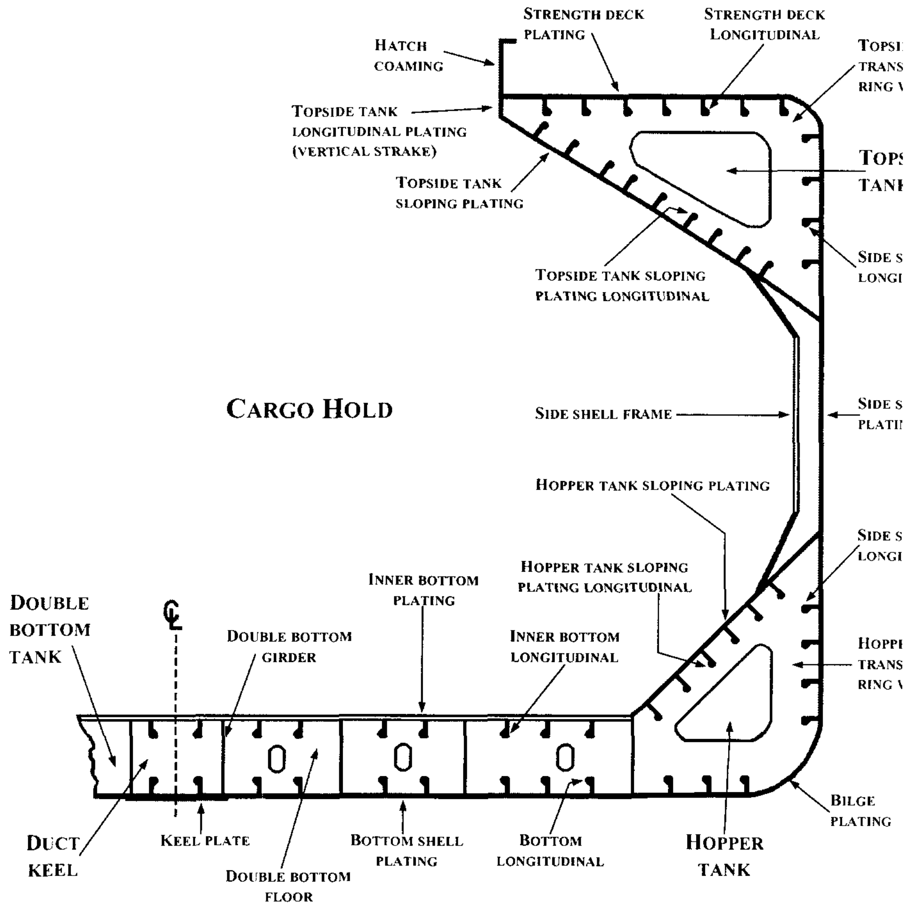


FIG.3 – TYPICAL CELLULAR STRUCTURE OF BULK CARRIER HOLD

12. The 'implosion/explosion' mechanism occurs when an enclosed structure prevents entry of water until it fails suddenly under hydrostatic pressure (the implosion phase). The follow-through effect of the incoming water is such that it over compresses the air enclosed in the structure to a value approximately (twice) that of the external hydrostatic value. (A useful analogy here is a spring compressing under an impulsive force). The result is a sudden outgoing flow of water and air creating further damage. (the explosion phase). The rising bubble can cause further damage to other neighbouring structure as it pulsates through further compression and expansion phases.

If on the other hand a piece of structure has sufficiently large water entry area, gradual equalisation of pressure will occur and implosion/explosion cannot take place. An interesting intermediate situation arises if there is only a small area for water entry, in which case the area of the hole, the size of the cavity to be filled and the rate of descent will determine whether a sufficient net external pressure will build up to cause structural failure.

Given that the ship was about 300m long, the relatively restricted distribution pattern of the wreckage led to the conclusion that:

> "No substantial part of the hull and none of the hatch covers separated from the main part of the vessel earlier than the commencement of the sinking process."

This together with the break-up of all the cellular hold structure indicated that the ship had not suffered structural failure of the hull girder on the surface; if this had been the case normal slow flooding of structure on either side of the failure would have been evident. This was sufficient to rule out the Bulkhead 65 theory and similar primary structural failure at another location (reference.5). Another important conclusion from looking at all the evidence was that the ship had not capsized – the hatch covers would have been loaded from inside by the falling ore – ruling out about half of the possible loss scenarios (see Table 1). There was also no evidence from the stern section compartments to support fire or explosion as the cause of the loss. Instead the evidence strongly pointed to the conclusion that the ship had been sunk by the progressive failure of the main hatch covers allowing the ship to founder. Nevertheless, a number of matters remained unresolved at this stage:

- Had the hatch cover failure occurred in head or beam seas (with large rolling).
- To what extent was an initiating event such as slow flooding of the bow section due to wave action on the surface necessary to trigger the hatch cover failure.
- If so what were the subsidiary causes of such premature flooding.

Survey of the bow section on the seabed showed that a number of ventilators and air pipes to the bow section spaces had been knocked off or damaged and that the Bosun's Store Hatch Cover was missing. All of these could have provided an entry route for water; the question was at what stage had this damage happened – before the sinking or during it.

The answer to some of these conundrums lay in a close examination of the images of the bow section, evidence from master mariners and associated analysis to determine how much bow flooding could have occurred and through which mechanisms.

The Typhoon

A typhoon is the name given in the Northern Pacific regions to an intense tropical-rotating storm.[13] It is caused by the formation of an intense low pressure accompanied by a cyclonic rotating wind field (which acts in an anti-clockwise direction in the Northern Hemisphere). The rotating wind speeds increase away from the centre, achieving a maximum value at a distance typically of 25-30 n.m., before diminishing further away. In severe typhoons, the peak sustained wind speeds[14] can be more than 100 kt. However the rotating weather system also moves forward with an overall translation speed (typically of 20kts) with the result that the wind speeds in the right hand (the 'dangerous') semicircle are higher than those of the left (the 'navigation') semi-circle. This is the basis of the advice to mariners, which is to navigate at all times to avoid the dangerous semi-circle. In the *Mariners Handbook* the advice is that it is vital to keep clear of the storm centre by 50nm and if possible by 200nm.

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13. Terminology varies throughout world. Known as a 'cyclone' in the Indian Ocean and Australia; and as a 'hurricane' in the North Atlantic region.
14. Maximum1 minute average in 1 hour.

A crucial first step towards answering the navigation and technical issues concerning the loss of the ship was to have a good understanding of the storm itself. Nowadays this can be done with reasonable accuracy using 'hindcasting' computer models that enable the wind and sea state to be estimated in retrospect. In Typhoon ORCHID, both wind and wave measurements were available from weather reconnaissance aircraft and wave buoys in the area to calibrate the model's prediction. Typically, significant wave heights (Hs) in typhoons and hurricanes are in the range of 8 – 18m, with modal periods of 10-20 seconds[15.] Estimates of Hs are typically accurate to within +/-10%.

The hindcast of Typhoon ORCHID[16.] indicated that in some respects it was not exceptionally severe. Of typhoons encountered in the North West Pacific during the period 1971 to 1986, ORCHID ranked 34 out of 77 in terms of peak wind intensity. In terms of significant Hs it was ranked somewhat higher, but still only with a peak value of 12.6m in a possible range of 8 – 18m. However, there were some other features of Typhoon ORCHID which made it considerably more dangerous to *Derbyshire* than was immediately apparent.[17.]

- The first unusual feature was its geographic scale. Typically the radii of maximum winds occur at 25-30 nm. from the centre; in the case of ORCHID this was 100nm – some 3 to 4 times greater than the average. This also influenced the wind speeds and the sea state at greater radii. It will be explained below how this is presumed to have critically affected decision making about navigation.
- The second very unusual feature was the looping nature of the typhoon track when in the vicinity of the *Derbyshire* that led to an unusually long exposure to the raised typhoon level sea state. Typically this would be of the order of 6 hours as the storm passes through an area; in the case of ORCHID along the assumed track of the *Derbyshire* the significant wave height remained at a value of over 8m for 36 hours and around 10m for 24 hours (FIG.4).[18.] Clearly, this would have caused a large increase in the time of exposure to the hazard. The ship was experiencing extremely bad weather from 1800 on the 8th, intensifying up to a significant wave height of 10.85m at 1700Z on 9 September (i.e. 0200 on the 10th local) (It must be remembered that all these predictions are mean predictions within a +/-10% tolerance band).
- The final critical characteristic was the dominant wavelength in the typhoon i.e. those waves with greatest wave height and energy. This was found to be close to 300m, remarkably similar to the length of the ship, consistent with a frequency of 0.45 rad/sec(see FIG.4 for estimated typhoon spectrum) or a wave period of 14sec.

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15. The principal statistical parameters used to characterise typhoon sea states (and indeed any random sea state) are:
    - The significant wave height Hs (which is the average of the highest 1/3 of the waves).
    - The wave frequency spectrum modal period (which defines the period and wave length of the dominant waves).
    - The degree of frequency concentration in the spectrum (the narrow bandedness).
    - Whether the waves are uni-directional or multi-directional.
16. Carried out for the RFI by Oceanweather Inc. under the direction of DR.VA CARDONE.
17. CARDONE V.: see RFI Transcript Day 8 and OCHI M: see RFI Transcript Day 9.
18. M. OCHI: see RFI Transcript Day 9; AG Exhibit 5.

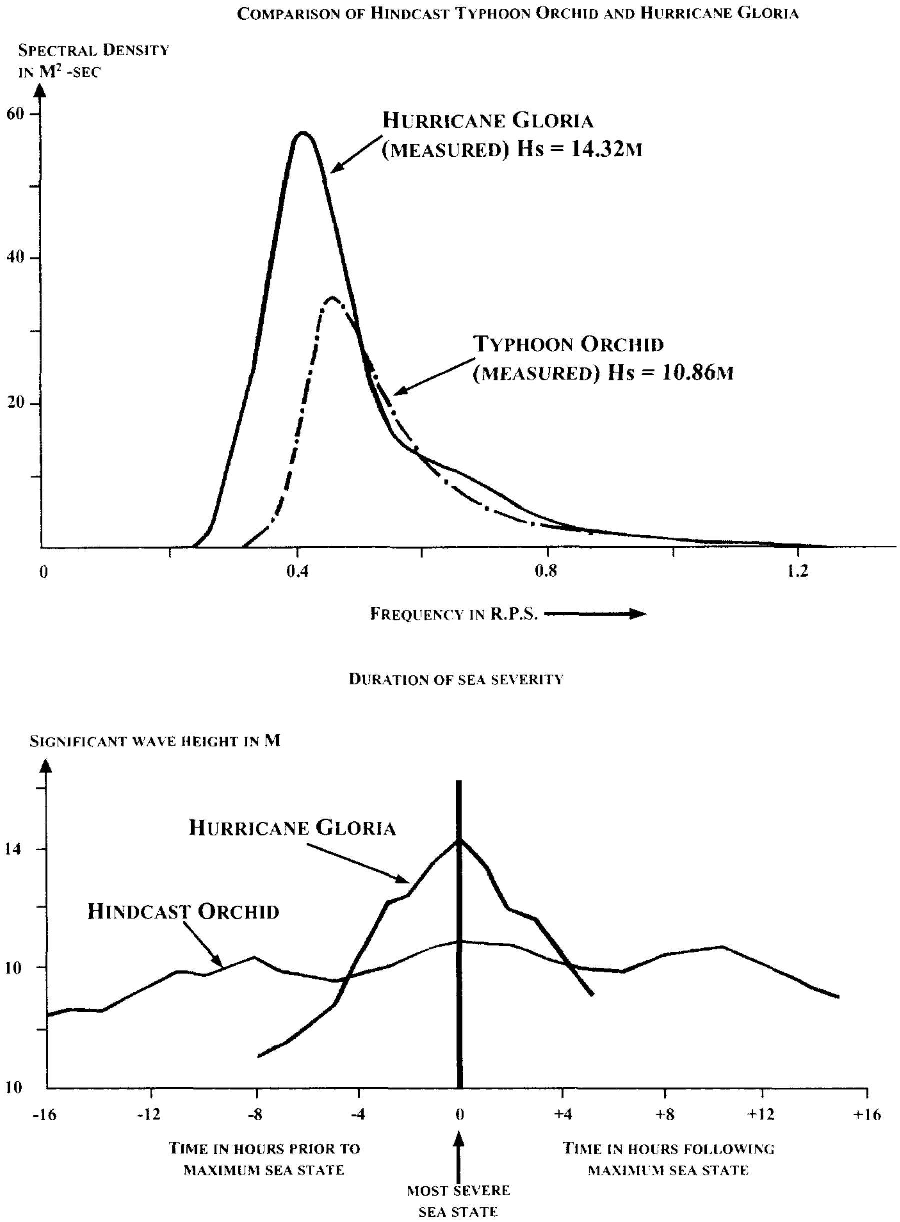

FIG.4 – OCEANOGRAPHIC CHARACTERISTICS OF TYPHOON ORCHID

Extreme waves

Use of the statistical parameter Hs to characterize a sea state fails to convey the real danger faced by a ship. A more crucial measure is the height of the single worst wave it might expect to meet in a certain period. Formula [1] describes the most probable extreme height (He) in terms of the number of waves encountered (N), showing that exposure length increases the risk.

$$He = [0.5 \ln N]^{0.5} Hs \qquad [1]$$

For the *Derbyshire,* similar calculations to this were used to predict a median[19] extreme wave height of 20m approx. Even higher waves (say up to 25m) were assessed as being possible with a lower chance of being encountered (e.g. 5% or 1% values). The wave profile of such extreme waves in a random sea is rarely symmetric, as they are effectively composed of a superposition of regular waves of many different wavelengths and wave heights. The worst profile that can arise for green water loading is a large wave with a higher crest than trough and a steep wave front (as shown in (FIG.5)[20] based on reference.9). Such characteristics can be accentuated by non-linear effects which further increase the crests and flatten out the troughs (see FIG.5 again). It was estimated that such non-linear effects might account for 10% of the crest elevation of waves of 20m height.[21]

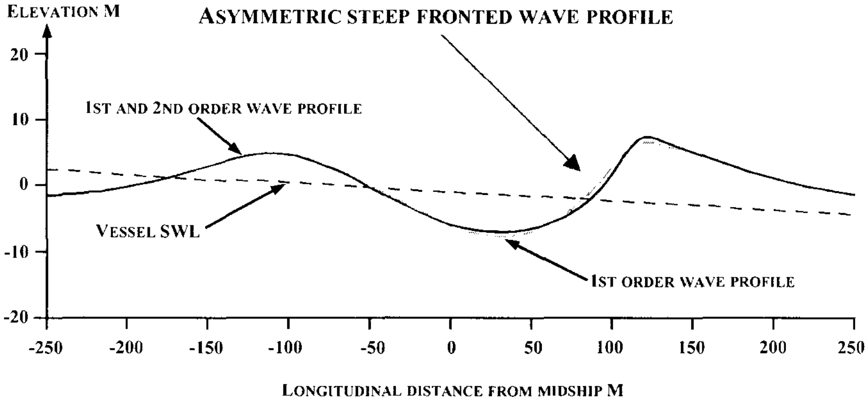

FIG.5 – STEP FRONTED TRANSIENT WAVE PROFILE

Reasonable Navigation and Weather Prediction – how the Ship was caught in the Typhoon

The investigation devoted considerable time to the issue of ship navigation in relation to the track of the typhoon, both in terms of what was known at the time on board the vessel and what is now known with hindcasting (and with hindsight!). A number of former Masters with experience of commanding large merchant ships, or who worked for Bibby Lines on sister ships of the *Derbyshire,* were consulted.[22] Available to the court were the weather reports at various times from both the weather routing company in California and from the Japanese national weather forecasting service over Tokyo radio and the US Joint Typhoon Warning Centre at Guam, giving the characteristics and likely track of the storm.

The evidence suggested that the Master of the *Derbyshire* would have been well aware of the developing typhoon from 6/7th September, the storm centre being some 650nm to the east. The report concluded that he acted reasonably in maintaining his rhumb line course for Tokyo Bay. He had every reason to believe from the weather reports which he was receiving that he would be able to cross ahead of the advancing typhoon without entering the 200nm advisory avoidance zone, and certainly well clear of the dangerous 50nm zone (FIG.6). In the event, because the extent of the typhoon was some 3-4 times worse than being forecast

19. i.e with 50% probability of being exceeded.
20. K. DRAKE Written Evidence pp. 284 – 304 Bundle AG 17. RFI Transcript Day 10.
21. K.DRAKE RFI Transcript Day 10.
22. CAPTAINS ROBERTS, WILLEY, BOYLE, DE COVERLY, see RFI Transcript Days 2,3,5,6,8-10,21

(e.g. radius for 50kt winds was closer to 250nm than the forecast 60nm) the ship unexpectedly encountered much more severe weather than anticipated. It was then unable to maintain the previously assumed speed to cross ahead safely of the storm, and was inevitably caught up by the typhoon. The option of avoiding the typhoon was then lost, and the ship was forced to slow down and increasingly adopt a course that minimized boarding sea damage. (Model tests showed that in Hs of 10m the maximum speed over the ground would have been no more than a few knots) Eventually the typhoon's track crossed behind the track of the ship, curving northwards parallel to the ship's own track so that the ship entered the dangerous semi-circle. Later, in the course of 9 September the ship came very close to the highest winds of Typhoon ORCHID (see FIG.6).

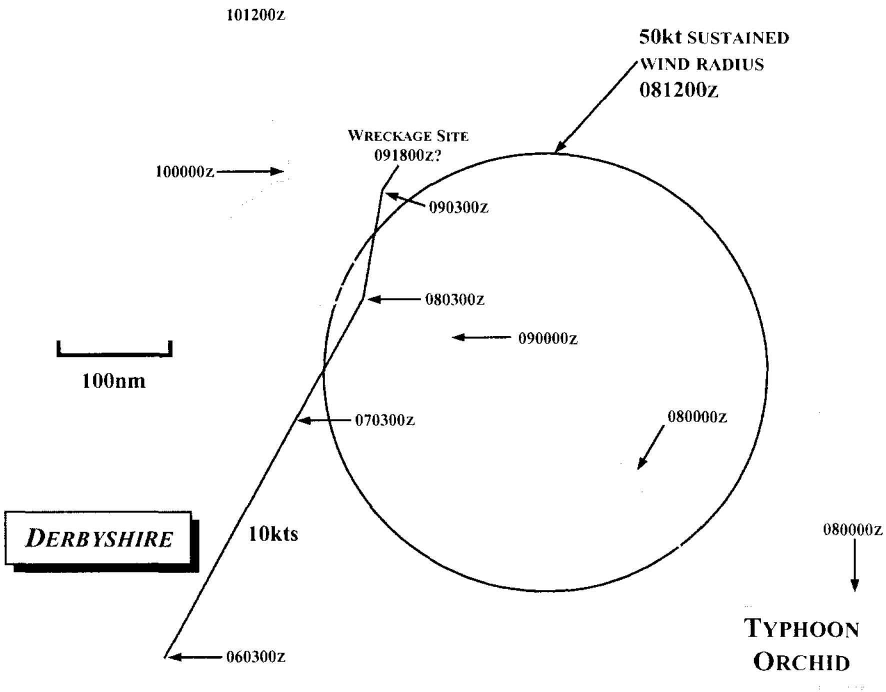

FIG.6 – TYPHOON AND SHIP TRACKS LEADING TO LOSS

The last hours

From the last known reported position of the *Derbyshire* at 0300Z on 9 September to the wreck site is approximately 35 nm. Modelling work by HOOK[23] using a manoeuvring simulation model (MATHMAN) showed that this distance was consistent with the vessel holding the sea at about 25° off the starboard bow (as advised by the mariners) with an average forward speed over the ground of 1.5 to 2 kt., requiring 80-90 rpm.

How the ship sank

An accurate assessment of how the ship responded in the typhoon – the extent of green water boarding and loading on the hatch covers – was an essential element of understanding how the hatch covers could have failed.

23. HOOK J. Burness Corlett and Partners: RFI Transcript Day11.

Model testing at MARIN

Model tests had originally been carried out for the first Formal Investigation in at the Danish Hydraulics Institute. In the late 1990s further testing was carried out at Strathclyde University for the DETR/MCA using a 1/65th scale model of the *Derbyshire* in unidirectional seas. However, this predated the hindcasting work by CARDONE (summarized above) of the typhoon using the latest oceanographic models that only became available in October 1999. Although less than 6 months before the official start of the RFI, it was decided by the Attorney General's counsel to embark on a further series of model tests at the new sea keeping facility at MARIN in the Netherlands, as importantly it had the capability to model multidirectional seas. In the event, the modelling work continued well into the spring of 2000 – overlapping the start of the RFI – as further supplementary testing was required to improve both the accuracy and validity of the measurements.[24]

The first objective of the MARIN tests was to provide statistical information on the green water loading on the No.1 hatch cover.[25] This information was established for a range of sea states and ship conditions[26] that would later enable calculation of the cumulative probability of a hatch-breaking wave during the course of the typhoon under various bow flooding and freeboard assumptions. Tests were also carried out to measure the possible rates of water ingress through each of the broken bow space orifices (and therefore also the rate of freeboard loss), again for different sea state and ship condition assumptions. Here again the complexities of green water movement around equipment and retention on the foredeck made a physical model essential.

Insight into Green Sea Loading Mechanism

Considerable insight into the relative vulnerability of long, low freeboard ships in a typhoon were provided by the model tests. As noted earlier, the modal period of Typhoon ORCHID was around 14 seconds with a corresponding dominant wavelength of 300m. The length of the Derbyshire was approximately 290m. This near coincidence of ship length and wavelength ensured that the *Derbyshire* was subjected to very large pitch and relative vertical motions.[27] This can also be appreciated from (FIG.7) showing the coincidence of the wave energy spectrum and the transfer functions for these responses.

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24. Particular care was taken to remove high frequency 'spike' pressure measurements which were a function of model scale hatch cover structural resonance, or loads which were too short term to have any loading significance.
25. The reason for using model tests rather than relying on computer calculation were:
    - In predicting ship response, computer models are not able to deal routinely with non-linearity in the wave crest elevation (greater than linear), nor more importantly with non-linearity in bow motion relative to the local water surface (significantly less than linear prediction for extreme motion) This parameter was important for assessing the probability of green water boarding.
    - The prediction of green water height on deck, and even more importantly the actual sustained loads on hatch covers, is highly complex for which there is no suitable alternative.
26. The parameters, which were varied for ship condition, were speed, reduced freeboard at the bow (due to different amounts of bow flooding) and heading angle
27. Due to ship length-wave length matching which increased pitch moment loading rather than resonance effects.

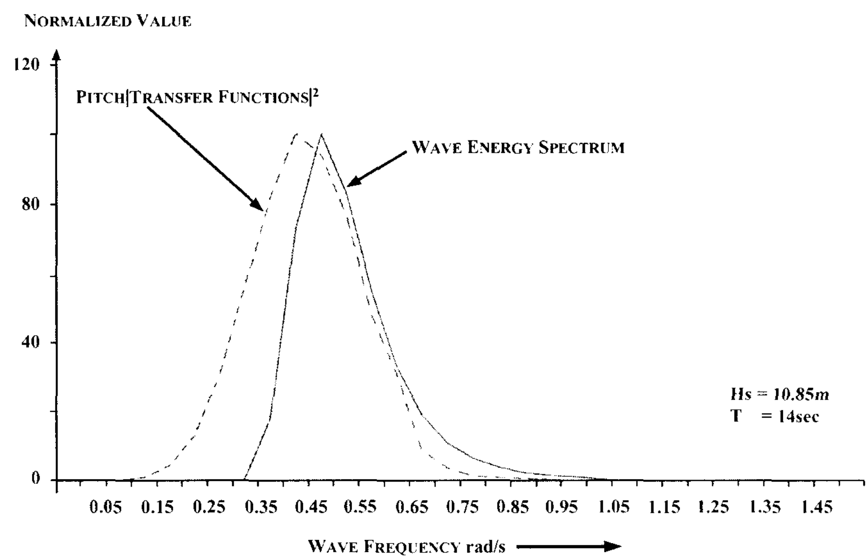


FIG.7 – COINCIDENCE OF WAVE ENERGY SPECTRUM AND PITCH TRANSFER FUNCTION

A typical sequence of events in these circumstances is for the ship to pitch down into the trough of a wave, and whilst 'nose down' to meet the next wave crest which in the worst circumstances will have a steep wave front (FIG.8). The effect of the large ship motion is to amplify the relative motion of the ship with the wave surface compared to that seen by a fixed static structure. The tests at MARIN for the *Derbyshire* showed that at 0kts the amplification of relative vertical motion compared to wave amplitude was about 2.1 and at 4 knots this rose to about 2.5.

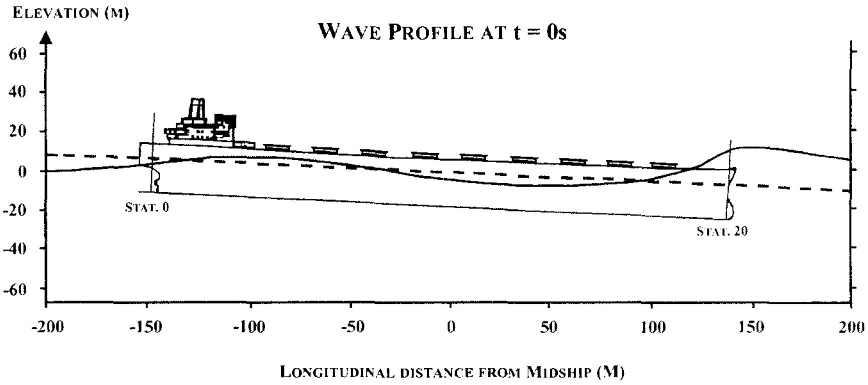


FIG.8 – SNAPSHOT OF SHIP ATTITUDE AND TRANSIENT WAVE FOR GREEN SEA LOADING

By the same reasoning, it can also be appreciated that ships of a different length could have fared better in Typhoon ORCHID than the *Derbyshire* (reference.9). In particular it is possible to demonstrate that ships of lower length, but with the same freeboard, would have been able to contour the waves to a greater extent and therefore to weather the storm better. It is for this reason that the longer Capesize bulk carriers are now regarded as more vulnerable to extreme sea states, such as those caused by typhoons, compared to their smaller sisters, the Panamax and Handymax.

Probabilistic Calculation of Risk of Hatch Cover Failure

The statistical green sea hatch loading information obtained from the model testing enabled estimates of the risk of hatch collapse to be made hour by hour over the course of the typhoon for various assumptions. These assumptions covered:

- Ship speed (0 to 4kt).
- The number of compartments in the bow section subjected to flooding (either individually or in combination)
- The start time and rate of flooding into those spaces.

Furthermore, the effect of the accuracy of the hindcast sea state estimate was subjected to sensitivity analysis (10%). An outline of the calculation procedure used is given at Annex A.

Basic Conclusions -- Sensitivity to Speed, Freeboard and Sea State

The basic conclusion from this risk assessment were as follows:

- In the given sea state the ship was operating on a 'cusp' between safety and calamity. The results were extremely sensitive to small changes in wave height, ship speed and loss of freeboard.[28] With small adjustments of any of them it was possible to move from a situation in which the risks of a hatch breaking impact were effectively zero to 100% (see Table 2). For example at 4kt. increasing the wave heights by 10%, lead to an increase in cumulative risk (Ck) at the end of the typhoon from 1% to 74%. However a reduction of ship speed to 2kt. in this higher sea state brought the risk back down to 4%. But the effect of flooding the bosun's store, resulting in a minor reduction in freeboard of only 0.4m put the risk back up to 42%.

28. This can be understood by the fact that for extreme values of relative motion the probability of impact pressure (Pr) will be proportional to the Rayleigh function exp(-(RMS RVM/ F) ^{2} where RMS RVM is the root mean square value of relative vertical motion (a function of sea state) and F is local freeboard.

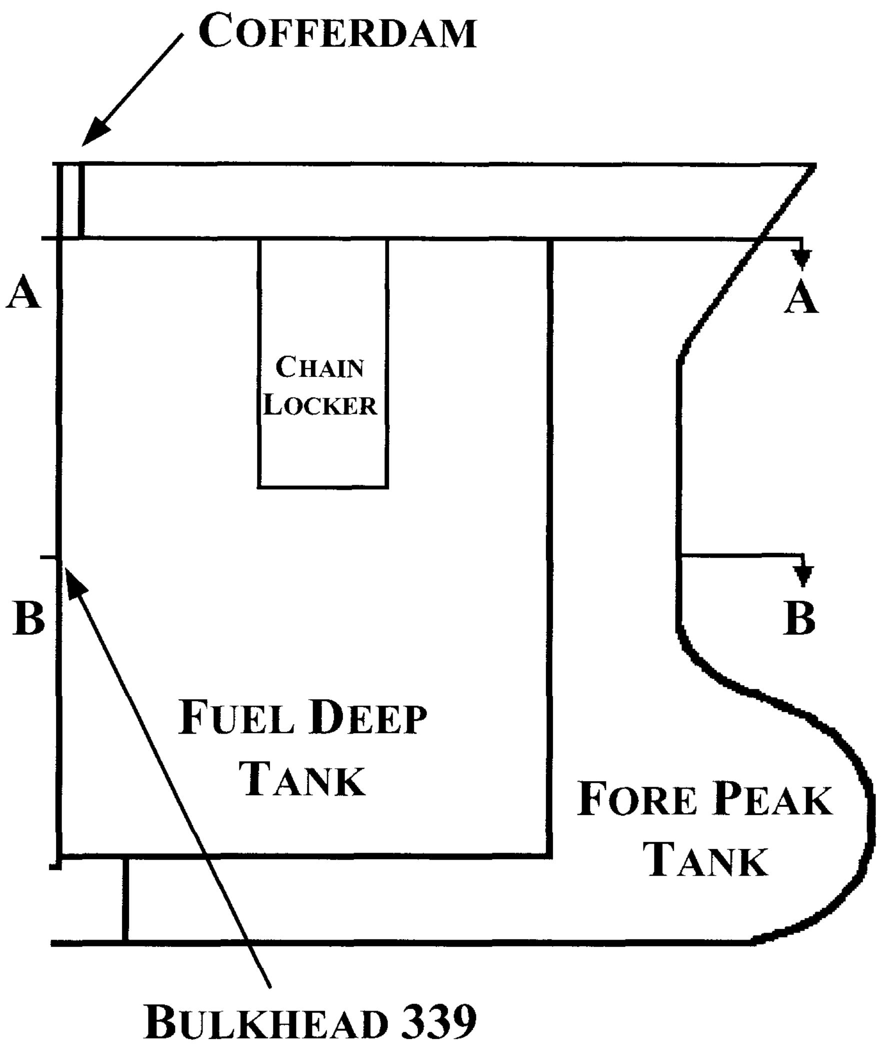
TABLE 2 – *Summary* – Statistical Risk Assessment of Hatch Collapse*

Sea State Hindcast	**Ship speed**	**Ship condition with slow flooding (end Δ freeboard)**	**Cumulative Probability of failure (Ck)**
Mean	2	Intact	0.00
Mean	2	Stores flooded (-0.4m)	0.00
Mean	2	Ballast flooded (-1.1m)	0.43
Mean	2	Stores + Ballast flooded (-1.5m)	0.93
+10%	2	Intact	0.04
+10%	2	Stores flooded (-0.4m)	0.42
+10%	2	Stores + Ballast flooded (-1.5m)	1.00
Mean	0	Intact	0.00
Mean	4	Intact	0.01
+10%	4	Intact	0.74
+15%	2	Intact	0.34
+15%	4	Intact	0.99

* Full results available in Appendix 17 of RFI Report (reference.1)

- There was benefit in reducing speed as much as possible in order to reduce deck wetness, commensurate with maintaining steerage. Based on the estimation of average speed that the ship made over the last 14-17 hours to reach the wreck site (see above), the report put the greatest weight on the results for 2 kt. This indicated that:
  - ❑ There was effectively no risk in the <u>intact condition</u> of the final voyage in the mean hindcast sea state.
  - ❑ The risk was measurable (4%) in the intact condition at the upper bound of the hindcast sea state (+ 10% higher waves).
  - ❑ The risk in the mean hindcast sea state was progressively affected by flooding and freeboard loss. Up to a loss of freeboard of 0.4m (stores flat alone), there was still no risk, but with a freeboard loss of around 1m (ballast tank alone) the cumulative risk went up to approximately 40%. With a further reduction in freeboard (to1.5m) the risk went up to 90%.

Ultimately, these statistical results could only indicate the relative risks of particular ship and sea conditions – those that could in combination have given rise to collapse of No 1 hold. But they could not define, with any certainty, which particular combination happened, in particular the degree of bow space flooding. For further refinement of the likely combination of circumstances, it was necessary to return to the wreck evidence.


COFFERDAM
A
A
CHAIN
LOCKER
B
B
FUEL DEEP
TANK
FORE PEAK
TANK
BULKHEAD 339

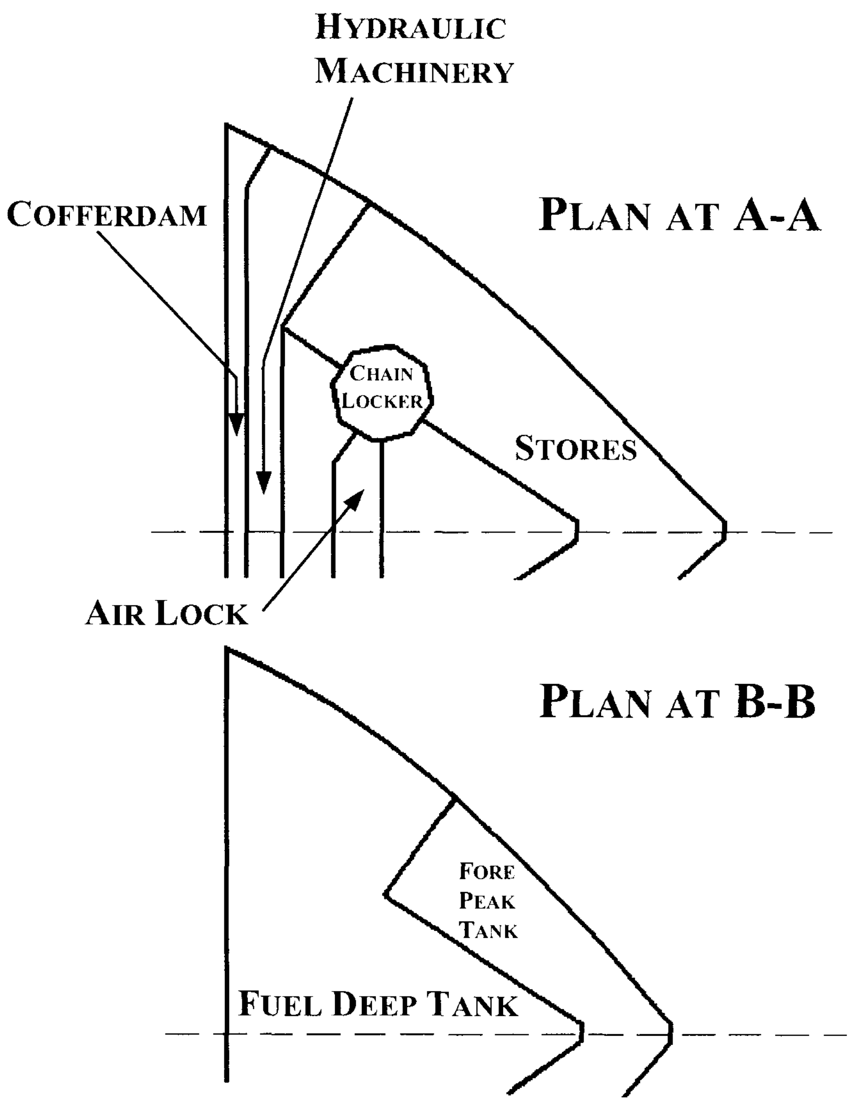


FIG.9 - BOW SECTION COMPARTMENTS

The Bow Spaces – potential flooding entry routes

The Bow Space (Fig. 9) was made up of 3 main compartments with the following approximate capacities:

- The Bosun's Store flat of $1100m^3$.
- An empty Water Ballast Tank of 2800 m^3.
- A Deep Fuel Tank (DFT) of 5200 m^3, which was approximately half full of fuel oil.

The Bosun's Store was linked to the external atmosphere by 7 relatively weak ventilators, and in the case of both the fore peak ballast space and the deep fuel tank by 3 smaller but stronger air pipes. On the wreck all of the Bosun Store ventilator heads were missing and in some cases the coamings as well. All 3 air pipes to the ballast space were damaged and open to the sea; however, in the case of the fuel tank only 1 pipe was damaged.

Personnel access to the bosun's store was via a $1.1m^2$ square hatch on the fore deck. On the wreck the hatch cover was missing and the aft side of the coaming had been subjected to an impact load from an object, resulting in a large sharp indentation (FIG.10). A hawser was draped over the open coaming. Finally a number of other significant pieces of fore deck furniture were missing, including the starboard windlass that was found in pieces within the main wreck field.

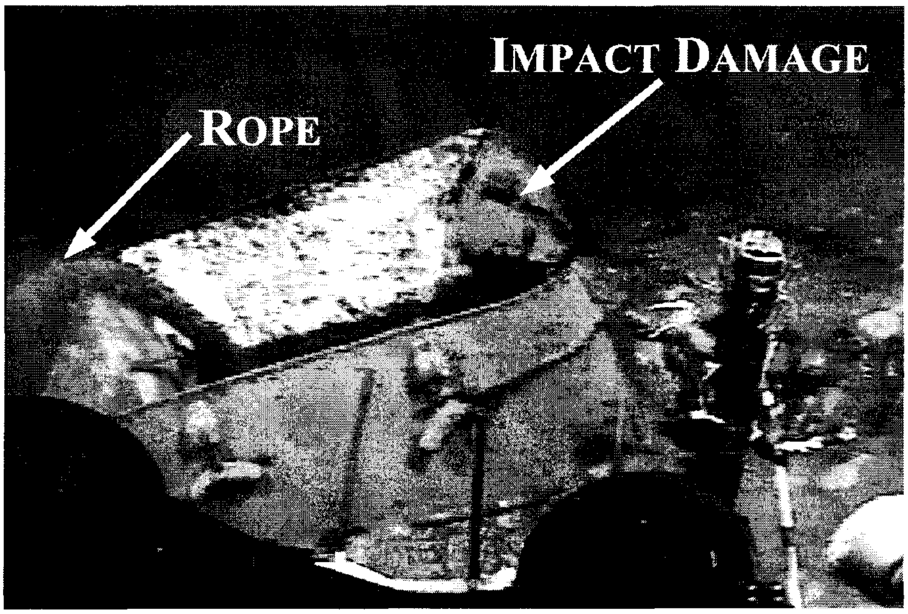


FIG.10 – VIDEO STILL OF DAMAGED BOSUN'S HATCH

MARIN flooding ingress calculations showed that at the peak of the storm it was possible to flood the Bosun's Store in as little as 2 hours, and the fore peak ballast tank in 5 hours, assuming all orifices were open, resulting in freeboard reductions of 0.4m and, in combination, 1.5m. This effectively gave an upper bound worst case.[29] However, the amount of water entry through the single small opening of the deep fuel tank was minimal.

It was also considered highly relevant that damage to the Bosun Store vents and partial flooding of the stores space had occurred on sister ships, and on the *Derbyshire* herself, on an earlier voyages.[30] This was not infrequent damage!

Which spaces were flooded – evidence from Bulkhead 339

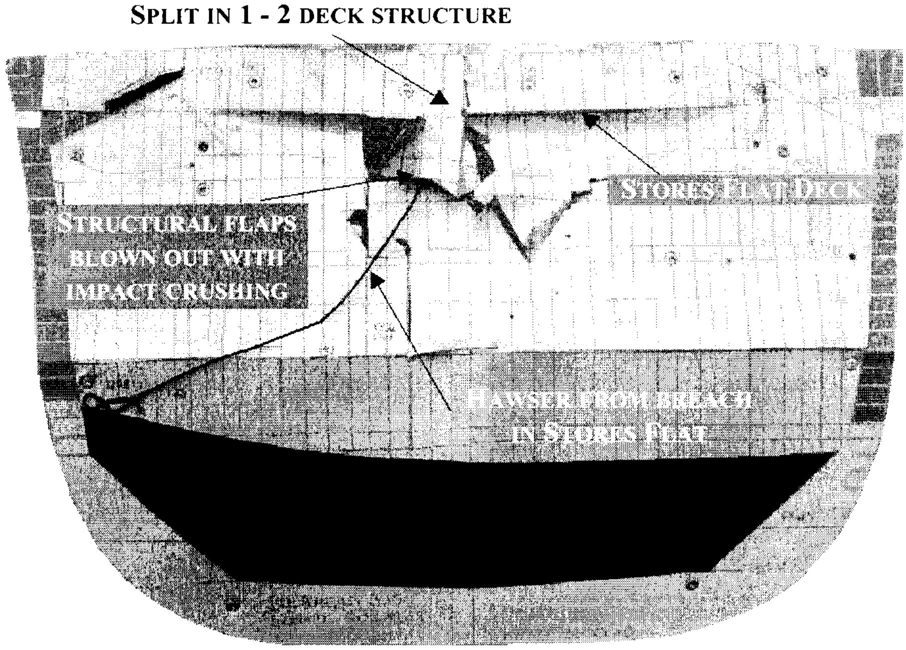


FIG.11 – BULKHEAD 339 DAMAGE (MODEL RECONSTRUCTION)

Apart from the damage to the fore deck fittings, the most significant key to the state of slow flooding of the bow spaces, before sinking, was the damage suffered by Bulkhead 339, which was a single skin bulkhead forming the boundary between No 1 Hold and the deep fuel tank (see FIG.9). The most notable features of the damage were a large bowing in of the upper half of the bulkhead, vertical and horizontal splits and flaps in the bulkhead (FIGs. 11 and12) and the permanent setting down and splitting of the deck and stores deck cofferdam structure (FIG.13). As the result of some crucial analysis work by SQUIRE[31] for the DFA,

29. Flooding rates through individual openings were substantially higher than had been predicted by previous theoretical calculations. One factor was the large relative motion amplification; the other was the presence of bulwarks which retained water for long periods (even with freeing ports modelled) – the 'swimming pool' effect.

30. Surprisingly this inherent design weakness was seen as something of an occupational hazard.

31. SQUIRE A. (London Offshore Consultants): RFI Transcript Days 32.

and supporting evidence from CORLETT,[32] this was shown to be consistent with hydrostatic loading leading to rupture, indicating that the large ullage space in the deep fuel tank was substantially unflooded at the time of sinking. This confirmed that flooding of the deep fuel tank had played no significant part in reducing freeboard, prior to collapse of the hatch cover.

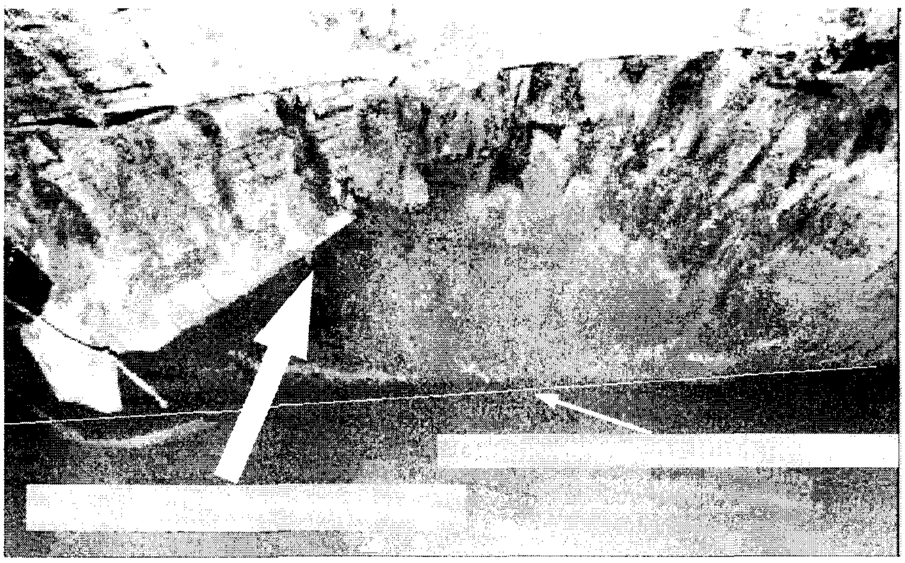


FIG.12 – BULKHEAD 339 FROM ABOVE SHOWING LATERAL DEFORMATION DUE TO HYDROSTIC LOADING

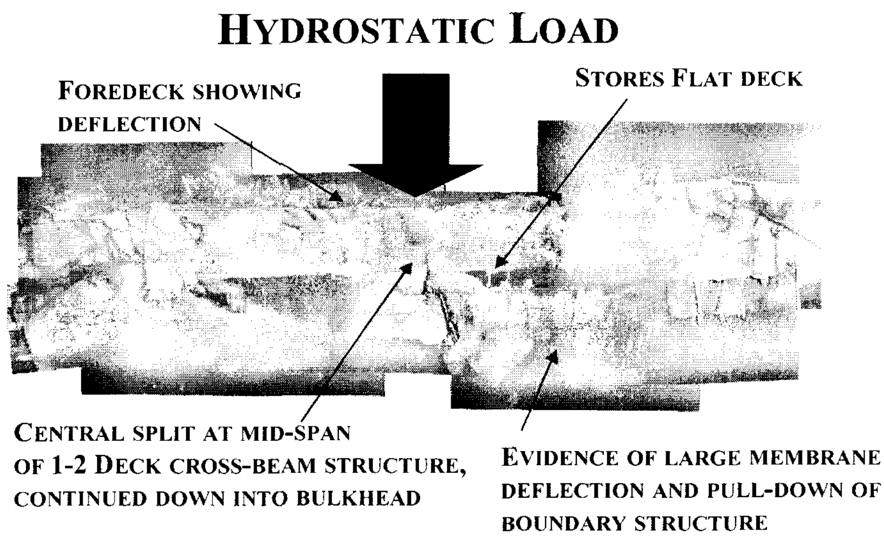


FIG.13 – FOREDECK – BOSUN'S FLAT COFFERDAM STRUCTURE COLLAPSE

For the stores flat, the relative weakness of the vents, the history of previous flooding and the relatively large openings and smallness of the space to be filled,

32. Corlett B (Burness Corlett & Partners) : RFI Transcript Days 34

led to the conclusion that this space had almost certainly been flooded prior to the sinking. Ultimately, there was no need to rely on the stores hatch being left open by the crew to explain the flooding of the Bosun's Store. Indeed the RFI accepted the evidence from several of the mariners that it was inconceivable that this hatch would have been left open.[33] The exiting hawser was explained by the fact that a messenger line attached to the hawser was tied to the underside of the hatch lid to assist deployment. Thus when the lid was forced off the rope was partially drawn out. This minor conclusion in technical terms was of considerable press interest, because it reversed the earlier conclusion of the Assessors report, and effectively exonerated the crew of any contributory negligence for the loss of the vessel.

The state of the forepeak ballast space before sinking remains the only uncertainty. Equalisation flooding had clearly occurred relatively early in the sinking process, as the external ship side boundaries were not noticeably deformed. But no survey images were available of internal boundaries to indicate whether hydrostatic loading or indeed whether rupture had occurred. The report concludes that some partial flooding was likely to have occurred in the immediate period before sinking, as the result of damage to air pipes, probably from other loose objects on the fore deck. The remainder of the flooding would have been admitted during sinking via the same air pipes and probably the rupture of internal boundaries. This therefore leaves open the precise amount of additional freeboard loss caused by flooding of this tank before sinking (anything up to an additional 1.1m).

Summary

Ultimately, the report concludes that slow flooding of the Stores Flat, and some partial flooding of the Ballast Tank, would have taken place prior to sinking, resulting in a small loss of freeboard ((5-16%)), but sufficient to have contributed to the frequency and magnitude of green water loading on the main hatch covers. It is something of an open question as to what would have happened without this bow flooding. The statistical analysis suggested that the ship was marginally safe (just) without this loss of freeboard in the mean hindcast sea state, but at some risk in the upper bound predictions.

Once the hatch of No1 Hold had collapsed, a domino effect ensued leading to the foundering of the ship after 3 holds had been flooded.

Adequacy of the International Freeboard and Hatch Cover Strength Regulations

Although it was concluded that the critical green sea loading which had caused hatch cover failure, was contributed to by some loss of freeboard, the marginal safety of the intact ship in the mean hindcast sea state, and the rapidly increasing risk evident in higher sea states raised some major questions about the hatch cover strength regulations. This became another major element of the RFI.

History of the ILLC 66 standard

The standards of most relevance to the loss are those concerning freeboard and hatch cover structural strength. When the *Derbyshire* was built in 1971 she conformed with the International Load Line Convention of 1966, a set of rules which governed permissible freeboard (as a function of ship length) and hatch cover strength (reference 10). The origin of these regulations can be traced back to 1930 when Governments first agreed them. These stipulated different minimum

33. A common practice on the *Derbyshire*, and her sister ships, was to use a lashing system around the hatch toggles to prevent them from 'walking'. Remnants of this lashing system were seen on the wreckage imagery.

freeboards for tankers with very small deck openings compared to merchant ships carrying dry bulk cargo, which had larger openings, often covered by wood or tarpaulin hatch covers. The principle of these 2 different categories of ship was carried forward into the 1966 Convention, where they were denoted as Type A ships (the tankers) and Type B ships (the dry cargo carriers). However, as bulk carriers were getting much larger, and now had steel hatch covers, a concession was agreed whereby bulk carriers could be loaded down to 60% of the difference between the Type A and B draughts, provided that the ship could survive one compartment flooding and had 'adequate' hatch cover strength and securing arrangements. This was the B-60 'B minus 60' concession and it was to this regulation that the *Derbyshire* was designed and built. It meant that for her length of 290m the minimum mean freeboard was 6.5 m i.e. 2.4% of length.[34] The cargo hatch coaming height was a little more than 2m above this value.

'Derbyshire' Hatch Cover strength

Under ILLC 66 the strength requirement for all cargo hatch covers (and the de-facto interpretation of 'adequate') was set at a nominal 1.75 t/m^2 design load (i.e. about 1.71 m head of sea water) coupled with a notional 'safety factor' of 4.25 between maximum design bending stress in hatch stiffeners and the Ultimate Tensile Stress (UTS) of the material. (For mild steel this equates to a ratio of 2.5 on yield.) Furthermore the regulations did not require the collapse pressure of the hatch covers to be determined, (i.e. taking account of buckling and plastic effects in the determination of strength) with the result that the real reserve of strength was unknown. Subsequent calculations for the *Derbyshire* showed that the No1 Hatch cover had a collapse strength of only 4.2 m head sea water (i.e. just under 2.5 times the applied load of 1.71m). In other words, it collapsed just as the maximum bending stress was reaching yield, without any further reserve beyond this point. With a well-designed structure, of the same weight, one might have anticipated a value of up to 3 being achieved allowing for the plastic shape factor (1.1–1.2) – but certainly not the illusory value of 4.25 based on UTS – giving a collapse pressure of about 5m head.

Risk of Hatch Cover failure at B-60 draught and in Higher Sea States

On her final voyage, the *Derbyshire* was well laden, but not to the maximum extent allowed, with the result that her mean draught was 0.45m less than permitted under the B-60 regulation of ILLC 66. Model tests and calculations simulating the increased (B-60) draught in the intact state showed that there was a very significant risk of a hatch-breaking wave in sea states with a Hs of 12m and higher (i.e. about 10% greater than ORCHID), even with speeds of less than 2kt. Although the probability of meeting such a sea state is exceedingly rare, this critical value of Hs (i.e. 12m) is much less than the maximum values that can be encountered in typhoons. The RFI report concluded that the ILLC 66 package of freeboard and hatch cover strength was an inadequate standard, given the catastrophic consequence of the hazard. It also concluded that revoking the B-60 freeboard concession (+ 0.76m increase in freeboard in the case of the *Derbyshire*) would not dramatically improve the critical sea state, and would therefore be insufficient on its own to solve the hatch cover strength inadequacy.

Adequacy of the latest standards – UR S21

Although the ILLC 66 regulations are still very much in force today, in the late 1990s the International Association of Classification Societies (IACS) undertook a

34. This compares with an advisory value of 4-5% on most frigates and reflects a mistaken feeling at the time that such large ships were effectively "above the weather"

major review of structural design standards for bulk carriers in the light of large losses being incurred. It concluded that the major cause of such losses was corrosion of hold side plating, the flooding of holds and in some cases the consequential flooding into other holds due to inadequate main bulkheads. This lead to a major review of structural standards for future and existing bulk carriers, resulting in new Unified Requirements being agreed. As a matter of prudence, it also agreed improved structural standards for the forward hatch covers in the first quarter of ship length. This standard, applied by all members of IACS, was called UR S21 and effectively overrides the ILLC 66 provisions for the forward hatch covers, but only on new ships constructed after 1 July 1998. It was not applied retrospectively (as was the case for the side plating and bulkhead standards) and so does not affect a substantial group of bulk carriers in service (over 400).

The RFI also investigated the adequacy of this revised standard in the light of the loss of the *Derbyshire*. Application of the UR S21 formula to the *Derbyshire* No 1 Hatch results in an increased design load of 5.5m head (c.f. 1.71m for ILLC 66) but only requires a yield stress related safety factor of 1.25 against bending stress (c.f. 2.5 (implied) for ILLC 66). In other words whilst the loading is increased substantially, this benefit is abated by a halving of the nominal safety factor. In combination, it would result in a structure with collapse strength between 6.9m and 8.3m head of seawater depending on the quality of the design in relation to buckling.[35] Calculations based on the model tests at MARIN indicated that such strength would probably have been adequate to prevent collapse in the particular circumstance of Typhoon ORCHID, but might not provide protection against more extreme typhoons with Hs above 14m. There were also indications from tests carried out at SSRC at Strathclyde for DETR/MCA, which were summarized in a report submitted to the Maritime Safety Committee of IMO (reference 11), that the UR S21 formula for the prediction of extreme hatch cover loading was physically in error for the longer Capesize bulk carriers, leading to underestimation.[36] However, the tests were not sufficiently validated, or comprehensive enough, at the time of the RFI to draw definitive conclusions. However, at the behest of the Judge, a most constructive outcome from this phase of the RFI was an undertaking by the DETR to fund further testing with the full support of IACS. The results from these tests are likely to be reported later in 2001. (see Postscript).

Cost of improving Hatch Cover strength

The RFI also heard evidence[37] that the cost of substantially increasing the strength of the forward hatch covers (say up to a strength of 10m head) was relatively modest, although not negligible. For the 2 most forward hatch covers this would represent an increase of about 10% of the total cost of a set of 9 hatch covers, equivalent to less than 1% of the UPC.

Concluding remarks – Towards improved safety

The RFI had a 2-fold purpose: to explain the loss and to review current safety standards.

35. URS 21 also includes a requirement to include a corrosion margin which would increase these values slightly.

36. A possible reason for the discrepancy is the square root term in the formula for hatch pressure loading in UR S21 which is:

$p = 19.6\ H^{0.5}$ where H is freeboard exceedance of extreme relative vertical motion.

Physics would suggest that pressure would be linearly related to H. The use of the square root term is thought to be a calibration device to increase values of p at small values of H.; however at larger values it may have the effect of artificially reducing the loading.

37. BYRNE D. (Transmarine Ltd.): RFI Transcript Day 30

It established the circumstances which gave rise to large green water loading on the forward part of the ship – the large pitching and relative motion in the dominant 300m long waves of the typhoon, aggravated by loss of freeboard, caused by down-flooding in some of the bow spaces. However, it also showed that it was the relatively modest strength of the No 1 hatch covers (4.2m), permitted under ILLC 66, which made disaster inevitable.

On current safety standards the RFI reviewed ILLC 66 and concluded that it was clearly inadequate for ships on world-wide service, which could encounter typhoons or other similar severe weather, given the catastrophic consequence of hatch cover failure. The more recent standard URS 21 was obviously a substantial improvement, but considerable question marks remain over its prediction of load for longer vessels. Furthermore, like ILLC 66, its definition of strength is not based on limit state methods, leading to ignorance about the real reserve of strength and potentially inefficient design.

The RFI report made a number of recommendations for future design:

- Design for reasonable extreme conditions.
- Review loading prediction of URS 21 (based on further model tests) and, if necessary, develop new set of extreme load formulae to be adopted by IACS as soon as possible, allowing trade-off against freeboard.
- Design using limit state methods.
- Apply new rules both to new designs but also, retrospectively, to existing Capesize bulk carriers.

The UK Government has accepted the recommendations of the RFI. However, given the international nature of shipping and shipping regulations, the application of this improved safety regime will depend on acceptance at international organizations such as IACS and the IMO.

Postscript

In October 2001 a special RINA conference *Design and Operation of Bulk Carriers – post MV Derbyshire* was held to hear the results of the further series of model tests designed to check the validity of UR S21.

These showed that the UR S21 formula was indeed in error for the larger Capesize Bulk Carriers, under-estimating extreme loads on the forward hatch by 10-30%. It is anticipated that the UR S21 regulation will be amended by ICAS. At the time of writing (November 2001) IACS and IMO are still debating the cost-effectiveness of replacing the hatch covers on existing Bulk Carriers (built pre 1998), designed to the lowest ILLC66 standard. A decision is expected hopefully in 2002.

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ANNEX A

Calculation of Risk of Hatch Cover Failure – Outline of Method

The basic method to calculate the risk of hatch cover failure is outlined below:

- Calculate the probability of pressure impact (Pr) greater than critical hatch breaking pressure 42kPa for a given impact. Pr will be a function of sea state and ship parameters and will apply to a particular short-term period in the storm.
- Calculate the probability of at least 1 pressure impact greater than 42kPa in 1 hour for a given hour (i). This depends on number of impacts n_i in that hour, and is equivalent to:

  $$Pi = 1 - (1 - Pr)^{n} = 1 - e^{-(ni\ Pr)} \qquad [A1]$$

- Similarly over the course of the typhoon calculate the cumulative probability after k hours, which is based on the hourly values obtained in [A1]:

  $$Ck = 1 - \{(1 - P_1)(1 - P_2)\ (1 - Pk)\} \qquad [A2]$$

  Noting that P_1, P_2 etc. must reflect change in sea state and ship and any freeboard loss due to flooding.

The problem of statistical extrapolation to calculate Pr

An issue of some contention in the RFI was the calculation of the value of Pr – the probability of pressure exceeding the critical pressure for a single impact. Except for the model test runs involving higher sea states and low freeboards (assuming complete bow flooding), it was often not possible to record many, if any, actual pressure measurements above the critical pressure value. This was also due to the relatively short testing time available (< 2hrs) available in each run. In these circumstances, the fitting of a statistically valid curve to the experimental results and in particular extrapolation to higher-pressure levels in the tail of the distribution had a major role to play in the results obtained and the credibility of the analysis. The difference between a value of more or less zero – say10^{-5} and 10^{-3} – for Pr could lead to an immense difference in the value of Ck (see [A1, A2] above) changing a risk of a few percentage into a near certainty.[38] Typically, the total number of impacts (Ni) was in the range 250 – 650. Ck became significant

38. Typical total number of impacts (Ni) was in range 250 – 650. Ck became significant when average Pr was around 10(exp-3) such that the Expected Number of Impacts greater than the Critical Pressure approached 1.

when average Pr was around 10^{-3} such that the Expected Number of Impacts greater than the Critical Pressure approached 1.

To prevent these predictions becoming a source of dispute, and therefore unreliable for the drawing of conclusions, the Court sought and appointed an expert on statistics, whose advice would be acceptable to all the parties, and who would then act as 'sole expert'. This person turned out to be PROFESSOR Jonathan TAWN of Lancaster University, and Vice-President of the Royal Statistical Society. Work carried out by TAWN and his co-worker HEFFERNAN[39] concluded that the most satisfactory curve fit to the MARIN data was provided by 2 parameter Generalized Pareto statistical model of the form[40]:

$$\Pr(\text{Impact Pressure}>x) = \{1 + \xi\,((x - x\text{min})/\sigma)\}^{(-1/\xi)} \text{ for } x > x\text{min}$$

where ξ is a shape parameter (skewness) , σ is a scale parameter determining both the mean and variation of the distribution and xmin is the minimum threshold pressure above which records were taken.[41]

39. TAWN J. 'Report on the Statistical Assessment of Risk for the Derbyshire.' 30 June 2000. RFI Transcript Day 42.

40. Other models considered, but rejected, were the Weibull distribution, the Modified Gumbel and Censored Gumbel distributions.

41. Whereas ξ had a fixed characteristic value for all conditions, σ was found to be a function of 2 'explanatory variables' – the experimentally derived predicted mean impact pressure and the freeboard change due to flooding. This data was provided by MARIN for all the ship and sea conditions, together with the expected number of impact pressures (n) exceeding xmin.