SNAME *Transactions*, Vol. 106, 1998, pp. 59–103

An Independent Assessment of the Sinking of the MV *DERBYSHIRE*

Douglas Faulkner, Fellow, Emeritus Professor of Naval Architecture, University of Glasgow, Scotland

The author was appointed by the UK Department of Transport as a fellow Assessor with R.A. Williams during Lord Donaldson's Assessment (1995) of the loss of the OBO ship DERBYSHIRE and throughout the planning and conduct of the two final surveys of the wreck. This paper is drawn from the independent report (Faulkner, 1998a) and may be considered complementary to those of the UK and EC Assessors (Williams and Torchio, 1998a and 1998b). The paper deals with the history and loss of the ship, including the concept developed in 1995 of 13 possible loss scenarios in a formal safety Risk Matrix of probability and seriousness. It analyses abnormal wave effects on hatch cover collapse, on ship bending, and on flooding of bow spaces and no. 1 hold. The implosion-explosion mechanics during sinking is outlined to explain the devastation of the wreck. The 1996 and 1997 underwater surveys are outlined as are the findings of fact. Each of the final 14 loss scenarios is analysed in the light of the firm and circumstantial survey evidence, plus many other factors of service experience, analyses and experiments. The updated Risk Matrix speaks for itself and leads to the prime conclusions and major recommendations.

Nomenclature[1]

1. INTRODUCTION

"I can command men and ships, but I cannot command the wind and sea." —Admiral Lord Nelson

1.1 The Ship

The *LIVERPOOL BRIDGE* (later renamed *DERBYSHIRE*) was ship no. 57, the last of a class of six OBO carriers designed by Swan Hunter at their Wallsend Yard in 1969 and built in the period 1970-76 at the Haverton Hill Shipyard on the river Tees, which Swan Hunter acquired from the Furness Shipbuilding Company in 1968. She was classed with Lloyd's Register and delivered to Bibby Bros., Liverpool, in 1976. Her relevant principal particulars were:

L	281.94 m	Service draught	17.04 m
B	44.20 m	Summer draught	18.46 m
D	24.99 m	max. Δ	203,800 te
C_b	0.84	max. DWT	173,200 te

On her last voyage from Sept Isles, Canada, to Yokohama she was carrying about 158,000 te (tonnes) of ore concentrates distributed in 7 of the 9 holds, as shown in Fig. 1 (Lloyd's Register, 1987) which also depicts the oil fuel, fresh water and minimal ballast water distribution. Her estimated displacement as she approached Japan was about Δ = 194,000 te and hence mean draught T ≅ 18.0 m and F ≅ 7.0 m.

The class was of double hull construction, with double skin sides and transverse bulkheads between holds, double skin cofferdams in the aft section and between hold no. 1 and the internal spaces at the fore peak stores deck level. The only major subdivision structure that was single skin was the transverse collision bulkhead 339, as can be seen in Fig. 1.

The first ship of the class *FURNESS BRIDGE*, completed in 1971 had the thick hatch side girders (which formed the internal longitudinal boundaries of the topsides WBTs) continued from hold no. 9 through bulkheads 65 and 64 and scarfed and butt welded to the thinner longitudinal machinery space bulkhead in the same plane. This design was modified for later ships so that a cofferdam 64/65 between the hold 9 and the port and starboard slop tanks could be constructed as a unit.

As a result, the 5 later ships of the class ended these hatch side girders at bulkhead 65 with partial penetration welds forming a cruciform connection, as had been previous practice in the VLCCs which the firm had built. Although this was an approved modification, it was later to be a major cause for concern to the DFA.

The final important design and operation feature to note is that these Type B cargo ships were categorised as B-60 ships under the 1966 ICLL regulations (Murray-Smith, 1969). This relaxed (reduced) the freeboard requirements providing that a one compartment flooding standard was met when fully

[1] Nomenclature used in this paper can be found in Appendix B.

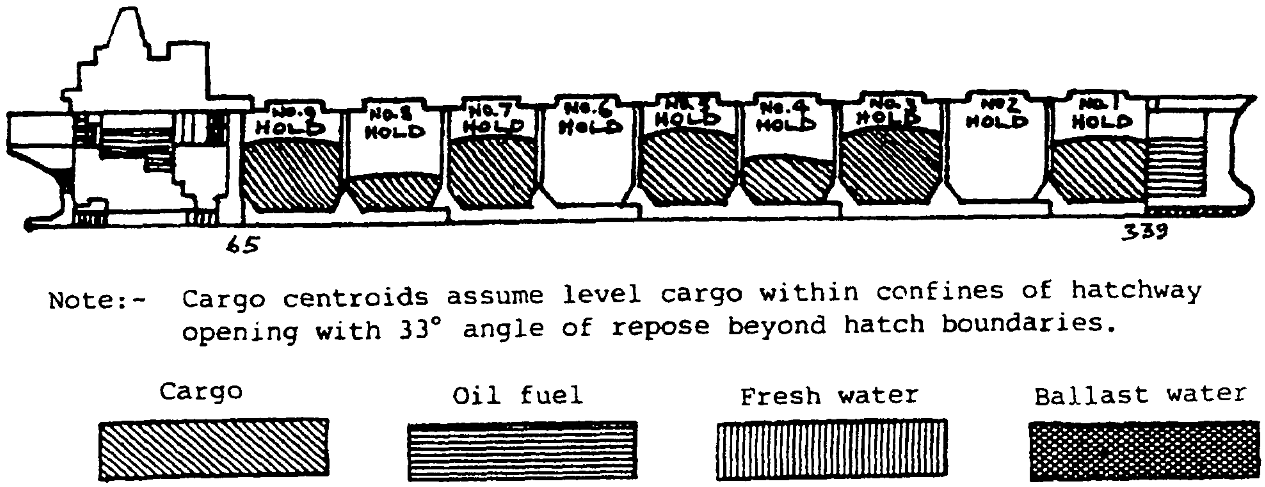


Fig. 1 Last known loading condition of M.V. *DERBYSHIRE*

laden. This gave a minimum summer load F ≅ 6.5 m for the class. This requirement could be met by *DERBYSHIRE* but many B-60 ships cannot (Lloyd's List, 1996).

1.2 The Loss and Events up to 1986

On or about the 9th of September 1980 when the vessel was hove to in the most dangerous semi-circle of Typhoon ORCHID, the ship was lost with all hands (44, including 2 wives) at about 25.86° N and 133.53° E on the northern flank of the Daito Ridge, some 400 miles South of Shikoku Island, Japan. There was no distress signal and only two sightings of oil upwellings seen some days later gave a clue to the position of the sinking. A lifeboat from the ship was sighted but this was not recovered and subsequently sank.

As there was no available evidence, nor any established evidence of structural or other weaknesses in the six ships, the Government decided not to hold a formal investigation into the casualty. Then, 18 months later in March 1982 the *TYNE BRIDGE* experienced severe brittle fractures in the upper deck when in ballast in the North Sea. A 2.8 m crack propagated away from the port aft corner of no. 9 hatch opening, and a 4.7 m crack propagating from a weld burn aft of frame 65 but travelled inboard and forward to cross frame 65. The internal structure was subsequently modified.

This casualty led to much speculation, especially as the DFA were gathering information regarding cracking in the vicinity of frame 65 in several ships of the class. Evidence was mounting of bad alignment and workmanship either as-built or as-repaired. The DoT therefore initiated studies, including one with Bishop, Price and Partners (eventually extended and published with Temarel, 1991) and the results were incorporated in a report (DoT, 1986). Opinions on five most likely causes of the loss of the ship were offered:

- *Explosion*—less likely because she had not carried oil cargo since October 79 and had been tank cleaned
- *Shift of Cargo*—could result from an ingress of water into holds thereby causing liquifaction of the cargo
- *Failure of Hatch Covers*—deck flexing could "spring" the covers followed by water entry and rapid flooding and foundering
- *External Hull Damage*—ship struck by submerged or partially submerged object
- *Structural Hull Failure*—failure of part of the hull could lead to water ingress, etc.

This report pointed out that some of these scenarios would be apparent to the crew, and a ship message would be likely. Other points made were:

- Any misalignment at bulkhead 65 is significant only for local strength aspects; nevertheless, more consideration should be given to the alignment of this intersection
- The series of assumptions and events which would lead to a massive hull failure at or about frame 65 are contentions (and not considered further)
- Four of the five sister ships had not (as of 1986) suffered any major structural distress; the fifth, *TYNE BRIDGE,* also survived and its brittle cracking in 1982 in the upper deck is not considered to be relevant to the loss of the *DERBYSHIRE.*

The report ended "in the last analysis the cause of the loss of the *DERBYSHIRE* is, and will almost certainly remain, a matter of speculation".

This final DoT report was substantially different form an earlier draft version in July 1985 which concluded that the most likely cause was "total structural failure" resulting from defective design and/or construction at the frame 65 connection. It was unfortunate that this report was not captioned "draft", was first leaked to the Press, then released by the Department and attracted very wide media attention. The builders and LR had not at that stage been consulted and the report was in fact seriously in error on several counts. This bad management by the DoT led to allegations of "cover up" and the DFA were outraged.

Shortly after in November 1986, the *KOWLOON BRIDGE* came to grief with no. 3 hold perched on the Stag Rocks off Bantry Bay following steering gear failure. There had been deck cracking aft, which had been temporarily reinforced to allow the ship to complete her voyage. Nevertheless, the stern eventually also broke off near to frame 65. As a result of this, and no doubt fuelled by the media and the pressure from the DFA, the Government ordered a FI into the loss of the *DERBYSHIRE.* It was inevitably biased toward a fuller assessment of the frame 65 loss scenario.

1.3 The FI and Events up to 1994

The Decision of the Wreck Commissioner and his three Assessors was "the Court finds that the *DERBYSHIRE* was probably overwhelmed by the forces of nature in Typhoon ORCHID, possibly after getting beam on to the wind and sea.....". The "Summary of Conclusions" of the Court (DoT, 1989) are:

1. the *DERBYSHIRE* was properly designed, properly built and constructed from material of approved standard
2. no inference can safely be drawn from the absence of any distress signal
3. the condition of the cargo when loaded and its loading were within the existing recommended parameters
4. the *DERBYSHIRE* was caught in the worst part of typhoon ORCHID and may have encountered local freak weather beyond what can be hindcast
5. the actions of her Master were not unreasonable
6. the possibility that the ship was lost as a result of torsional weakness in her hull is extremely low
7. the combination of circumstances necessary to postulate separation of the hull at frame no. 65 is very unlikely, though some element of doubt must remain
8. it is improbable that immediate or even sudden structural failure of the forward hatch covers caused rapid sinking
9. sequential flooding of holds is a possible cause of loss but not thought probable
10. if cargo liquifaction did occur, which is doubtful, it still cannot be concluded that it was the prime cause of the loss
11. if the ship got beam-on to the weather, structural failure and/or cargo shift would have become much more likely; it is quite possible that that happened, but it cannot be proved.

Again, the DFA were outraged by the lack of a firm conclusion regarding frame 65. Nevertheless, the subject had occupied about 40% of the proceedings.

The 1990 presentation and discussion in the RINA of the paper *"A theory for the loss of the M.V. DERBYSHIRE"* (Bishop, Price and Temarel, 1991) was valuable in bringing many facts together and in leading to a vigorous and beneficial discussion. The paper included a number of factual inaccuracies, and whilst the theory itself was not criticised, its application and inferences certainly were. A later debate goes into this more fully (Grigson, 1997). The charisma of Prof. Bishop in particular, had a profound effect on the DFA. They then believed absolutely that this apparent combination of poor construction and "horns of high stress" at the frame 65 connections was the final proof beyond any doubt that this was the cause of the loss. In fact these stresses were unremarkable and mainly still water cargo loading effects.

By 1994 DFA had raised sufficient funds through the ITF to mount a survey to find and examine the wreckage. This they did in May and June 1994 (ITF, 1994; Mearns, 1995). Although the emphasis and conclusions were overly subjective and extremely biased, the mission did correctly conclude that whatever happened the loss was sudden and catastrophic.

The survey was valuable in identifying and locating the bow section and in suggesting the extent of the wreck field. Evidence of unexpected and extensive fragmentation and some brittle fracture of the hull was thought to be due to substantial implosion-explosion actions during sinking (now confirmed). There was speculative evidence of excessive corrosion of the fore deck plating (later disproved) and for the possible location of the stern section as Target 9 some 600 m from the bow (later confirmed).

1.4 Lord Donaldson's Assessment 1995

The ITF survey did provide sufficient new evidence to require further formal action. The starting point was Lord Donaldson's Assessment (*DERBYSHIRE*) in 1995 whose Terms of Reference in essence were:

- to assess what further work is needed to learn more of and, if possible, make a judgement about the cause of the loss
- for each option determine the likely costs, the probability of success and the benefits to ships' safety.

The two Technical Assessors appointed to assist Lord Donaldson were Professor D. Faulkner and Mr. R.A. Williams.

The lucid report speaks for itself (Donaldson, 1995) so only the FSA aspects will be mentioned. Lord Donaldson concluded that only a further, more extensive, but final examination of the wreck site would satisfactorily resolve the mystery. He considered the likely cost of about £2M to be fully justified because of the potential benefit to ship safety.

If it were not possible to determine the reason for the loss with a reasonable degree of certainty, the secondary objective was to learn more with a view to narrowing the field of possible causes. Lord Donaldson also recommended that possible abnormal wave actions should also be considered, based on the evidence and analyses presented in his Annex (Faulkner, 1995b).

1.5 Risk Assessment of Loss Scenarios

A FSA in reverse so to speak was used when assisting Lord Donaldson (Faulkner and Williams, 1996a and 1997). This determined and ranked in relative terms the possible initiating causes for the loss. A review was therefore made of service experience for the class and of casualty data for ships generally (Faulkner, 1995a and 1995c) and specifically for bulkers (Intercargo, 1995; Jones and Roe, 1991, etc.). Discussion with those familiar with bulker operations (Spyrou, 1997, etc.) targeted reading (Ramwell and Madge, 1992; Isbester, 1993; Jubb, 1995) also helped to formulate the judgements made. For example, Table 1 (Faulkner and Williams 1996b) summarises the percentages of total loss causes of bulk carriers, excluding war losses, in the calendar years 1960-94 (LR, 1995) and 1990-94 (Bureau Veritas, 1995).

An interpretation of this data suggests that cargo shift and capsize is very rare in big ships and that 30-35% of losses are likely to be due to inadequate structure. In this period no bulkers have broken in two at sea, although at least one lost its bow. Although none have lost their stern, serious cracking at the bridge front has occurred. Table 1 also suggests that navigational errors account for about 35% of losses, and fire

Table 1 Breakdown percentages of loss causes for bulk carriers

Attributed causes	*1960–94*	*1990–94*
Possible hull damage	29.9	28.6
Wrecked or stranded	28.3	24.1
Fire and/or explosion	18.6	20.5
Collision	9.6	8.9
Missing unexplained	4.5	9.8
Machinery damage	3.9	3.6
Engine room flooding	3.4	4.5
Cargo shift	1.1	–
Total	100%	100%

and/or explosion accounts for about 20%. More than 75% of marine casualties are attributed to human error.

From all this, two indices were judged on a scale of 1 to 5. These were the notional probability of an initiating event (P_i) and its seriousness (S_c) in terms of subsequent consequences. They were combined as a product to define a notional Risk Numeral for each of the 13 loss scenarios:

$$R_n = P_i \times S_c$$

for both Normal wave actions, which correspond to normal design, and for Abnormal wave actions, which would correspond to rare "Survival Design" (Faulkner, 1997a; Faulkner and Buckley, 1997). The latter are given in Table 2.

Table 2 Risk numeral components

Loss Scenarios	Abnormal Wave P_i	Abnormal Wave S_c	Abnormal Wave R_n
Primary Structure			
C1 Deck cracking Frame 65	3	4	12
C2 Deck cracking mid-sections	2	3	6
C3 Torsional weakness	2	1	2
Fore End Vulnerability			
C4 Hatch cover collapse	5	4	20
C5 Hatch attachment failures	3	2	6
C6 Fore deck collapse (corrosion)	3	3	9
C7 Fore peak flooding	2	4	8
Other Scenarios			
C8 Cargo shift/liquifaction	1	2	2
C9 Propulsion loss	2	5	10
C10 Rudder loss/steering failure	2	5	10
C11 Explosion/Fire in E.R.	2	5	10
C12 Pooping—from forward waves	2	2	4
C13 Pooping—running with the sea	3	2	6
C14? The unforeseen scenario— the sea often springs surprises			

The 13 loss scenarios are in three groups, the last group has three scenarios (C9, C10, C11) where the ship would be stationary, and for each the serious consequence numeral S_c = 5 (the highest level) in abnormal seas because the ship would become beam-on to the weather. As such, she would be very vulnerable to roll-induced damage to hatch covers leading to water ingress and foundering (Faulkner and Williams, 1996b). Capsize is not likely because of the very high transverse stability.

The highest Risk Numeral was 20 for Hatch Cover Collapse (C4) and this would now be 25 (with S_c = 5 instead of 4) as it has subsequently been found from dynamic calculations that *DERBYSHIRE* could not survive the two forward holds flooded in these seas.

The second highest risk numeral was for loss scenario C1 deck cracking at Frame 65, leading to separation of the aft end and supposed rapid sinking. For this R_n = 12 which is close to the assumed "intolerable" risk level of about 16 and is certainly higher than could reasonably be implied from the FI conclusions. This increase arose from the results of the abnormal wave time stepping simulations (Faulkner, 1995b) which suggested that part at least of the stern might come out of the water, as has also been experienced in similar ships—see, for example, the RINA Colloquium discussion. This then would induce a high tensile stress at Frame 65 where any overloaded poorly constructed weld connection might crack and provide the dynamic load trigger to reduce toughness and *initiate* a brittle fracture in the hull girder. Even then, the risk of continuous *propagation* can be shown to be small.

Perhaps the only loss scenarios which would not in all likelihood allow time to launch lifeboats and/or to send a distress signal are C1, C4 and perhaps C7, C13.

An *a priori* Risk Matrix for the loss scenarios is given in Fig. 2. Those scenarios in the top right corner are considered to be "intolerable" and something needs to be done about these whatever happens. There is only one in that category, which is hatch cover collapse (C4), and for this reason papers were published (Faulkner, Corlett and Romeling, 1996 and Faulkner, 1997b) without prejudice to the outcome of the *DERBYSHIRE* investigation. Whatever the final outcome, hatch cover vulnerability must be regarded as a "near miss" for several B-60 bulk carriers. Figure 2 contains some downward pointing arrows which will be explained later as *a posteriori* adjustments to R_n arising from updated information from the Phase 1 survey of the wreck.

1.6 Ship Communications

The important messages to and from the *DERBYSHIRE* are presented in the FI report (1989). The last position report from the ship on 9th September at 0300Z was "vessel hove to violent storm force 11 wind NE × E seas approx 30 feet overcast continuous rain pressure 995 mb". In contrast, the M.V. *ALRAI* at about the same time and approx. 80 miles (north?) of the *DERBYSHIRE* reported "60–100 ft waves with wind force 12 and visibility nil . . . and 962 mb".

The plot of the track of typhoon ORCHID by Ocean Routes, the weather routeing agency for *DERBYSHIRE*, can be deduced from the FI report and compared with the very consistent tracks shown in its Appendix II from Tokyo, Guam and Hong Kong. In the period leading up the 8th September the Oceanroutes track was several hundred miles different from these, and might possibly have left Captain Underhill in a dilemma.

Mariners remarks at the RINA Colloquium (1996), at a recent RINA Conference (Evans et al, 1995) and from other sources do seem to suggest that weather routeing may not always act in the best interests of ship safety due to economic emphasis on meeting charter dates and minimising fuel used.

2. FORENSIC ANALYSES FOR FREAK WAVE ACTIONS

2.1 Lateral Thinking

In 1995 the author was puzzled as to why, after so many man-years of intelligent effort, no loss scenario, including Frame 65, stood out as being likely. He wondered if previous investigators were restricted by applying conventional tools and thinking to explain the loss. By any standards the loss was *extraordinary* for a well found ship only four years old under the command of an experienced master.

The author's starting point therefore was to look for an *extraordinary* cause. He reasoned that nothing could be more extraordinary than the violence of a fully arisen and chaotic storm tossed sea. He therefore studied the meteorology of revolving tropical storms and freak waves (Coles, 1991; van Dorn, 1993 and Draper, 1964) and found that steep elevated waves of 25 m to 30 m or more were quite likely to have occurred during typhoon ORCHID (Faulkner, 1995b).

P_i				
5			C4 — —	— —→ ?
4	ALARP	ZONE		
3	C5, C13	C6	C1 ?	
2 C3	C12	C2	C7	C9, C10, C11
1	C8			
1	2	3	4	5 S_c

		$P_i x S_c = R_n$
C1	Deck Cracking Fr.65	3 x 4 = 12
C2	Deck Cracking Mid-Sections	2 x 3 = 6
C3	Torsional Weakness	2 x 1 = 2
C4	Hatch Cover Collapse	5 x 4 = 20
C5	Hatch Attachment Failures	3 x 2 = 6
C6	Fore Deck Corrosion Collapse	3 x 3 = 9
C7	Fore Peak Flooding	2 x 4 = 8
C8	Cargo Shift/Liquifaction	1 x 2 = 2
C9	Propulsion Loss	2 x 5 = 10
C10	Rudder Loss/Steering Failure	2 x 5 = 10
C11	Explosion/Fire in Engine Room	2 x 5 = 10
C12	Pooping – From Forward Waves	2 x 2 = 4
C13	Pooping – Running with the Sea	3 x 2 = 6

Fig. 2 Risk matrix for abnormal waves (1986)

Later on it was found that *DERBYSHIRE* was not only trapped at about the very worst radius of the dangerous semicircle of the typhoon, but that starting just three hours after her last message typhoon ORCHID executed three high-speed conditionally unstable cyclonic loops with increasing forward speed up to 30 knots toward the NW and North with rotational steady wind intensities reaching 75-80 knots (Cardone, 1987). This is illustrated in Fig. 3 which shows the envelope of highest rotational wind speeds and the last known and final wreck positions of the *DERBYSHIRE*.

It was therefore recognised that quite novel analyses would have to be undertaken to establish possible characteristics of the seas to which the ship might well have been subjected and then to examine the response of the ship to these seas so that the risks associated with the previously described loss scenarios could be better established.

2.2 *Survival Waves*

When working for the US Navy's Model Basin twenty years ago, Buckley first advocated new loading conditions for the primary structural design of ships (Buckley, 1978). This was followed by work for the Ship Structure Committee (Buckley, 1988) which advocated extreme climatic wave spectra for more general structural design, including wave impact design. In parallel, the 1979 ISSC Environmental Conditions Committee I.1 defined very similar waves of limiting steepness by:

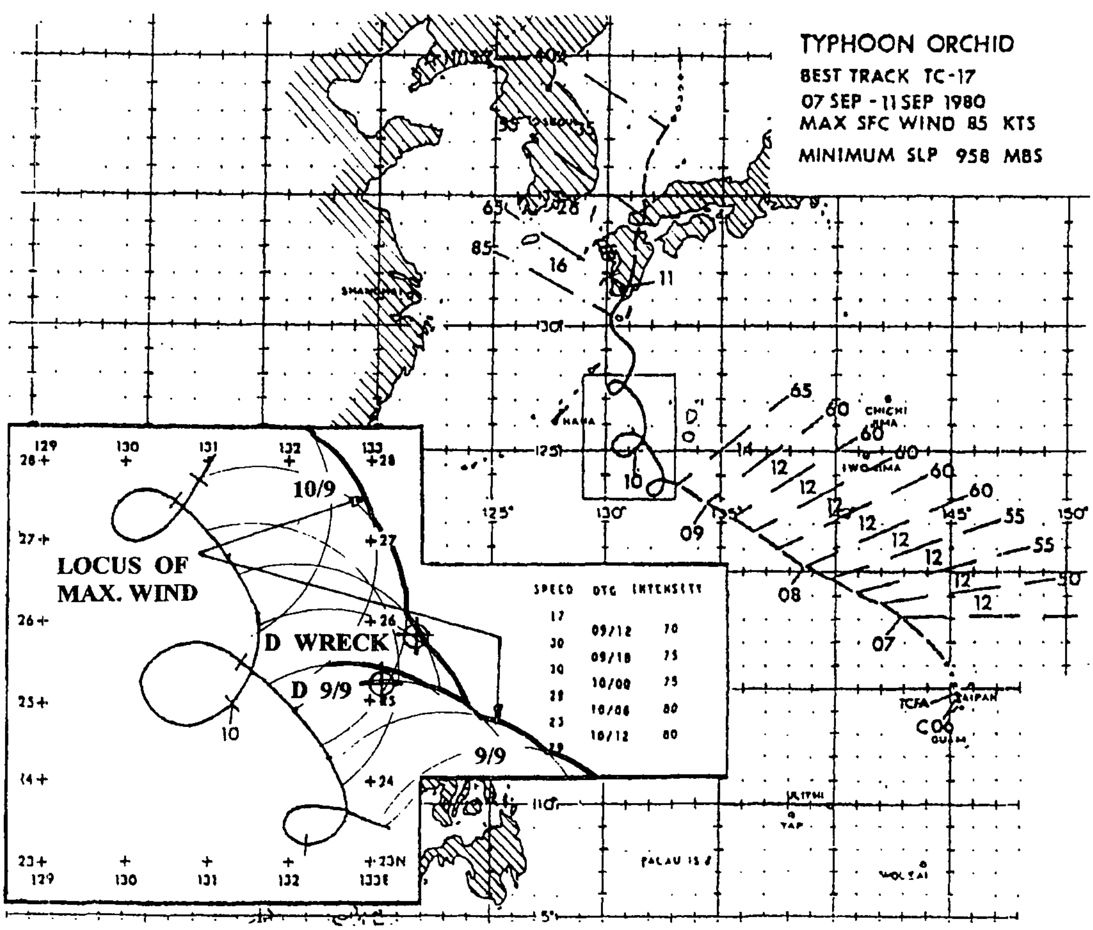


Fig. 3 Typhoon ORCHID track and last known position of MV *DERBYSHIRE*.

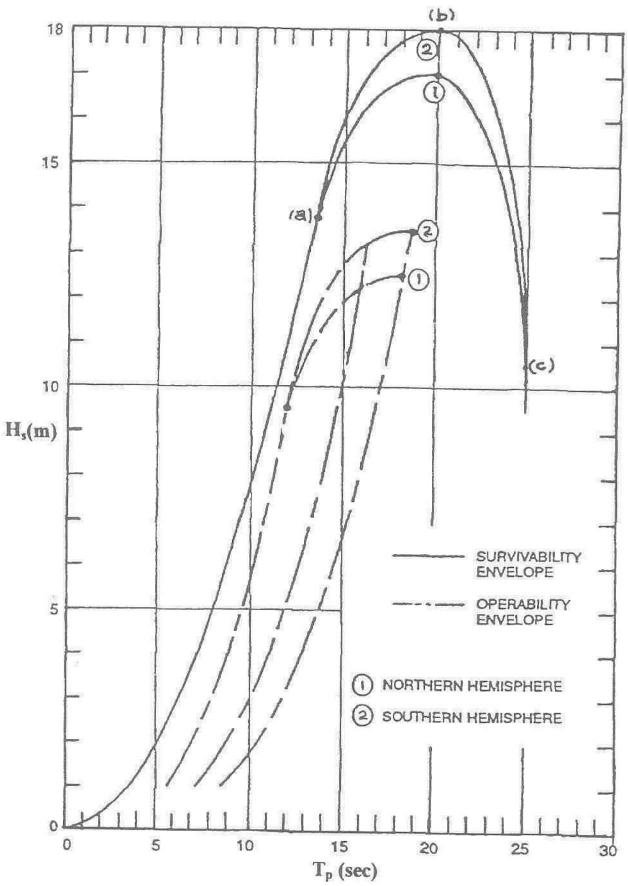


Fig. 4 Global survivability and operability envelopes

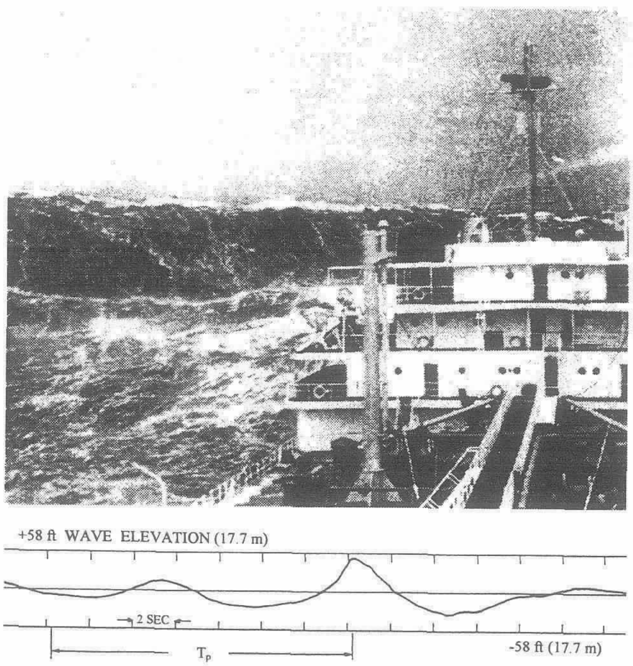


Fig. 5 Steep elevated wave record, and a ship encountering one

$$T_p = 3.6\sqrt{H_s} \tag{1}$$

This was based on the steepest boundaries of global wave scatter diagrams and is very close to Hogben's contemporary work (see Hogben et al 1986, and Hogben 1990). Following the work for Lord Donaldson these two independent pieces of work were brought together (Faulkner and Buckley, 1997) and *survivability* and *operability* design wave envelopes of H_s vs T_p were presented—see Fig. 4.

To define the *abnormal waves* to be used for Lord Donaldson's Assessment (Faulkner, 1995b) H_s = 14 m was assumed based on FI data for typhoon ORCHID during the 24 hours following the ship's last message. For primary bending studies eq(1) was used for defining T_p, but for roll-induced actions:

$$T_p = 3.2\sqrt{H_s} \tag{2}$$

was used based on contemporary conditional probability data (Dahle and Myrhaug, 1995). The range of wave lengths considered for use with these wave periods was:

$$16\ H_s \leq \lambda \leq 20\ H_s \tag{3}$$

The low probability extreme wave height for survival design (H_d) and the asymmetry parameters which are important for ship damage and flooding are:

$$H_d = 2.5\ H_s \geq 25\ \text{m} \tag{4}$$

$$\alpha = 0.65\ ,\ m_f = 0.6 \text{ and } m_b = 0.4 \tag{5}$$

These parameters were based on wave profile data measured during hurricane CAMILLE in 1969 (Buckley, 1983 and 1991) and have recently been supported by numerical simulations (Drake, 1997) and experimentally (Clauss, 1998) where H_{max} = 2.56 H_s, very close to eq(4). See also Kjeldsen (1984), Myrhaug and Kjeldsen (1986), and Gaythwaite (1981) who explains why young RTS waves become so steep. Figure 5 shows a TS from a steep, elevated wave record and a ship encountering one (Buckley, 1983). Currents which oppose waves also steepen them. Mariners frequently referred to such waves as "walls of water".

Pyramidal waves are a feature of cyclonic RTS storms. These migrate away from the tropics, sometimes drawing in further energy from other nearby depressions. The fore deck damage to QE2 in September 1995 is an excellent example arising from hurricane LUIS moving NE off Newfoundland's Grand Banks (Lloyd's List, 1995). A wave height of nearly 30 m has been confirmed (MAIB, 1997). Eilersen et al (1989) point out that the spilling breaking limit is H = 2.9 H_s. This is a vital subject related to weather deck impact damage, as shown in Appendix A.

The above wave heights and asymmetry parameters were provisionally suggested as being appropriate for survival design of ships having L ≥ 150 m say. However, casualty data and logic suggest that smaller ships are likely to be troubled by lower height waves which occur more often. Taking note of an excellent report by Bales (1982) on designing for the (extreme) environment it is *provisionally suggested* that the above equations are considered when examining critical survival design conditions but where H_s is chosen as a function of ship length (m):

$$H_s = 15 - (3 - L/100)^{2.5} \tag{6}$$

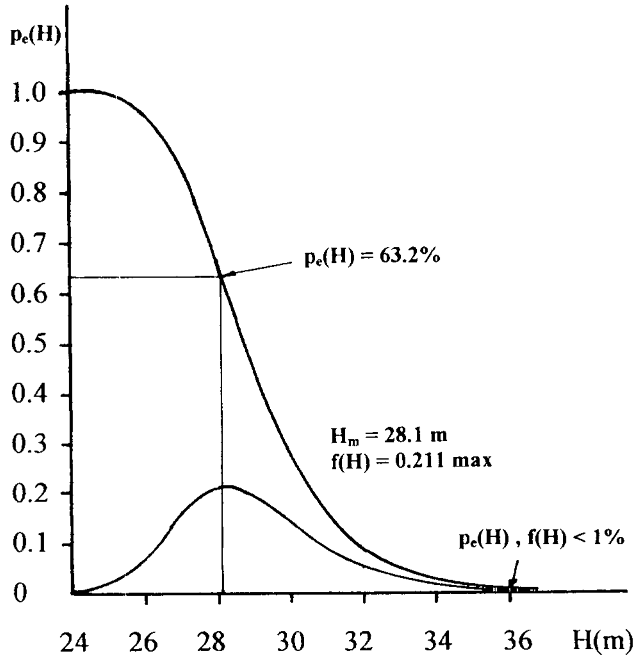


Fig. 6 Probability density and exceedence plots

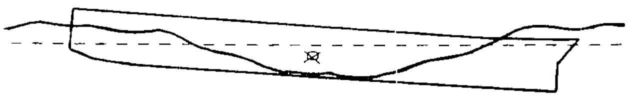


Fig. 7 FPSO maximum sagging in non-linear waves

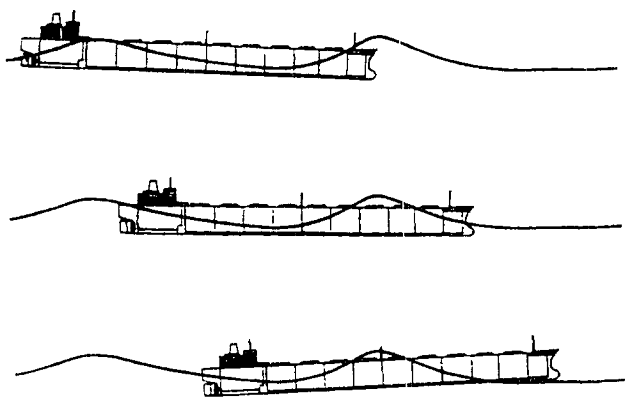


Fig. 8 M.V. *DERBYSHIRE* encountering a 30 m × 260 m steep elevated wave

Over the range 75 m ≤ L ≤ 300 m H_s varies from L/10 to L/20. For smaller vessels H_s = L/10 is suggested—a little more severe than L/12 (Spencer, 1975). For larger trading ships or moored FPSOs higher values of H_s than 15 m, may need to be considered and Fig. 4 may be used as guidance. For example, for designs West of Shetland one oil company is proposing H_s = 18 m.

Probabilities

Assuming that individual wave heights in each sea state follow a Rayleigh distribution, and noting that extreme storms are reasonably narrow-banded, Longuet-Higgins (1952) derived a time dependent probability distribution for *maximum* wave heights in a short term stationary storm for which:

$$H_m = H_s\,[0.5\ \ln N]^{0.5} \tag{7}$$

$$H_e = H_s\,[0.5(\ln N - \ln(-\ln(1-p_e)))]^{0.5} \tag{8}$$

For D = 12 hours, H_s = 14 m and T_p = 13.5 s this gives the most probable extreme wave height H_m = 28.1 m with a 63.2% probability of being exceeded . Ochi recommends a value of p_e = 1% for design, which in this survival extreme case is H_d = 2.52 H_s which is virtually the same as eq(4). Low probability values are:

$p_e = p_e(H)$	%	25	10	5	3	1
H_e	m	30.2	31.8	32.9	33.7	35.2

It can be argued that equations (7) and (8) may not be appropriate for RTS waves because they are not narrow banded. However, until ε exceeds 0.9 for very wide banded processes the differences are no more than 5% using Ochi's band width dependent equations (1990). Moreover, as he points out, for a given period D the number of peaks for a non-narrow-banded spectrum is much larger than for a narrow-banded one. Overall, it is therefore felt that eq(8) can be used unmodified, and this was supported by Hogben (1997) who also provided evidence to support the use of eq(4) for design.

From eq(8) it is useful to derive p_e in terms of any H and N:

$$p_e(H) = 1 - \exp(-\exp\gamma)\ \text{where}\ \gamma = \ln N - 2(H/H_s)^2 \tag{9}$$

The probability density function of the extreme process can then be derived by differentiating F(H) = 1-p_e(H):

$$f(H) = (4\,H\,e^{\gamma}/H_s^2)\,(1-p_e(H)) \tag{10}$$

This is shown with p_e in Fig. 6 for N = 800 (D = 3 hours) and H_s = 14m. These equations are now used where appropriate to assist the assessment of loss scenarios C2, C4, C7 and C8-C11.

2.3 Ship Bending (C2)

Frieze et al (1991) presented a comprehensive, informative and important case study of the structural reliability of the ultimate and fatigue strengths of a FPSO having L = 194.2 m, B = 32.0 m, C_b ≅ 0.81 and Δ = 51,430 te over 1, 20 and 100 year exposures in the northern N. Sea. Short term storm data was used in which H_s = 15 m and T_z = 12s. Assuming T_p ≅ 1.4 T_z = 16.8 s this lies close to the left hand boundary of Fig. 4 which corresponds to survival waves of limiting steepness given by eq(1).

TS simulations of the wave data derived long-crested wave profiles as the sum of 100 regular wave components having statistically independent phases. Using a non-linear strip theory and taking added mass and damping at a 12s wave period to correspond to wave lengths about the length of the ship where maximum response could be expected, a time domain simulation was performed 30 times, each covering 5 minutes = 25 wave passages. Figure 7 represents the simulated wave profile and ship position at the instant of maximum sagging moment. The wave height for maximum sagging is H = 15.8 m approximately. The results were converted to long term most probable sagging and hogging bending moments which compared well with extensive full scale measurements.

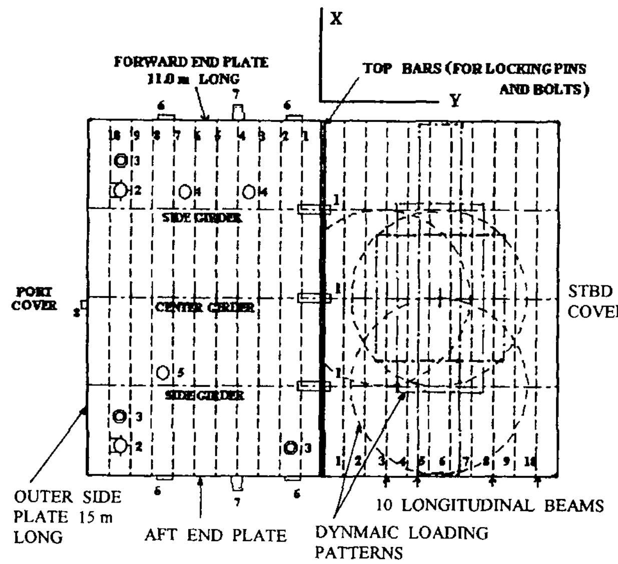
These moments have been compared (Faulkner, 1998b) with the unified IACS S11 requirements for wave-induced bending moments (Nitta et al, 1992) which are 1937 MNm in sag and 1795 MNm in hog. Over 2 storm durations of 18 minutes (90 maxima) and 3 hours (900 maxima) the ratios of the derived wave bending moments to the IACS standard values were:

Duration	*18 mins*	*3 hours*
M sag / IACS	1.3 (1.2)	1.8 (1.5)
M hog / IACS	1.1 (1.3)	1.4 (1.6)

The values in brackets are those derived using linear strip theory transfer functions. Values such as 1.8 and 1.4 must surely be of interest if not concern.

Similar, but necessarily much more approximate extended static balance (Thomas, 1968) analyses of the M.V. *DERBYSHIRE* encountering a steep elevated wave 30 m high × 260 m long were undertaken (Faulkner, 1995b). Figure 8 shows three time-steps of the vessel, the second and third steps showing approximately the worst sagging and hogging wave-induced moments of the ship. These were judged to be more than twice the IACS standard of 6,353 MNm sag and 5,985 MNm hog values and were reported (Faulkner and Williams, 1996b) where C = 10.67 m. IACS Z min = 57.75 m3 whereas for the ship Z deck = 58.34 m3 and Z keel = 84.65 m3 amidships. The pitch attitude of the ship corresponded reasonably well with observations made during tests on a 1/50 scale model (DMI, 1985).

Some surprise was expressed in discussion (Rainey, 1997), so a slightly more sophisticated approach covering three wave lengths 0.9L, 1.0L and 1.1L was undertaken. This gave a maximum wave-induced sagging moment = 1.8 × IACS standard and a value 1.4 for hogging, which fortuitously corresponds exactly with those presented above. All that is suggested is that these type of TS studies should be undertaken more rigorously as the results are potentially important for survival analyses of ships.



1. Heavy duty secureing catches (3)
2. Access/Ventilator openings (2)
3. Butterworth openings (3)
4. Openings for heating coils (2)
5. Hatch clamp slot (1)
6. Wheels (4)
7. Emergency towing brackets (2)

Fig. 9 Hatch cover detail and loading patterns

2.4 Hatch Covers (C4)

General Features

Figure 9 from Faulkner (1997d) shows the plan view of a typical pair of hatch covers and main fittings. Most covers were 14.95m long × 11.0 m wide. The ten dotted lines parallel to the X (ship) axis are fabricated longitudinal Tee beams spaced 994 mm apart with maximum depth 635 mm at mid-length and tapered to 483 mm at the fore and aft ends for drainage and flanges 280 mm × 25 mm. They are fillet welded to the web of the centre girder.

The three dotted lines parallel to the Y (transverse) axis are "girders". The centre girder is 920 mm deep with a small 75 mm × 25 mm flange on which the drive rack is mounted. The two side girders are intercostal, of depth 560 mm and flange 100 mm × 25 mm. All webs and plating are 10.5 mm thick with fillet weld throat thickness of 3.5 mm. The oil tight covers are secured to the hatch coamings by 100 cleats, approximately 0.5 m apart attached to snugs on each fore and aft side plate. Also shown are several top side and end plate features to aid recognition between port and starboard covers. Port covers have sockets for guard rails. Unfortunately the usual hatch cover identification numbers had been painted over. The only recognition features were the helicopter roundels painted on the 2 covers of no. 8 hold and on no. 3 starboard cover. No. 1 hatch covers were 0.23 m shorter than for those given above for covers 3 to 9; no. 2 covers were 2.29 m shorter (which did aid recognition).

Strength Assessments

Regulation 16 of the 1966 ICLL (Murray-Smith, 1969) required forward hatch covers (0.25L) to withstand green seas by designing for:

- uniform pressure (static) not less than 1.75 tonnes/m^2
- level of stress not to exceed minimum UTS/4.25

Along the rest of the ship the load is reduced to 1.2 tonnes/m^2. A limiting plate thickness for mild steel is b/100 or 6 mm.

For low strain collapse the UTS criterion is quite irrational, and yet still exists. For mild steel this gives a maximum design stress of 0.40 σ_o. With s ≅ 1.25 for well designed fabricated Tee sections the plastic collapse load factor for a simply supported hatch cover (no end continuity of stiffeners) is then about 1.25/0.4 = 3.1, leading to a minimum expected collapse head of p_u = 3.1 × 1.71 m = 5.3 m of sea water.

At the time of the FI two estimates were made for the inelastic collapse head p_u of the covers which were both about 4.1 m. However, the Lord Donaldson work (Faulkner, 1995b) found that, even allowing for the tripping brackets, the three deep transverse "girders" were essentially ineffective with M_t ≅ 0.2 M_p and low bending strength because of their narrow flanges (face plates). Moreover, because for the main longitudinal stiffening $A_s > bt$ (= 1.2 bt on average), the bending induced compression in the thin welded plating of the covers is substantial and reduces its effectiveness substantially as bending increases to $b_e = 0.41$ b at collapse. Making a more complete allowance for these adverse features and for welding stresses (Faulkner, 1975) the lowest plastic collapse load is:

$$p_u = 8 \ Mp/L^2b \qquad (11)$$

which is = 3.7 m with plastic hinge collapse of the lonitudinals at their mid-lengths (centre girder) referred to as Y mode failure. It is understood that this was later confirmed more rigorously from inelastic FE calculations to be *3.8 m* sea water head. The analyses also showed that there were several modes of plastic collapse quite close to the 3.7 m arising from the taper in the longitudinals.

Although this is only 0.75 of the strength of a well designed cover (5.1 m as above) this should not be taken as an indication of bad design 30 years ago. Regrettably, although much was then known and practised in other disciplines about compression strength of thin plating and inelastic collapse of structures, this was not the case in marine design. Moreover, although the stiffeners in the covers in *DERBYSHIRE* comfortably met the maximum stress requirements of the 1966 ICLL, they were, like many others of their time no doubt, quite inefficient load bearers. This is a good example of the weakness of working stress design methods which make no reference to any consideration of real collapse. Maximum stress is often a very poor indicator of collapse capability, and yet its influence is still dominant. It is of course vital in fatigue considerations.

Dynamic Collapse

Six or seven of the 18 wrecked covers showed unexpected X mode bending or tearing between longitudinals (Williams and Torchio, 1998a). This may have been caused by plunging green sea wave actions over part of the covers. A necessarily crude elasto-plastic analysis was therefore undertaken during the final survey assuming three different uniform load imprints of 30 m^2 (18%) spread along the central spans of longitudinals 2, 3 and 6, as illustrated in the port cover of Fig. 9. This gave an average $p_u = 5.0$ m from:

Imprint size (m × m)	15×2	7.5×4	5×6
Pressure head (m)	4.4	4.9	5.6

But the assumptions made were so approximate that a more rigorous inelastic FE analysis was recommended with dynamic load signatures and several imprints, such as the circles shown in Fig. 9. It is understood this was initiated but the results were inconclusive.

An unfortunate feature of A grade mild steel is that if the initial pressure pulse is steep (milliseconds) then brittle fractures are possible. This may arise from the *gifle* peak associated with water impact, and there is evidence of such cracking and tearing in the wrecked hatch covers. However, the implosion-explosion actions during sinking (see later) promote such fractures and makes interpretation less certain.

Wave Profile Loads

The first TS step in Fig. 8 shows the fore end of the ship about to be swamped by a simulated steep elevated wave. Figure 10 shows the quasi-static wave profile loading on the forward hatch covers. No allowance is made for the usual bows down attitude induced by the long troughs which leads heavily laden large low freeboard ships to plunge into the oncoming steep crests rather than rising to the sea. Nor is the dynamics of sea waves considered (see Appendix). With these non-conservative assumptions a simple model for the peak and average pressure heads are:

$$h = \alpha H - (F + C) \qquad (12)$$

$$h_b = h[1 - mL/4h] \ , \ L \leq 2 \ h/m \qquad (13)$$

where $\alpha = 0.5$, $m = 0$ for linear waves and $\alpha = 0.65$, $m = 0.5$ was assumed for the steep elevated waves of typhoon ORCHID, and is the mean of the crest face and back slopes. F = 6.9 m and average C = 2 m. Surprisingly good agreement was found for waves up to 25 m high between eq(12) and hatch cover the mean peak pressure measurements on a 1/50 scale model of the *DERBYSHIRE* during seakeeping tests (DMI, 1985 and Faulkner, Corlett and Romeling, 1996).

We are now in a position to evaluate peak and average pressure heads acting on no. 1 hatch cover which has L = 14.72 m. These are shown for a range of wave heights together with the probabilities of exceedence for D = 1 hour, 3, 6 and 12 hours in Table 3.

Beam Sea Risks

Loss scenarios C8 to C13 in table 2 all lead to loss of propulsion or steering and the ship falling beam on to the sea. The laden *DERBYSHIRE* was very stable with GM ≅ 8 m and a natural roll period of about 11 s. With $H_s = 14$ m eq(2) gives a steep fronted wave period of T = 12.0 s. Although the capsize risks are small, these figures do suggest that vigorous rolling might well occur in beam seas, especially with the possibility of tandem waves.

The more serious risks then for low freeboard stable cargo carriers are likely to be the effects of steep, elevated breaking or near-breaking waves on the side structure, deck and hatches (see Appendix A). For *DERBYSHIRE*, the sides are

Table 3 Hatch cover pressures and probabilities

H	*(m)*	*20*	*22*	*24*	*26*	*28*	*30*
Linear waves:							
$h = h_b$	(m)	1.1	2.1	3.1	*4.1*	5.1	6.1
Non-linear waves:							
h	(m)	4.1	5.4	6.7	8.0	9.3	10.6
h_b	(m)	2.3	3.6	*4.9*	6.2	7.5	8.8
Probabilities p_e							
D =	1 hr	0.99	0.85	0.53	0.23	0.09	0.03
	3 hrs	1.00	1.00	0.89	0.55	0.24	0.08
	6 hrs	1.00	1.00	0.99	0.80	0.42	0.15
	12 hrs	1.00	1.00	1.00	0.96	0.66	0.28

Notes:
1. mean pressures above p_u (4 m are underlined
2. for non-linear wave H = 22.7 m, $h_b = 4$ m
3. in practice the waves will be a mix of nearly linear and clearly non-linear form. On advice for RTS storms the probabilities should be biased toward the non-linear values. A bias of 75:25 is suggested.
4. for H = 35 m p_e = 1% over 12 hours and h_b = 8.6 m for linear waves and 12.0 m for non-linear waves.

of double skin and the deck strength varies from about 40 m to about 80 m sea water head. However, as we have seen, and in complete contrast, a 4 m pressure head would burst the hatch covers. It is therefore recommended that apart from the forward hatch covers, those along the length of the ship should be designed to a substantially higher uniform sea water pressure head of say *3.0 m*, not the 1.2 m as at present. This suggestion is supported by many mariners.

Hatch Coaming Risks

Green sea impact on flat vertical structure is a subject badly in need of more research (Meyerhoff et al, 1994). Damage to bridge fronts, bulwarks, coamings, seals, etc. continues to occur. Faulkner and Buckley (1997) reviewed earlier Japanese research (Kawakami, 1969; Suhara et al, 1973), more recent model tests (Graham, 1988; Zhu, 1995) and theoretical research (Korobkin, A, 1994; Buchner, B., 1995) and for the present favour for design pressure (p_d) the results of reputable experiments represented by:

$$P_d = C_p \, 0.5 \, \rho \, v^2 \qquad (14)$$

where v is the relative velocity. For the *gifle* peak pressures which typically have a 2 to 10 millisecond rise time, the results from essentially normal flat impacts provide C_p values from about 10 to nearly 400, with 65 perhaps being a reasonable average. This phase of the impact is certainly relevant for brittle materials. However, it is the longer follow on *bourage* or momentum transfer phase which is more relevant for structural damage in ductile materials and mean C_p values are lower, varying from about 1 to 10. See Fig. 14b. Present provisional recommendations are:

- $C_p = 9$ for normal plating design where plate widths b are around 1 m, or a 5% upper bound value of $C_p = 15$ could be considered for plastic hinge collapse design with a low safety factor
- $C_p = 3$ for stiffened panel design loads
- Higher values of both are expected close to bulwarks and other re-entrant corners.

Recent Norwegian research (Kvalsvold et al, 1997) provides a somewhat different more analytical approach which looks promising for predicting peak stresses in stiffeners.

The C_p approach was used for predicting the pressures on coamings where v = 1.2 c + ship speed. The 1.2 is to allow for flow augment from wind and channelling. Average derived values for the waves used in the DMI tests on the stationary *DERBYSHIRE* model were 226 kN/m^2 which agreed reasonably well with the 203 kN/m^2 measured, but only when $C_p = 1$.

The maximum pressures estimated for the *DERBYSHIRE* were 327 kN/m^2 = 32.5 m head. This is very close to the coaming plate plastic hinge collapse between stiffeners as estimated by LR. The stiffeners themselves are also vulnerable, so there is a real risk of substantial deformation of the coamings in such storms, especially from breaking waves (see Appendix A).

Casualty Evidence

Some evidence, mainly from LR casualty reports, of hatch cover weaknesses was presented at the FI and later by Byrne (1995). It can be seen from Table 1 of the Faulkner, Corlett and Romeling reference (1996) that in the period 1969-87:

- 8 OBO and bulk carriers were almost certainly lost directly due to heavy weather breaching the hatch covers and/or coamings, or possibly to the loss of the covers
- 12 other vessels were lost by mostly forward flooding in heavy weather, caused potentially by, or by contribution of, the breach or loss of hatch covers
- 6 of these 20 ships were lost in the W. Pacific in the winter 1980/81
- the average age of these 20 bulk carriers was about 14 years, their averaged deadweight was 35,700 t, and average lives lost 23
- these 20 ships represent 16% of the 128 bulk carriers lost over the period.

It must be stressed that the evidence is far from complete. Two cases of coaming failure are cited in the Table. It is of interest to note that from the wreck of the *KOWLOON BRIDGE*, sister ship of the *DERBYSHIRE*, it seems that coaming failure also occurred, which could perhaps explain her noticeable trim down at the bow on completion of her Atlantic crossing.

Over the last eight years 108 bulk carriers and combination carriers of average age 19.2 years have been lost (LR, 1998). Nearly 30% of 87,500 DWT average were in iron ore and sank in heavy weather and 11% of 94,375 DWT average sank with no details, as with the DERBYSHIRE. These losses continue at an intolerable rate.

It is quite possible that some of the many unexplained heavy weather losses may have been caused by hatch cover or coaming failures because fore end plunging due to flooding of large holds can be rapid (Brown, 1997). Jones and Roe (1991) claim that 70% of bulkers are lost in very heavy weather.

To these losses would have to be added the well documented loss of the *CHRISTINAKI* in 1994, and perhaps the *DERBYSHIRE* and *LEROS STRENGTH* when their formal investigations are complete (Aftenposten, 1997).

Improved Design of Covers

The simple beam equation (11) is unusual for a grillage and arises because the three cross girders are ineffective. It is then much more efficient to place the load bearing stiffeners across the shorter span. By eliminating all three girders and replacing the 10 longitudinals by 14 similar cross-section transverse beams it can be shown that this simpler structure is slightly lighter, certainly cheaper to construct, and yet is 85% stronger. The collapse head is then p_u = 7.0 m which is 33% better than the minimum (5.3 m) which could reasonably be expected from the ICLL requirements!

However much of an improvement this may seem, it still leaves an inefficient stiffener-plate cross-section. Taking p_u = 12 m as the minimum collapse head recommended for no. 1 hatch cover, a much more efficient design has been generated which is about 12% heavier than the original but is significantly cheaper to construct because it is a beams only design. The weight estimate applies only to the top plate and its stiffeners. The weight of the four end plates and associated stiffening could remain unchanged.

This design has 15 mm plating and nine beams, eight of 680 mm total depth and the centre one incorporating the drive rack would be deeper to provide the drainage taper. Because of the uncertainty as to where a plunging breaker might act, a simple beams only design would appear to be attractive.

New Strength Criterion

Table 3 data and casualty evidence provide a compelling case to make hatch covers much stronger, and it is gratifying to note that some class societies have offered increased requirements. Following a more complete review (Faulkner, Corlett and Romeling, 1996) it was recommended that with the existing stress-based criterion, hatch covers for nos. 1, 2 and 3 holds should be designed for sea water heads of 4.5 m, 4 m and 3.5 m respectively.

It is demonstrably more rational to base the pressure design criterion on an ultimate collapse approach which should be demonstrated for approval. On this basis it is now provisionally suggested that with a load factor against collapse of 1.5 the design heads of sea water for hatch covers 1 and 2 are set at *9m* and *7.5m*, and at *6m* for no. 3 and all other covers. These requirements should be mandatory and not optional.

These values imply less than 1% probability of collapse during a 12 hour exposure to the dangerous semi-circle of a severe typhoon like ORCHID, but includes some allowance for in-service corrosion.

2.5 Fore End Flooding (C7)

The *SIR ALEXANDER GLEN*, a sister ship, experienced severe weather damage to fore deck fittings and moderate flooding of fore peak spaces. *DERBYSHIRE* herself had lost one ventilator head. The RINA Colloquium discussion brought to light several other similar cases for other ships. Statistics also show that by the middle 80s the annual incidence of heavy weather damage forward to bulk carriers had increased tenfold as compared with the incidence immediately following the 1966 ICLL when freeboard was reduced.

Because of all this a middle level risk numeral $R_n = 8$ was allocated to C7 loss scenario for the *DERBYSHIRE* as an initiating event. The final survey found that 3 or 4 of the 0.5 m diameter mushroom vents (MVs) to some of the fore peak ballast tanks (2,869 m^3 total) were damaged and open to green seas. The 0.9 m × 1.2 m hatch cover giving access to the Bosun's store (686 m^3) is missing. The official report refers to the possibility of an engineers' store having a damaged ventilator. It is quite trivial (170 m^3) but is included.

Philosophy

Figure 11 shows a quasi-static conservative idealisation of a sinusoidal wave passing over an orifice on the fore deck. This is similar to the Fig. 10 approach adopted for hatch cover pressures. Most important, it uses a similar pressure head and probability modelling so that the results may be compared even though one may argue over the numbers. Non-linear waves are also considered to provide a weighted probability solution (Faulkner, 1997e).

The second important point to note is the fundamental difference between the two events. The first is the bursting of the hatch covers by the first occurrence of a single sufficiently high almost certainly non-linear wave, and the second event is the slow ingress of water from hundreds of linear and non—linear waves passing along the ship at about 267 per hour (1 hour/T_p). In reliability theory the first is referred to as a *first passage* or *out-crossing* from a safe region single event, and is analogous to ultimate back breaking of a ship. The second phenomenon is referred to as *up-crossings* of a *threshold level* event, more analogous to fatigue damage. Truncation at critical wave height threshold levels is then required, as will be seen. Figure 12 is an attempt to illustrate these differences.

Moving Wave-Orifice Theory

Orifice theory is surprisingly complex. For small sharp edged orifices (and there's the catch) under gravity head flow

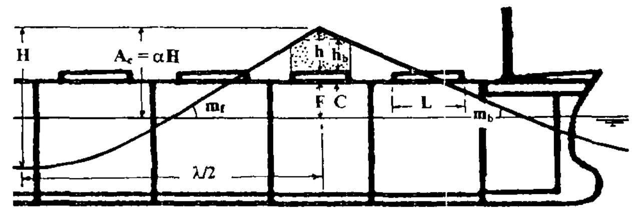


Fig. 10 Hatch cover design head for extreme steep elevated waves

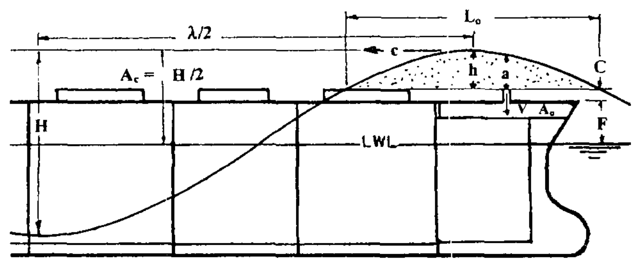


Fig. 11 Linear wave crest passing over an orifice

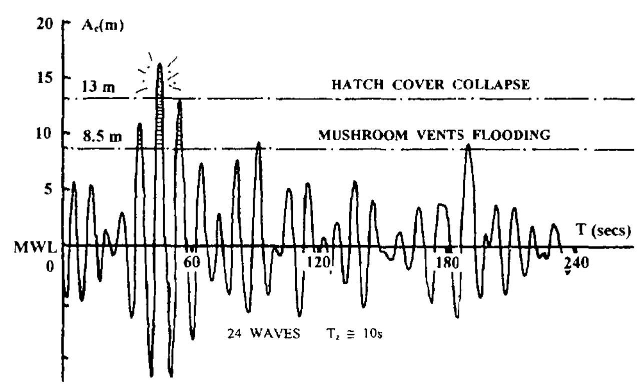


Fig. 12 Truncation of waves for first passage events and up-crossing threshold events

c_d is usually in the range 0.6 to 0.65 (Massey, 1970). No experimental data could be found for parallel flow through vertical tubes (MVs) or rectangular (hatch) coamings. Although it was recognised that at low orifice Reynolds numbers c_d would reduce (for a < $5\sqrt{A_o}$? [Marks, 1979]) this was ignored for simplicity and to be conservative and a value $c_d = 0.6$ was used. Under gravity flow the mean downward velocity through the orifice is:

$$v = c_d\sqrt{2ga} \tag{15}$$

where a = ζ – (F+C) is the time varying water head from the crest profile over the period t_1 when water ingress starts to t_2 when it finishes. The total volume passing through the orifice during the passage of a single wave crest of peak height h above the orifice is then:

$$V_h = \int vA_o\,dt = c_dA_o\sqrt{2g}\int_{t_1}^{t_2}\sqrt{a}\,dt \tag{16}$$

Linear Waves

For a linear sinusoidal wave of amplitude:

$$\varsigma = (H/2)\sin(2\pi/Tp) \qquad (17)$$

it can be shown from symmetry that eq(16) becomes:

$$V_h = 2c_d A_o \sqrt{2g} \int_{t_1}^{T_p/4} \sqrt{\varsigma - (F+C)}\, dt \qquad (18)$$

where:

$$t_1 = \left[\sin^{-1}\left(\frac{F+C}{H/2}\right)\right]\frac{T_p}{2\pi} \qquad (19)$$

C = 1.3 m was taken as the mean height above the deck of the MV and hatch orifices considered so that F+C = 6.9 + 1.3 = 8.2. The integration of eq(18) was then performed numerically over a truncated wave height range from H_1 to H_2 where:

- H_1 provides the minimum wave amplitude for steady water ingress to take place so $H_1 = 2\,(F+C) + \Delta h =$ *18 m*
- H_2 relates to the peak head of water $h \cong 4$ m above which hatch cover no. 1 would certainly burst; from Table 3 for linear waves an upper threshold of $H_2 =$ *26 m* is taken.

For these extreme waves f(H) is zero at H = 21 and below so the limits of integration were taken from H = 22 m to 26 m and the results are:

H (m)	22	23	24	25	26
Integral ($\sqrt{m}$ s)	2.04	2.37	2.67	2.97	3.29
$N_H = f(H)\,N$	7	36	93	143	153

During any required period D the most probable number of waves passing along the ship are $N = D/T_p$. For example, for D = 3 hours N = 800 and if this is multiplied by the pdf f(H) from eq(10) this provides an estimate of the waves N_H in each of the $\delta H = 1$ m wave bands as illustrated in the Table above. The total sum of these waves is 432, a little more than half, and allowing for round off errors this is reasonably consistent with the most probable wave height for D = 3 hours from eq(7) being 25.6 m with a 63.2% probability of being exceeded. It follows that we can combine the integration with f(H) to give the total volume of water ingress from N waves as:

$$V_{iD} = 2c_d A_o N \sqrt{2g} \sum_{H_1}^{H_2} \int_{t_1}^{T_p/4} \sqrt{a}\, dt.f(H)\delta H \qquad (20)$$

Then the flow rate $V_i = V_{iD}/D$ where D is related to N.

Abnormal Waves

If the crest of pyramidal and other steep, elevated waves are idealised as a triangle, as in Fig. 10, then local crest amplitude a is a linear function of time up to the passage time t_o for the crest to pass over the orifice. The integration of eq(16) then reduces to a simple closed form:

$$\int_{t_1}^{t_2} \sqrt{a}\,dt = \frac{2}{3}\sqrt{h}\, t_o \qquad (21)$$

where $t_o = L_o/c$ and by geometry $L_o = h[m_f^{-1} + m_b^{-1}]$, c is wave celerity $gT_p/2($ and h is given by eq(12) where $\alpha = 0.65$ and (F+C) = 8.2 m. Based on Dahle and Myrhaug (1995) an average value of m = 0.25 is taken for m_f and m_b so $L_o = 8$ h. Applying all this to eq(16) the volume of water ingress from one crest is:

$$V_h = 47.4 \frac{c_d A_o}{T_p \sqrt{g}} h^{3/2} \qquad (22)$$

Then, summing this ingress for the number of crests in each $\delta H = 1$ m wave height band the total volume entering the ship in time $D = NT_p$ for each orifice area A_o is:

$$V_{iD} = 47.4 \frac{C_d A_o N}{T_p \sqrt{g}} \sum_{H_1}^{H_2} h^{3.2} f(H)\delta H \qquad (23)$$

This can be compared with eq(20) for linear waves.

Mixed Wave Calculations

For D = 3 hours (N = 800) equations (20) and (23) lead to water ingress rates of $V_i = V_{iD}/D$ of:

$$V_i = 1802\ A_o\ m^3/hr \text{ for Linear waves}$$
$$= 164\ A_o\ m^3/hr \text{ for Abnormal waves}$$

The much higher V_i values for normal linear waves than for abnormal waves is due to two factors. For example, for H = 25 m:

- the longer flatter crest gives an area over the orifices 3.0 times greater
- the area under the pdf(H) from H = 21 m to H = 26 m is nearly 17 times greater, as can be appreciated from Fig. 6.

The decision for a 75:25 probability mix of abnormal and normal waves is because for non-narrow-banded spectra, such as occur in RTS storms, the number of elevated peaks (maxima) is much larger than for narrow-band spectra (Ochi, 1990). One other justification is mentioned later. With this 75:25 mix:

$$V_i = 574\ A_o\ m^3/hr \qquad (24)$$

It is important to understand that since f(H) varies with the number of waves considered then V_i will also vary with D the time considered. Table 4 illustrates the filling rates and times (T_f) for each of the three fore peak spaces considered and the resulting loss of freeboard (δF) at no. 1 hatch cover given by:

$$\delta F = m[Tpc^{-1} + (L_t/L)L_m\ Mct^{-1}] \qquad (25)$$

Table 4 Flooding of fore peak spaces (D = 3 hrs)

Spaces, etc.	*Ballast Tanks*	*Bosun's Store*	*Engineers' Store*
Volume (m^3)	2869	686	170
Orifice type	4 MVs	hatch	1 MV
A_o orifice (m^2)	0.8	1.08	0.2
V_i (m^3/hr)	459	620	115
T_f (hours)	6.3	1.1	1.5
% full in 3 hours	48	100	100
δF when full (cm)	90.6	21.5	5.3
δF in 3 hours (cm)	43.5	21.5	5.3

where m is the flooded mass in tonnes and for T = 18 m level draught Tpc = 116 te and Mct = 2330 te m.

It follows that in 3 hours the loss of freeboard is about 70 cm if all three spaces are open to the sea, and 65 cm if the engineers' store is ignored. In terms of the already very high hatch cover collapse risks (Table 3) such effects are quite secondary, and are certainly not essential to cause no. 1 hatch cover to collapse.

Truncation Effects

The upper truncations of H_2 = 26 m and 23 m adopted in these analyses are somewhat artificial because they ignore the possibility of higher waves which would certainly breach no. 1 hatch cover. Nevertheless, their probabilities of occurrence (= p_e) are quite real and unacceptable as can be seen from the lower part of Table 3. The situation is even worse because the quasi-static approach adopted completely ignores the adverse effects on hatch cover loads of ship motion and the dynamics of plunging waves and other green sea effects.

Flooding the Forward Fuel Tank

Section 4 of the official report makes much of the almost total lack of implosion effects in the bow section. In 4.58 it therefore presumes that the bow became almost full at the time the ship sank. This is followed by much unsupported speculation which attempts to explain how the necessary flooding could have happened. In this assessor's judgement, the most unconvincing of these speculations relates to the filling of the deep fuel oil tank in the bow, which is discussed more realistically in section 2.7.

The official report gave a fore perpendicular (FP) trim of 2.5 m from bow flooding, but this has been criticised, no doubt because it is badly defined. It is now checked. Taking the Assessors' judgement that about 2000 tonnes of fuel oil remained in the forward tank this would lead to a maximum water entry mass of 3240 tonnes. Using eq(25) this leads to a reduction ΔT at the FP of *1.15* m. Adding this to the summation from complete flooding of the 3 fore peak spaces (mentioned in Table 4) gives a total reduction of bow freeboard of 2.5 m which agrees with the Assessors' value. This draught reduction would be 2.1 m at no. 1 hold.

Ship Motion Effects

The effects of water ingress at the bow on ship motions was briefly investigated. The total volume of water ingress into the three fore peak spaces in three hours is estimated from Table 4 to be about 1560 tonnes. This increases I_θ by about 3.4% which would reduce the maximum pitch motions by less than 2%, equivalent to a reduction in pitch induced-bow trim of about 10 cm for a ± 2.5° normal pitch. This would change to about 26 cm reduction if all three spaces were completely filled and 42 cm if the deep fuel oil tank was also flooded.

Because of their high inertias and natural pitch periods, these large ships do not rise to the waves, as appropriately experienced masters have confirmed. They tend to bury into them.

2.6 Cargo Shift (C8)

Table 2 shows a very low risk numeral of 2 for cargo shift because:

- there was negligible supporting evidence
- the ship was very stable with very low likelihood of capsize
- the FI considered a 6° list from progressive movement of moist ore to be doubtful and not likely to be the prime cause of the loss
- any significant cargo shift would have taken time and would almost certainly have been reported in the circumstances.

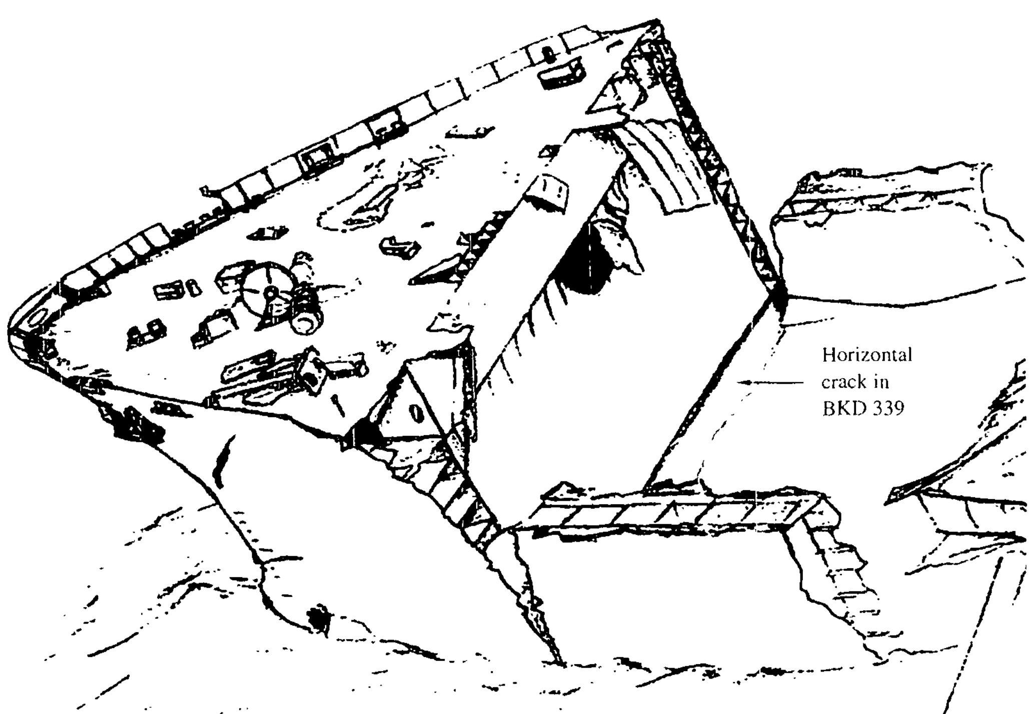


Fig. 13 Sketch of the bow

To support the first point, Table 1 shows about 1% loss in 35 years. In support of the last point, four ships reported cargo shift in the years 1978–87 and sent distress messages. Three were lost, one was successfully towed into harbour, and all crew on all ships were safely evacuated (Faulkner and Williams, 1996a).

During the Lord Donaldson work it was postulated that through damaged coamings and or seals it was possible that the top layer of ore in the hold could become saturated and mobile. Assuming an ore density of 5,100 kg/m^3 and a ± 20° harmonic roll at 11 and 12 s periods side impact "punching through" calculations based on eq(14) and $C_p = 3$ gave rise to a side pressure of 122 kN/m^2 which was no danger to the double skin *DERBYSHIRE*. Older, single hull vessels would be vulnerable to this type of loading which should be investigated.

Later, progressive cargo shift calculations based on earlier work by Skinner (1987) showed that for untrimmed cargoes in partly loaded hulls, a list of 8° or a little more might develop. Again, in discussion with mariners, it was felt that such lists would have been reported. A review of the UK research on the topic (summarised for the IMO by Kruzewski, 1992) was undertaken for the DoT (Faulkner, 1997c).

It would appear from these calculations that the current trend toward homogeneous loading of less height cargo in all holds could lead to a greater chance of cargo shift. This would be aided also by creating even stiffer ships as a result of the lower cargo heights, and hence brisker rolling. Using high WBTs to lower GM reduces available deadweight which would be unpopular.

2.7 Sinking Actions

Following the most likely loss scenario C4 of breaching of no. 1 hold and plunging by the bow, there are four actions which require some examination. Chronologically they are taken in order here.

Cargo Shift Actions in No. 1 Hold

Figure 13 shows a sketch by Robin Williams of the bow, but modified for the 20°–30° tilt to port. There is a very long horizontal split in the single skin collision bulkhead about 8m above the hold floor level which follows a butt weld right across the ship. Unfortunately, it was not possible to examine the fracture surfaces in any detail. But it is a straight line fracture and is likely to be brittle in parts at least. Bulkhead 339 is "substantially bowed inward" toward the deep fuel tank in places and above this fracture.

A likely explanation for this, which could also go a long way toward explaining why the forward deep fuel oil tank has not imploded, is associated with a ship motion-induced dynamic slide forward of saturated ore concentrate following the collapse of no. 1 hatch cover. The possible collapse of the forward hatch coaming, as described in C14? and in Appendix A, could also lead to ore mobility. The resulting dynamic impact could well cause the straight line fracture, especially if, as is likely, the stress front has a sharp rise.

Figure 14(a) shows diagrammatically an idealisation of a layer of ore sliding in slurry form down the untrimmed forward slope of partially saturated ore during the first few minutes of flooding of hold no. 1. Trimming of ore was not widely practised in 1980. Calculation assumptions are:

- initial forward acceleration at the top of the slope $f = 2.5$ m/s^2 taken from published data on storm induced pitch and surge motions

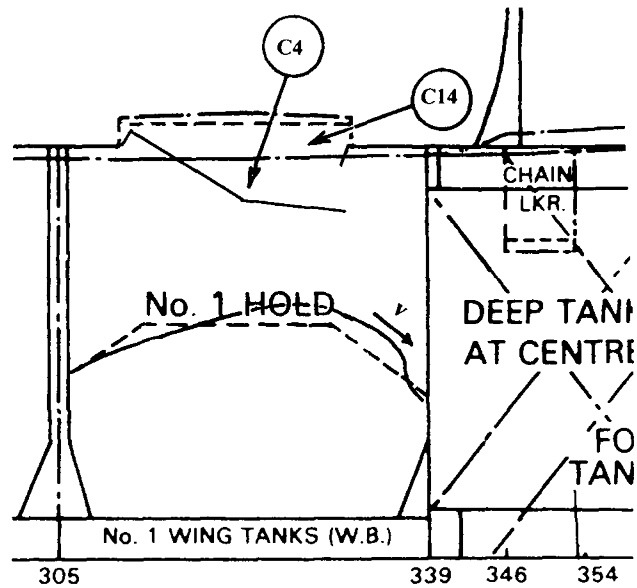


Fig. 14a Sketch of No. 1 hold and ore slide

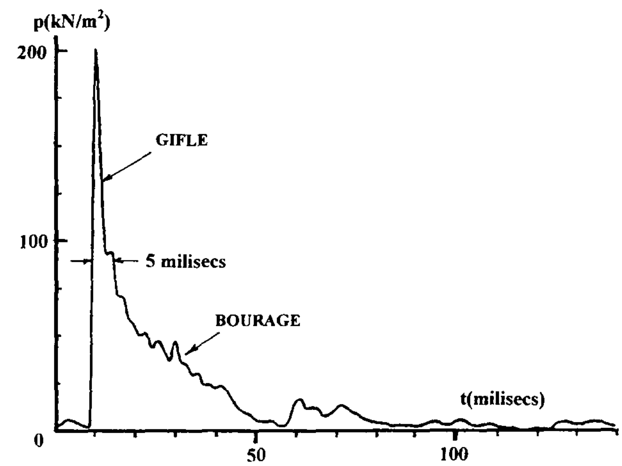


Fig. 14b Pressure vs. time loading

- this acceleration of about 0.25g is maintained by the ore slurry on the downslope which is taken as 33° and $s \cong 5$ m for the slope length
- the initial velocity at the top of the slope is zero, the final impact velocity is v
- bulk ore mass density $\rho = 5{,}100$ kg/m^3 and eq(14) is assumed to apply.

From Newton $v = \sqrt{2fs} = 5$ m/s, and from eq(14) assuming $C_p = 3$ the mean structural impact pressure is $p_i = 191$ kN/m^2 equivalent to a 19 m head of sea water. Local peak pressures would be much higher.

The two modes of static failure considered for plating were three-hinge plastic collapse (p_u) and edge shear yield (p_τ). Assuming $\tau_o = \sigma_o/\sqrt{3}$ these pressures for mild steel having $\sigma_o = 235$ N/mm^2 are respectively:

$$p_u = 4.5\sigma_o(t/b)^2 = 200 \text{ kN/m}^2$$

$$p_\tau = 2\tau_0(t/b) = 3730 \text{ kN/m}^2$$

whilst there is clearly no danger of shear yielding, the idealised local impact load could be on the verge of deforming the plate. No such deformation was seen, but in view of the uncertainties no conclusion can be drawn.

However, and potentially far more damaging, is the initial *gifle* pressure spike (see Fig. 14b). Even taking $C_p = 15$, this gives $p_i = 956$ kN/m^2 and this could be much higher. Such impacts would, beyond any reasonable doubt, induce a brittle fracture in A grade mild steel, particularly along a weld run. The evidence shows this would cause rapid flooding of the FO tank. This could also explain the plating "blow out" as seen toward the top of bulkhead 339 in Fig. 13.

In summary, whilst this hypothesis is uncertain, it does have two circumstancial evidences plus analysis to support it. Also, no other plausible explanation has been advanced.

Bow Flooding During Sinking

Once no. 1 hold starts flooding and the fore deck becomes permanently immersed, then the rate of water ingress through all orifices becomes:

$$V_i = c_d\, A_o \sqrt{2ga} \tag{26}$$

where c_d may be taken as 0.6 on average and a is the time varying local head of water which naturally increases as the bow trim continuously increases. Beyond $a_o \cong 25$ m implosion actions would probably have started in any bow space still at atmospheric pressure by then. As a first, probably conservative approximation, assume that (a) increases linearly with time (t) until $a = a_o$ when the implosion depth is reached in time T_o. Then, a time integration of eq(26) leads to V_T the volume entered in any compartment over time T as:

$$V_T = (2/3)c_d\, A_o\sqrt{2ga_o/T_o}\; T^{3/2} \tag{27}$$

Or, in metric units, when $a_o = 25$ m, the time to fill a compartment of volume V is:

$$T\left(\left(V\sqrt{T_o}\right)/8.86\, A_o\right)^{2/3} \tag{28}$$

This then leads to Table 5 which shows the flooding time in minutes to completely fill the 3 fore peak spaces of Table 4 for a credible range of times T_o for the ship's deck to reach its first bow implosion depth of 25 m.

The Table verifies that, even if the two store spaces were not previously filled, there would be no danger of them imploding during sinking because $T < T_o$.

The fore peak ballast tanks on the other hand would require more than the minimum credible $T_o = 4$ minutes to be sure they would not implode. Assuming they were already 20% full (see earlier) they would require $T_o = 5.4$ mins. to become full. If $T_o = 4$ mins. was a possible time from irreversible plunging (requiring no. 2 hold to become full) to the fore deck being 25 m or more under water, these tanks would be about 74% full. Even then, there really would be *no risk* of damaging implosion occurring because:

- the maximum possible implosion-explosion potential energy from the remaining 750 m^3 of air is less than 300 kJ or about 100 kg of TNT (see later); but, more importantly,
- this energy could not in any case be mobilised because there would in fact be insufficient pressure difference between the pressure inside and outside of these tanks.

The reason for this last unequivocal statement follows from the fact that once continuous filling starts as deck submergence increases the air within the tanks either finds a way to escape, probably mainly through the least pressurised of the four MVs, or it remains in the compartment with increasing pressure from compression which approaches that of the outside sea pressure entering the compartment through the orifices.

Therefore, it is only necessary to explain why the fuel oil tank did not implode. The Assessors suggest (in 4.74 of their main report page 1:109), the tank was being ventilated prior to arrival in port and the manhole covers had been removed to effect this, thus allowing down flooding from the stores space above. The argument just given above would then be essentially relevant and the fuel tank would not implode. However, removing manhole covers into a confined space seems dangerous and very unlikely, especially as the 3 floating ball air pipes are there to do just that. The previous section offers what seems to be a more plausible explanation which *is* backed up by evidence.

Ship Bending During Plunging

The recent forensic investigations into the loss of the *TITANIC* (Garzke et al, 1996; Hacket and Bedford, 1996) have aroused great interest. The finding that the *TITANIC* started to break her back when the stern was out of the water and completed the process during sinking was approximately examined for the *DERBYSHIRE* during the final survey. The most severe bending moment would appear to be more than twice that to cause deck yield (about 15 GNm) probably toward the end of no. 6 hold. This has not been confirmed, but it does suggest that excessive yielding and crack extensions in the upper deck and side structure could well have initiated. But, the sequence of sinking at that stage would have been very quick and final separation of this (and other) sections is then much more likely to have been caused by the numerous implosion-explosion actions around the cross-section.

It is interesting here to reflect on Fig. 15 which shows the remains of the inboard section of the starboard WBT which runs through holds 8 and 9. It is substantially intact but folded and twisted at its centre. Because of the absence of any significant implosion-explosion actions (see next section), this assessor first wondered if the fore end fracture (at about frame 124 fore end of no. 8 hold) was initiated by an overload tearing of the deck as the stern lifts further out of the water. As the vessel then plunged the water would enter the WBT through these splits, thus reducing any implosion effects. This must remain as a speculative possibility. the UK/EC Assessors' report examines this target C230 in detail and decides (from video stills 265–267) that the fracture at about frame 124 is "exploded and ragged".

Table 5 Filling times (minutes) for the fore peak spaces for a range of times to implode

T_o *(mins)*	*4*	*6*	*8*	*10*
Ballast Tanks	5.7	6.5	7.1	7.7
0.8 × Ballast Tanks	4.9	5.6	6.2	6.6
Bosun's Store	1.8	2.1	2.3	2.4
Engineers' Store	2.2	2.5	2.7	3.0

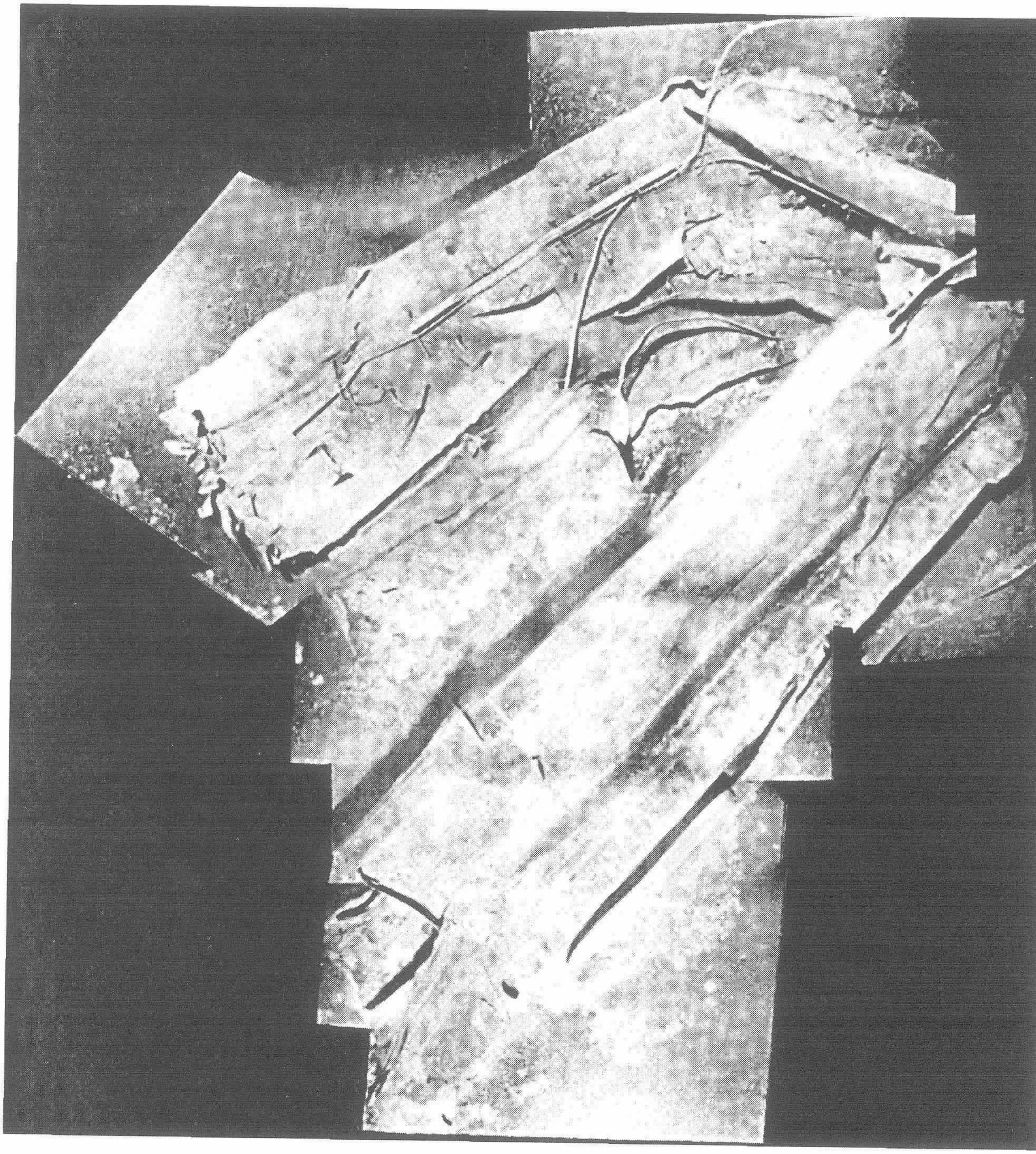


Fig. 15 The remains of the inboard section of the wing ballast tanks for holds 8 to 9 starboard (target C230)

Implosion-Explosion Actions

This phenomenon has recently been discussed for the *TITANIC, LUSITANIA* (Garzke et al, 1996) and other ships, but is not widely expected and therefore understood. The mechanics have been explained (Faulkner, 1997c—now in Williams and Torchio, 1998a) and so only the essentials are summarised.

Description Like all double skin OBO ships *DERBYSHIRE* had many empty void spaces (see Fig. 16). Her hatch covers would burst at the very early stage of sinking and the void spaces would be squeezed until at pressure (p_u) their weakest surface would collapse inward compressing the air to some higher pressure (p_e) like a spring. This internal air then explodes outward causing the devastation seen in the wreckage. This outward *shock wave* type pressure pulse has a steep rise like the *gifle* phase of water impact in Fig. 14b. This explains why many of the fractures are brittle because grade A mild steel quickly loses what little notch toughness it has in the presence of such dynamic loads.

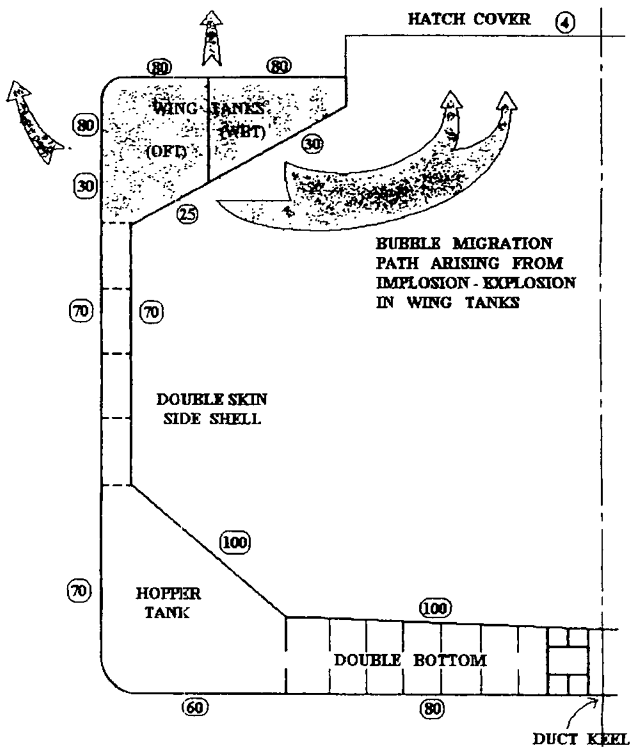


Fig. 16 Cargo space voids and estimated implosion pressure heads p_u (m) of seawater

The second *bubble migration* phase immediately follows in which the expanding air escapes as a bubble or bubbles which in bursting out will oscillate in volume and then continue the damaging process. Any structure in its way, or to which it is attracted, can receive successive expanding bubble pressure "thumps" which have been known to permanently deform the shell plating of submarines, for example. This phase therefore continues to tear open the structure in a more ductile manner.

Mechanics Void spaces are complex but, as a first approximation, the compression actions of the weakest boundary is treated as a constant load (p_u) piston compressing air in a cylinder till it reaches a highest maximum pressure (p_e) allowing for spring overshoot.

By making various assumptions it is shown that the maximum potential energy (PE) that could be released is:

$$PE \cong k\ V_o\ (p_u + p_o) \tag{29}$$

where p_o is the atmospheric pressure, V_o is the initial void volume and $k < 1$ is a function of γ in pV^γ = constant which controls the implosion characteristics.

Potential Energy Table 1 in Faulkner (1997c) shows the details for all cargo space holds from which the total available potential energy from all of these cargo space voids assuming a value of $k = 0.9$ is:

$$PE = 47.9 \text{ GJ} \cong 16.0 \text{ tons TNT}$$

This assumes 1 giga joule is equivalent to 340 kg of TNT, or about 1000 sticks of dynamite. Not all of this potential was released as the wreckage shows that most transverse hold bulkheads and double bottoms are mainly un-imploded.

This is thought to be due to their high implosion pressures approaching 100 m head and to their unit type construction. For example, the PE from the connected WBTs, sides and hopper tanks alone are 49% of the total, and their implosion pressures average around 50 m head. Such energy would break the connecting fillet welds of the double skin transverse bulkheads exposing their open ends to an in-rush of lowish pressure water broken up by their internal egg-box construction. The air would therefore mostly escape before their side skins could implode at the greater depth.

However, on top of the PE calculated for the initiating implosion-explosion would have to be added the energies from the follow on bubble phase. A calculation of this for one WBT alone shows that the first bubble maximum radius would be about 6.4 m pulsating at a 0.6s period (Kendrick) and releasing in total an energy = 640 MJ ≅ 218 kg TNT. It is now obvious that even allowing for partial implosions the total process energy release is substantial.

Kendrick's assessment of the initial blast energy and first bubble radius and periods for the hold void spaces is summarised in a table at page 1:197 of Appendix 9 of Williams and Torchio (1998a). However, it is pointed out that Kendrick's energy equivalence is 1 GJ = 238 kg TNT, 30% lower than that above. Moreover, his table omits to include p_o = 10 m which is required using his equation. When these two adjustments are made, Kendrick's energy results agree within about 10% with those obtained from eq(29).

Prediction of Collapse Pressures (p_u) Because of the extensive use of strong deep frames the implosion pressures were largely determined by three-hinge collapse of the rolled or fabricated continuous longitudinals given by:

$$p_u = \frac{k16\sigma_o A_s (z_s + t/2)}{b(1 - 1/2\alpha)L^2} \tag{30}$$

where $A_s < b_e t$ and k is an arbitrary factor set at 1.2 to allow for some measure of large deflection membrane actions. For heavy stiffeners where $A_s > b_e t$ then the plastic moment is approximately $\sigma_o Z$. The bracket term in the denominator of eq(30) allows for load shedding to the transverse boundaries. Shear strengths at grillage boundaries were examined, but were never the weak link.

Plating seldom fails before stiffeners because its continuous nature allows excessive membrane actions to develop at increasing pressures. However, the following failure criteria was developed based on the long-plate plastic membrane approach and a limiting central deformation $w = b/8$ which approximately corresponds to shear yield at the boundaries:

$$p_u = k_1 k_2 8\sigma_o (t/b) \tag{31}$$

where k_1 is a plate slenderness parameter to bridge the stocky 3-hinge collapse criterion to the slender membrane yield at about $\beta = 2.5$, k_2 is to allow for the substantial membrane "shape hardening" effects for plate aspect ratios $\alpha < 3.0$ say.

Finally, the lateral plate implosion-explosion pressure to cause weld pull-out by shear yield in the fillet welds of leg length ℓ is $p_e = 2\ \tau_o\ (\ell/b)$. But this was reduced by 0.5 for low penetration welds. Taking $\ell = 0.6\ t_w$ and $\tau_o = \sigma_o/\sqrt{3}$ then gives:

$$p_T = 0.35\ \sigma_o (t_w/b) \tag{32}$$

These varied between about 2 to 4 times the predicted collapse pressure p_u and a lot of weld pull-outs were seen. This is not to be taken as evidence of bad workmanship as such connections are not designed to withstand implosion-explosion actions.

3. PHASE 1 SURVEY

The final survey was split into two; phase 1 in July 1996 and phase 2 in March and April 1997. Phase 1 was a limited budget reconnaissance "survey of opportunity" undertaken by Oceaneering Technologies Inc (OTECH) of Maryland operating out of Okinawa. The firm had undertaken the 1994 ITF survey and were very keen to please.

3.1 Aims of Survey

In order of priority the objectives were to:

- find and identify Target 9 (supposed stern)
- if this is not the stern, extend the sonar survey until it is located
- visually check the status of the stern spaces, propeller, rudder, the frame 65 region
- re-confirm that Target 63 was the bow and check its status, deck fittings, etc.
- time permitting, investigate other major targets
- determine the water clarity.

3.2 Equipment and Conduct

OTECH's survey vessel the *PERFORMER* was 5,575 ton displacement 10 knot, dynamically positioned, DSV. It was equipped with LBL acoustic transponders for the seabed, side scan sonar and the MAGELLAN 725 ROV using differential GPS for accurate positioning and Mesotech forward looking scanning sonar for navigating. Camera equipment was:

- a wide angle SIT zoom video of range about 30 m
- high resolution CCD camera with about 10m range
- 35 mm still color camera with 750 frame capacity and 300 watt dual head strobes.

Lighting was by a 400 watt HMI gas arc system, and all images, except the 35 mm stills, were relayed in real time to the control van and to the three Assessors in the conference room (2 UK and 1 EC Assessor).

With an intensifying tropical storm HERB approaching, the underwater survey was limited to about 10 hours. After some 1½ hours the ROV found the bow, but it took much longer to find Target 9, which was the stern. The remaining 1½ hours was spent slowly surveying it before hastily retrieving the equipment and heading back to Okinawa.

3.3 Main Findings

The Stern

- is about 600 m from the bow at a bearing of 310° and lies at perhaps 60°–70° to starboard
- considerable implosion-explosion damage
- very little of the superstructure remains in way of the bridge and accommodation
- bulkhead 65 is missing
- rudder is in place and secured to the palm plates
- engine room is lying open with little signs of equipment, fire or explosion
- a suggestion that the propeller is in place was the "scrolling" of the seabed around the stern frame
- transom deck has extensive damage, including to some ventilators.

The Bow

- has few signs of implosion-explosion and lies at 20°–30° to port
- the deck is fractured over the whole width just aft of the collision bulkhead 339; it is mainly ductile but with some signs of straight line brittle fracture
- the supposed excessive corrosion (C6) is not confirmed
- the starboard windlass is missing and other equipment is damaged.

More Generally

- only incomplete views of two hatch covers were seen, one broken in two; no ID markings or numbers were seen
- widespread devastation of the wreckage, with evidence of fillet welds "unplugged"
- iron ore appears to be widely distributed
- seabed penetration is light
- the seabed slopes down about 16° to N × NE and is of average depth 4250 m
- water clarity is excellent
- video quality is generally very good, but more lighting is needed for still photographs.

3.4 Loss Scenario Deductions

C1 *Deck cracking Frame 65:* positional evidence goes strongly against this scenario, as do some of the fracture lines; P_i reduced from 3 to 1

C2 *Deck cracking elsewhere:* no evidence, no change

C3 *Torsional weakness:* no evidence, no change

C4 *Hatch cover collapse:* no evidence (but revised casualty and survivability analyses suggests S_c should increase from 4 to 5)

C5 *Hatch attachments:* no conclusions can be drawn

C6 *Fore deck corrosion:* nil, so C6 ruled out

C7 *Fore peak flooding:* no implosion might suggest bow was flooded before sinking; inconclusive; perhaps increase P_i because of deck damage

C8 *Cargo shift/liquifaction:* no evidence, no change

C9 *Propulsion loss:* propeller very probably in place; reduce P_i from 2 to 1

C10 *Rudder loss/steering failure:* rudder is in place, reduce P_i from 2 to 1

C11 *Explosion/fire in ER:* no sign of charring, but evidence is inconclusive so no change

C12 *Pooping—from forward waves:* evidence is inconclusive so no change

C13 *Pooping—running with the sea:* inconclusive, no change.

3.5 A Posteriori Updating

From above, each of the loss scenarios C1, C9 and C10 have been reduced to 1 and C6 is reduced to zero. For C4 it is suggested S_c increases to 5, for C7 P_i might perhaps be increased. There changes are shown as dotted lines in Fig. 2 (Faulkner and Williams, 1997).

In spite of the typhoon, the survey was regarded as being successful, and well worth the small outlay.

4. PHASE 2 SURVEY

4.1 Overview Summary

This overview summarises the choice of contractor, the survey objectives, statistical information and the scope of sections 4 and 5 of this paper.

Contractor

The two UK Assessors advised the DoT that the Deep Submergence Laboratory (DSL) of the Woods Hole Oceanographic Institution (WHOI), Cape Cod, be engaged for the task. The three main advantages over a commercial contractor were:

- quality of equipment, staff and archiving
- the scientific non-commercial approach
- experience with *TITANIC, BISMARK,* etc.

There were also technology transfer benefits in the final Memorandum of Agreement between the UK DoT and the US NSF.

Objectives

The stated single objective was "to investigate the 13 loss scenarios identified in Lord Donaldson's Assessment"—with a view to determining the cause or the most probable cause of the loss of the M.V. *DERBYSHIRE* insofar as this was possible. If this was not possible then it is important to avoid yet more speculation by demonstrating that there is nothing more which could reasonably be done to establish the cause. A secondary unstated objective was to demonstrate that the technology now exists to successfully undertake a mission of this complexity for future important losses.

Statistics

These are drawn from the main report:

- 43 days were spent on site, 6 days mainly evading super typhoon ISA and 6 days in transit from Guam to wreck site to Yokohama; some days were lost replacing from WHOI the P-code navigation system which failed
- over 137,000 Electronic Still Camera images were captured digitally on tapes and disks
- from these 119 major contacts were mosaiced
- over 2500 contacts were classified by *DERBYSHIRE* hull location in a data base
- over 1800 hours of video recordings were made.

Scope

It is not intended here to dwell in detail on the objectives, planning, equipment, conduct of the survey or its many findings of fact. They are covered in great detail elsewhere (Williams and Torchio, 1998a) and many of the findings have more to do with the imploded-exploded wreckage than with the loss. Section 5 will mention the more important findings which are possibly related to the 13 loss scenarios when deductions are drawn for each of them.

4.2 Equipment, Team and Organisation

Equipment

The R/V *THOMAS G. THOMSON* (AGOR-23) was available for the survey. She is 83.5 m long survey vessel, displaces over 3000 tonnes, has a transit speed of about 15 knots, has high accuracy GPS (P-code) navigation and excellent station keeping with Z-drive propulsion and a bow thruster. The underwater vehicles deployed were:

- DSL-120 kHz split-beam high resolution SWATH bathymetric towed sonar
- ARGO II towed platform with heading control propulsors
- JASON and MEDEA self propelled ROV platform system with a 5 dof manipulator

and each has a 6000 m depth capability. ARGO II had an array of advanced imaging sensors configured specifically for photo-mosaicing of the wreck field in parallel 5 m to 7 m track intervals to give 30–50% overlap. MEDEA serves as a transition point from the main tow cable via a neutral 30 m umbilical to the self propelled ROV JASON. It provides an "eye in the sky" with its own lighting and SIT video camera to help guide JASON to targets of interest. JASON is specifically designed to support a wide variety of science operations with a variety of cameras and sensors. With its 7 thrusters it has fine positioning control with 3 dimensional speed capabilities of about 1 knot. A hydraulic drive rotary metal sample cutter and a coring tool were deployed.

A dazzling array of high resolution and high definition video and still cameras (including stereo for target depth definition) were deployed on ARGO II and JASON. Some were forward looking, some downward looking, and some with zoom and 50 magnification macro capability. A bank of powerful HMI, incandescent and strobe lights, both forward and down looking, ensured that excellent photo images were obtained, including high quality mosaics of important wreckage features.

The Team and Organisation

Andy Bowen, Senior Engineer of the DSL, was the NSF/WHOI Expedition Leader. 11 other WHOI staff included pilots, navigators and engineers for sonar, imaging, instruments and data handling. Robin Williams, UK Assessor, was nominated by the DoT as Chief Scientist to "decide any questions related to the survey plan and specifications in consultation with the NSF/WHOI Expedition Leader".

The UK/EC team of fifteen on board were grouped:

- 3 Assessors: Williams and Faulkner (UK) and Torchio (EC)
- 1 medical doctor from the MOD
- 4 Interpretation Group of 1 Master, 1 Chief Engineer and 1 Second Engineer who had served on sister ships and a Master Mariner from MOD Salvage who co-ordinated the group
- 4 Oceanographic/Survey experts, 2 from SOC Southampton and 2 from IFREMER France (the Institut Francais de Recherche pour l'Exploitation de la Mer).
- 3 PhD students, naval architect, sonar imaging, marine biology, to assist with data processing

The Assessors were to direct the investigative aspects of the survey. The Chief Scientist was empowered to "decide any questions related to the survey plan and specifications in consultation with the NSF/WHOI Expedition Leader". He also reported progress on a regular basis to the DoT.

All of the team, except the doctor and the EC Assessor, undertook watchkeeping groups in the control van on the transom deck on a daily 2×4 hours basis. The team also put in substantial additional hours each day on data processing, instrumentation, reviewing and interpreting data. Faulkner undertook the necessary analytical work in relation to the loss scenarios.

Main Technical Activities

The five main activities of Phase 2 (Williams and Torchio, 1998a; Faulkner, 1998a) were to establish:

- via a high resolution sonar survey of the site a "road map" of the area for later imaging
- a photo-mosaic survey of the whole wreck field, with later processing of key wreckage targets for photo-mosaic images
- close up pictures at several angles of key targets using color cameras
- macro-photographs of key fracture edges at high resolution for failure to be defined
- cutting some metal samples to validate conclusions from the macro-photographs.

All but the last were undertaken, plus some seabed/iron ore coring. The navigation repeatability is said to be better than 5 m, but this was never tested.

The macro-photography was primarily to aid the investigation of the C1 scenario (which over influenced the survey) and was limited in time as the end of the survey was approached. No macro-photographs were taken of the fractures in the hatch covers. These were potentially more interesting because some, at least, may have occurred while the ship was fighting the storm. Metal cutting was programmed for the last day or two of the survey and was aborted because of technical difficulties.

5. EVIDENCE AND DEDUCTIONS

As stated earlier, in making deductions this vital section draws only from the important and relevant evidence from the findings of fact, together with other external evidence and analyses. This itself requires judgement, and so some guidelines are first offered.

5.1 What is Truth?

Scientific truth does not depend on human opinion. However, with marine casualties there is usually no absolute certainty and this applies to the *DERBYSHIRE*. This assessment relies on combined intelligence and wisdom to perceive the most probable truth beyond any reasonable doubt. This required an assessment of external information from various sources, as outlined earlier in Sections 1 and 2. In some cases this is augmented by further information not already given where this is judged to be possibly relevant.

Circumstantial Evidence

Much of the evidence from the survey findings of fact when used in arguing for or against establishing any particular possible cause or causes of the loss of the *DERBYSHIRE* is *circumstantial*. In law this means it does not bear directly on the fact in dispute, but on various attendant circumstances from which the judge or jury might infer the occurrence of a fact in dispute. The interpretation used here is similar.

The strength of such circumstantial evidence is its contributory potential. That is, whilst each piece of evidence is inconclusive by itself, collectively with other such facts or external data it may lead to a most probable result beyond any reasonable doubt. It is recognised that some circumstantial evidence may work for and some may work against any particular loss scenario.

One item of circumstantial evidence which has been widely used, and will be used here, is the absence of a distress message. However, the fact that none was received (by the Owners at least) is not a proof that none were sent. The FI outlined the radio transmission difficulties which can arise in such extreme weather conditions. The absence of any 3 hourly weather reports required by SOLAS is very apparent, and may indicate that *DERBYSHIRE* was experiencing such difficulties.

Basic Premises

Since implosion-explosion actions have affected the wreckage so much, it is important to state the three basic propositions which relate to structural failure:

- *Lemma 1:*

Any compartment which has imploded must of necessity have been intact at the time of sinking

- *Lemma 2:*

Conversely any compartment found fairly intact will have been completely, or nearly completely, flooded before sinking, or will have been flooded in the early stages of sinking before reaching its implosion depth.

If an incomplete compartment has more or less kept its shape, then there must have been a rent or break in the structure which has permitted flooding at depths less than implosion depth

- *Lemma 3:*

If a hull has separated into two parts before sinking, it is most unlikely that the two parts will then sink simultaneously. Therefore, it is nearly certain that the two parts will lie far apart on the seabed.

There is then a less certain expectation that the time needed for the sea to destroy watertight integrity will allow partial flooding above implosion depth, and consequently to less extensive implosion-explosion damage of the wreck.

It will be seen that these premises are important for loss scenarios C1, C2, C3 and C7.

The Logic of Formal Safety Assessment

Section 1.5 outlined the FSA logic adopted in this investigation. A fourth basic premise is offered here because it is important and has been disregarded in the official reports:

- *Lemma 4:*

FSA logic requires that all possible scenarios be considered in the final assessment, unless there is direct evidence which proves that a particular scenario was the unique cause of the loss.

It therefore follows that for those scenarios which cannot be ruled out beyond reasonable doubt, the three considerations that need to be considered for each are relevant: Survey Evidence; Casualty and Service data; and, Theory and/or Test data. See 5.5 for *Lemma 5*.

The logical approach adopted to bring these final judgements together is the updated Risk Matrix. It is hoped that this will reduce further speculation to those "near miss" scenarios having risk numerals higher than 8 say, out of a possible 25. It is suggested that the recommendations should also be guided by this approach.

5.2 Main General Survey Evidence

Just a few of the more interesting general findings which have no bearing on the loss are mentioned here, with additional clarifying comments as necessary:

- correcting longitude, the wreck of the *DERBYSHIRE* is about 34 nautical miles from her last known position and at a bearing of about 24° from it (NE × N)

- all but one piece of the wreckage lies within a rectangle 1200 m × 833 m = 1km^2 oriented with its main axis SE to NW, as is the orientation of the bow to stern whose centres are 620 m apart
- about 70% of the wreckage lies NE of the bow to stern axis and 30% SW; which may be due to the influence of the local Kuro Siwo current
- the one piece outside this wreckage rectangle is 880 m SW × W from its centre, and is a double skin ship side unit; some of the other hydrodynamically slender foil type structures have also glided to the remoter parts of the wreck field
- other similar double skin units, such as transverse hold bulkheads, cofferdams and double bottom units, are reasonably intact with implosion-explosion induced separation at their boundaries with other structure; some are bent, probably by bubble forces
- most of the remaining structure is severely mangled; the superstructure from about the second level upwards, including the wheelhouse, top mast and funnel, is upside down and severely crushed
- some quite dense items of main and auxiliary machinery were more widely dispersed from their source than, e.g., were lighter wreckage items like hatch covers; this may be due to the implosion-explosion of the two large air reservoirs in the engine room which are estimated to generate at least 486 MJ of energy, equivalent to 165 kg of TNT
- the main engine itself was not seen but could be hidden in a hollow below the upturned aft end double bottom structure
- about 100% of the double bottom structures, and 80% to 85% of the ship deck and sides were identified
- there are no clues from the wreckage as to the specific time of the sinking; this will be discussed again in relation to loss scenario C13
- the findings from phase 1 are confirmed, except the location of the bow and hence the wreck field (about 500 m difference).

5.3 Main Relevant Evidence and Deductions

The important factual findings from both surveys are discussed in relation to the loss scenarios. Where scenarios are absolutely ruled out, the more important circumstantial evidence, external data and arguments which also support this deduction are nevertheless identified. References to the "official report" are to (Williams & Torchio, 1998a).

C1 Deck Cracking Frame 65

- Port and starboard slop tanks aft of bulkhead 65 imploded-exploded, as did the wing and hopper tanks froward of bkd 65 in no. 9 hold. By *Lemma 1*, the ship must have been intact in this region at the time of sinking. This scenario is therefore ruled out.
- *Other arguments:* complex deck fracture path which meanders across the ship and fore and aft of Fr.65; no casualty support; fracture mechanics considerations; wind and sea would have driven the wreck SW of the stern; *Lemma 3* applies.
- A further probability based argument which is also relevant to C2 and C3 is that none of the hatch covers are essentially intact and attached to their coamings, as they probably would be if the ship had broken in two at any cross-section.

C2 Deck Cracking Elsewhere

- This scenario is only fatal if it leads to extensive deck cracking and hull separation. Most of the structure of the hold compartments has been severely damaged, and no wing or hopper tanks remain intact. By *Lemma 1* this scenario is ruled out. *Lemma 3* also strongly supports this.
- *Other arguments*: no life saving equipment was launched (see later), no distress message was received, no hatches intact and very low incidence of such losses.

C3 Torsional Weakness

- This manifests itself as sprung hatch covers or fatigue cracks at hatch corners, which, if they extend beyond the coaming into the deck, can lead to very minor water ingress, or eventually to unstable crack extension across the deck and a C2 type scenario. All hatch covers were found close by; there were fatigue cracks, but they did not extend into the deck. By *Lemmas 1* and *3* this scenario is ruled out.
- *Other arguments:* as for C2, but in addition double skin ships are torsionally very strong.

C4 Hatch Cover Collapse—Evidence with Comments:

- All 18 hatch covers can be shown to be in the wreck field, based on 13 complete covers and 10 part covers to make up the remaining 5 (Faulkner, 1997d); the official report uses 13 or 14 complete and 7 part covers (see sketch 26 page 2:66).
- Only for 3 of the complete covers can their location in the ship be established for certain (see 2.4 re identification clues); using the main report notation these are HS as no. 2 port cover, HI as stbd no. 2 and HE/AD as port no. 3; complete cover HO is either stbd 3 or stbd 8 and port covers HAE and HMG taken together would be about 80% of the companion cover to HO; the official report gives other possible allocations, including HR as starboard no. 1 cover (see below).
- All covers suffered external pressure as their initial or primary failure mode, but 3 for certain and 3 less certain had evidence of subsequently being blown outward; Figure 17 shows HD, half of a hatch cover which has split between centre longitudinals and shows it has been bent diagonally outward.
- Y type bending or tearing primary failures across the centres of the longitudinals were seen in 7 of the 13 complete covers, and X type bending or tearing occurs in the remaining 6 (see 2.4); in some cases there is a mix of both types of failure, again some being outward failures.
- A few of the Y bend failures are located about 0.35L to 0.4L from the fore end of the cover, rather than at the centre of the longitudinals; in two or three cases the bends are bulges rather than straight hinges, and some of the hinges are skewed across the longitudinals.
- About half of the covers were badly distorted, some with extensive tearing; most had heavily distorted and torn end plates.
- About half the covers were upside down; of those that could be seen, 14 had access/ventilator opening lids missing, and there is evidence of 5 covers with one or more of their three heavy duty securing catches being left in the open position (refer to Fig. 9).

Assessors' Deductions with Comments:

- The evidence of inward hinge lines and bulges being about 0.6L to 0.65L from the aft ends of covers led the Assessors to suggest this may be evidence of wave actions in the process of sinking by the bow. On this evidence they show a possible layout of the covers, referred to earlier, and a sequential description of hatch failure.

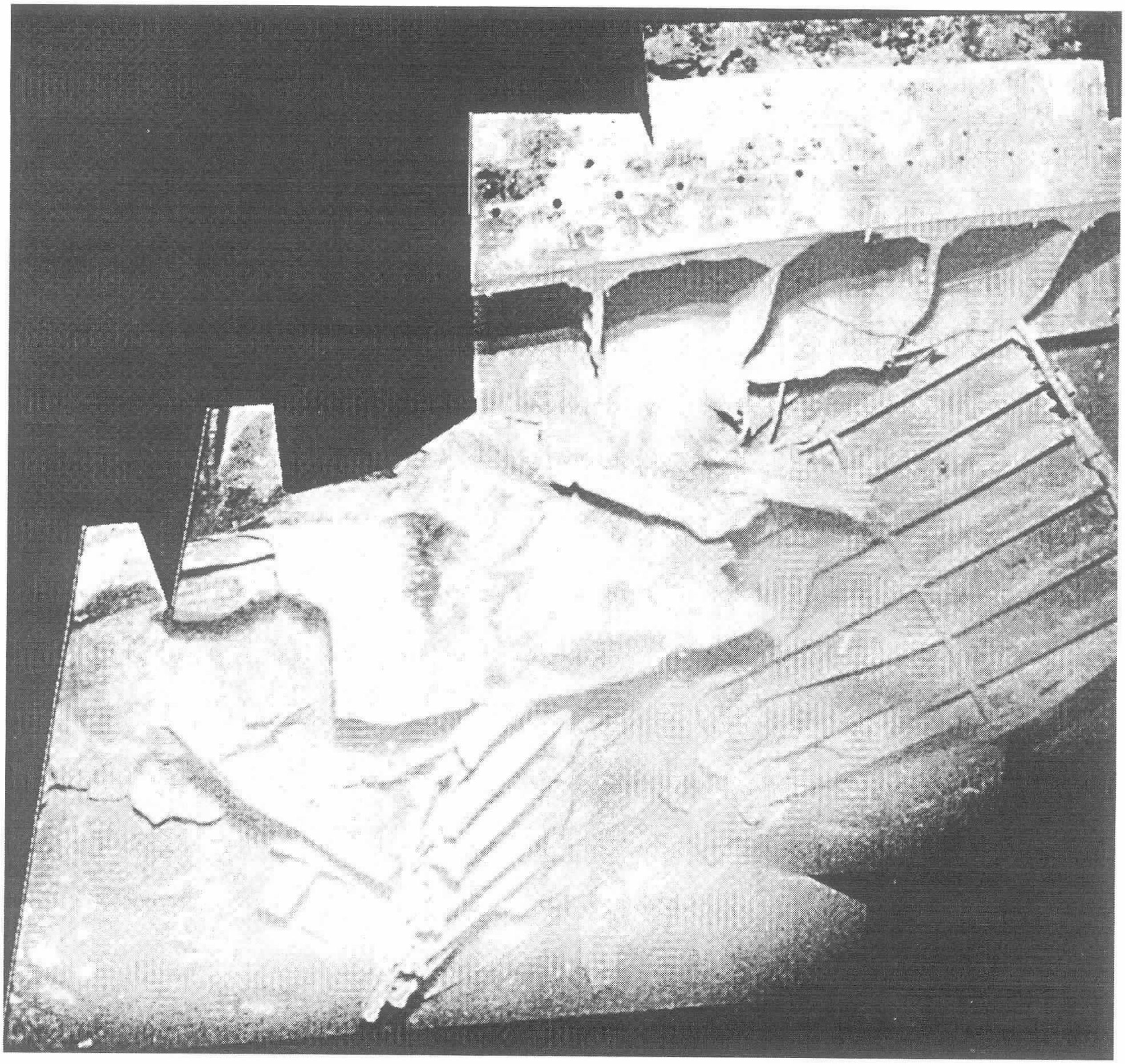


Fig. 17 Half of a hatch cover HD and adjacent part of coaming

- For the static component of pressure, simple beam theory shows that for a plunging ship at inclination (the linearly diminishing load leads to the maximum bending moment occurring at (L from the least loaded end where:

$$\alpha = \left(\sqrt{(t^2 / 3) + t + 1} - 1\right) t^{-1} \qquad (33)$$

  where t = tan θ. For θ = 15°, 30° and 45° this defines the position of the plastic collapse hinge as (= 0.51, 0.52 and 0.53 respectively. This is so near the centre as to make no difference to the collapse position or pressure. The predicted "55–65% of the length" put forward by the Assessors to support their contention is pure guesswork (in 3.732 page 1:93). Nor would the taper of the beams help their assertion.
- There is the possible action of breaking waves as the ship sinks, but the probabilities of a hit at any particular position are out of anyone's control in the cauldron of typhoon ORCHID.
- A potentially more important deduction from the Assessors is their firm assertion that hatch cover HR is no. 1 starboard, and that "it was initially destroyed by the dynamic pressure loading of a plunging wave". They have attempted to seek support for this from two eminent metallurgists, even though there are no macro photographs of the fractured surfaces. This assessor would like to believe the assertion, but feels that there is no firm evidence to support such speculation.
- For example, it is noted that the Y mode of failure for cover HR at midlength is as expected from *uniform* pressure. Because these longitudinals are fillet welded to the central girder at that position some may have "pulled out" as bend-

ing approaches the collapse level. In so doing their release of energy would also be dynamic and could fracture the plating exactly as seen. Several of the hatch covers have similar fractures to that on cover HR. The other complication is the unknown effects on any cover of the subsequent implosion-explosion actions from within the hold.

- The Assessors' emphatic, but nevertheless specious statement (in 5.9 page 1:120) ruling out hatch cover weakness as the primary initiating cause of the loss (and indeed ruling out the six scenarios C8-C13 in the process) will be dealt with in C7.
- The Assessors in 3.732 page 1:93 refer to static and dynamic inelastic finite element (FE) calculations and they deduce:

a) The impact from a plunging wave could fracture a cover in half at the 3.5 mm fillet weld connections of the longitudinals to the centre transverse girder. The Assessors apply this only to cover HR (which they claim is no. 1 stbd) and conclude that it "was initially destroyed by the dynamic pressure of loading of a plunging wave" (4.133 page 1:114).

b) Under a static uniform pressure, plasticity starts at 3.8 m head and would collapse the cover at about 4.8 m head, thus confirming "that the design was in accordance with the ICLL 1966 which required the covers to withstand only 1.75 m."

Author's Deductions:

- Regarding the Assessors' deductions (a) and (b):

a) As mentioned above, several other covers fractured completely or partly along the centre transverse girder. If the Assessors' deduction is correct, then one must assume that these covers were also struck and breached by plunging waves, and this has been ignored. Two more serious criticisms arise directly from the evidence. Many of these longitudinals in other covers carried the full plastic moment at or near these 3.5 mm fillet welds well into the plastic stretching regime. This hardly seems consistent with the implied weak fillets. Secondly, the Assessors have also ignored the 6 covers which failed through X type bending *between* longitudinals. It was this difficult to explain behaviour which gave rise to the need for FE calculations in the first place.

So there are several reasons why the Assessors' deduction is incomplete and unconvincing.

b) Deduction (b) of the Assessors is demonstrably absurd. It implies that their interpretation of the 1966 ICLL is that covers are only required to withstand 1.75 m of sea water head. It will be seen from 2.4 Strength Assessments that in a well designed mild steel cover, stiffener yielding should start at about 4.3 m head, and plastic collapse at about 5.1 m—not 1.75 m. The Assessors have overlooked the safety factor!

Incidentally, in the absence of stated assumptions regarding effective plate widths and boundary restraints, both of which are critical, the two pressure heads quoted by the Assessors in (b) are meaningless. The severe weld pull outs, tearing and distortion of the end plates suggests there was little restraint at the hatch cover boundaries.

From these observations it would appear that the FE calculations and the Assessors' interpretations are open to serious questions and are unconvincing and inconclusive.

- The evidence of X type failures, local bending and some straight line fractures, does suggest that at least 6 of the 18 hatch covers failed due to dynamic wave actions as there really is no other explanation.
- It is ironic that no firm deductions can be made from the survey evidence for this most likely of all the loss scenarios, and indeed as the final event for loss scenarios C8 to C13 as will be seen.
- Recourse to other external arguments and data is therefore essential.

Other Arguments:

Most of the other arguments have already been made in section 2.4 but are summarized here:

- Model tests at DMI measured pressure on hatch covers and coamings. Even for simulated steep elevated waves no more than 26 m high, these pressures correlated well with the theory advanced for predicting them in the Annex to Lord Donaldson's report. This theory ignores wave and ship dynamics and is expected to become more non-conservative with higher waves.
- In the hove-to position the *DERBYSHIRE* only requires one steep elevated wave of 23m height or more to collapse no.1 hatch cover, or one linear wave higher than about 26 m to do so. The notional probability of exceeding these values has been estimated for the sea conditions prevailing up to the early morning of the 9th September 1980, and are given in Table 3. They are high and Fig. 5 shows one such wave.
- Bow flooding reduces freeboard in way of no. 1 hold and inevitably increases the probability of hatch cover collapse. This was examined in 2.5 for realistic and unrealistic degrees of bow flooding and found to be negligible compared with the probability of collapse with no bow flooding.
- These probabilities are unacceptably high, and would have become higher during the afternoon and the night of 9th September and into the 10th when typhoon ORCHID executed three high-speed conditionally unstable cyclonic loops, with intensifying winds, as described in 2.1. The conditions would be ferocious.
- Casualty data (in 2.4) suggests that every third month a bulk carrier in dense ore is lost in rough weather and that every eighth month the loss is likely to have been due to breaching the forward hatch covers.
- Some Classification Societies have already implemented substantial increases in hatch cover strength. There can now be no doubt that the 1996 ICLL requirements are totally inadequate as regards hatch cover strength, especially so for heavily laden B-60 bulkers where buoyancy loss is greatest due to flooding.

Conclusions (C4):

- This scenario cannot be proved absolutely. But, on the collective basis of limited circumstantial evidence, experiments, theory and casualty data, it must be put at $R_n = 25$ in the extreme corner of the "intolerable" zone of the FSA risk matrix.
- It is also reiterated that it is not just no. 1 hatch cover which is vulnerable, they all are, and failure of covers anywhere along the ship's length is the likely end event for all of the other loss scenarios.

C5 Hatch Attachments

- The evidence shows that all 18 hatch covers are within a closely defined area of the wreckage field and were driven into the holds by sea actions. None were lost, so this scenario is ruled out.
- It is interesting to note in passing that one bulker of the 108 lost in the last eight years (LR, 1998) "sank after loss of hatch cover".

C6 Fore Deck Corrosion

This was previously ruled out.

C7 Fore Peak Flooding—Evidence at the Bow:

- The alignment from the bow to the stern is SE to NW and the bow is inclined to port by about 25°.
- The bow has suffered only minor implosion-explosion actions and appears to be attached to the remaining lower levels of no. 1 hold structure and below the mud line.
- Four broken ventilators are missing on the fore deck, as is the cover for the access hatch to the Bosun's Store (both assessed in 2.5).
- The aft coaming to the stores hatch is stove in with vertical splits along its edge which are also bent inward (video still 77) and the hinge pins are missing. In contrast, the side coamings are only slightly distorted at their aft corners.
- The starboard windlass, mast and other heavy fittings are missing and considerable bodily impact damage exists on the fore deck (Richardson, 1998)
- Collision bulkhead 339 has a major split across the ship at a weld line about 8 m above the hold floor. This was described in 2.7. Para 3.40, page 1:48 of the UK/EC Assessors' report suggests that the top and bottom edges are bent outward indicating "internal pressure". This is not agreed and conflicts with the very clear video stills 12 and 13 of the report, and with the Assessors' own statement in 4.74 page 1:109 "The section of bulkhead 339 in way of the fuel tank was substantially bowed inward by external pressure on the hold side indicating that this tank was not completely filled with fluid during the initial stages of sinking".
- The port side shell has a crack and bulge below the ship's name running downward at about 45° from aft to forward; other lesser cracks are reported port and starboard.

Deductions From Evidence

Sections 2.5 and 2.7 address the more important possibilities quite fully and are summarised:

- From *Lemma 2* the absence of major implosion-explosion means the bow was mainly flooded before the external to internal pressure difference on any of its boundaries reached their implosion level (of about 45 m). The alternative explanation that the bow broke away from the vessel and was eventually breached by the sea and sank is untenable in the light of evidence just described.
- There can be little doubt that some level of green sea flooding would have occurred through damaged openings before sinking actions started. But, there is no evidence whatever of this or of the extent of the flooding.
- It certainly does not follow from lack of implosion-explosion damage that major flooding took place before the ship started to sink. As the conservative calculations in 2.7 and Table 5 show, after the filling of no. 1 hold, the time to flood ballast spaces and stores in the bow is a matter of minutes.
- Even then, irrespective of any doubt about the calculations, the logical arguments which follow these calculations show that there would really be no risk of damaging implosions anyway. This is because there would be insufficient difference between the water and air pressure inside ballast tanks and the sea outside, for the reasons given in 2.7.
- The explanation offered by the Assessors as to why the deep fuel oil tank in the centre of the bow is intact is that the manhole access covers at the top had been left open to ventilate the tank before reaching port. This is quite contrary to normal practice since the fuel tank has several permanent vents. If this fuel tank was fairly intact this would be explained by *Lemma 2* and by the arguments in 2.5 and 2.7 in Cargo Shift Actions in No. 1 Hold which *is* supported by evidence.
- The physical damage to the aft coaming of the Stores hatch has almost certainly been caused by the unseated windlass or other heavy object. In doing so, this would certainly have distorted, and very probably sprung loose any cover from its butterfly clips and sheared the hinge pins (see Richardson, 1998). Down flooding to the Bosun's store would start and the reduction in freeboard when full is 21 cm at no. 1 hold.
- In 3.71 page 1:50 the two Assessors refer to the two toggles each side of the aft port corner of the coamings being tightly roped together around their threaded shanks and this prevented the proper use of the wing nuts in securing the hatch (video still 75). They then refer to this "unsecured fore deck hatch" in the second of their four conclusions. This implication of crew negligence has been challenged on the basis of the Summary report (1998b), notably by Grigson (1998) and by Richardson (1998). It is also understood that P&O have issued instructions for butterfly nuts to access hatches to be lashed together with cord for greater security when the hatch is closed.
- This assessor suggests that because the side coamings of the stores hatch are essentially straight and upright, with just local bending at the two corners, the hatch lid must have been in place and secure at the time it was unseated. The reason for this is that the gross inward bulge of the aft coaming with vertical splits along its top edge, indicates large horizontal membrane stretching actions and these could not develop unless such forces can be reacted. The two side coamings are not strong enough to do this and would bend inward if no lid was present to resist this. On the other hand, the lid and its own inside coaming would initially be strong enough to resist these membrane actions.
- This lends strong support to Captain Richardson's belief that the aft end of the hatch was probably struck by the freed windlass behind it, distorting the coaming and lid, shearing the hinge pins and springing the lid free from its butterflies.
- No significance is attached to the splits in the side shell of the bow. They are unlikely to have been caused by hitting a semi-submerged object, for the reasons given earlier and later in C14. They are more likely to have been caused by bottom impact, for which there is evidence. The 45(bulge crack port side is oriented as for shear from a forward impact.
- The bow to stern orientation aligns approximately with the likely orientation of a ship hove to at that time in typhoon ORCHID. This evidence is not conclusive, but it is backed up by evidence from other wrecks and suggests that the vessel at the time of the loss was more probably hove to than beam-on.

Other Arguments

- The "GLEN" and other ships have experienced bow flooding from broken ventilators, air pipes, etc. But, this appears not to have led to any serious consequences.

- In effect the Assessors argue that the collapse of no. 1 hatch cover would only occur if the bow spaces were flooded. This assessor regards the likely extent of bow flooding to be a quite secondary effect and is not essential to cause no. 1 hatch cover to be breached by the sea. Both issues are of course linked by seas over the bow actions.
- Sections 2.4 and 2.5 go into both topics in some detail, which is not repeated here. In essence, these argue from analyses and notional probabilities, that the ship would not survive long enough for the fore peak spaces to fill before no. 1 hatch cover, or some others, first failed from the dynamic actions of a single high wave. Using the same notional probability modelling for both events, the risk of hatch cover collapse is a higher order of magnitude, even if one were to allow for *unlikely* flooding of the fore peak spaces. The reduction in freeboard is trivial in the context of gross hatch cover overloads from just one wave of 26 m or more (or a 23 m non-linear wave).
- It will no doubt be argued that for the flooding cases examined in 2.5 the 75:25 probability mix is arbitrary and biased toward slow fore peak flooding. This is agreed. But, as well as Ochi's reasoning, there is another physical factor to justify this judgement. Extremely ferocious, turbulent and highly elevated seas, which would prevail at the time, are less likely to fill openings than are more stable green seas. As an added comment, they are also much more damaging to structure as the Appendix shows.

Conclusions (C7):

- This assessor concludes unequivocally that the breaching of no. 1 hatch cover to flood the hold does *not* depend on the prior flooding of the fore peak spaces in the context of typhoon ORCHID (see 2.5).
- It follows that, whilst fore end flooding does occur and should be prevented, it is a secondary factor in the context of the loss of the M.V. *DERBYSHIRE*. It is not an essential initiating event.
- This conclusion applies to the grossly weak hatches designed to ICLL 1966, and would also apply to properly designed hatches 2.5 to 3 times stronger than this present requirement. Paradoxically, for intermediate strength hatches (say 50:50 chance of no. 1 hatch cover surviving typhoon ORCHID), the Assessors' conclusion would become more valid; that is, extensive fore end flooding could then be the last straw.
- Because of the evidence, analyses, and other arguments made, the risk matrix notional probability of this initiating event occurring is increased from $P_i = 2$ to 4 (high probability). But because the trim consequences are less serious than first thought S_c is reduced from 4 to 2. Then $R_n = 8$ which is on the middle line of the ALARP zone, and suggests that safety related improvements should be made.

Other Loss Scenarios C8 to C13

Two general points are stressed to save repetition before considering this last group of six possible loss causes:

- Based on the supposed "slow filling of the bow prior to sinking" the two Assessors have ruled out all of these six other scenarios (but strangely, not any of the remaining scenarios). Under *Lemma 4* this would require the slow filling of the bow to be proven absolutely. Demonstrably this is not the case, nor is there any evidence for slow filling (over many hours). The circumstantial evidence of damaged ventilators and the missing stores hatch merely suggests that some unspecified water ingress is likely to have occurred. The Assessors dismissal of the remaining six scenarios is therefore quite invalid. Rather strangely, the Assessors seem to have had rapid capsize in mind for these other loss scenarios (see 4.162 page 1:117) rather than hatch cover damage.
- Section 1.5 pointed out that all of these six scenarios would result in the ship becoming beam-on to the weather, three of them with the ship stationary (C9, C10 and C11). Whilst it is conceivable that the final loss event for C8 could include capsize, because of *DERBYSHIRE*'s high stability it is considered that by far the most likely terminating event for all six scenarios is brisk rolling leading to collapse of any or several of the eighteen hatch covers. They occupy about 30% of the cargo deck area and are an order of magnitude weaker than the rest of the deck or the ship sides.

It follows from these points that all of these six scenarios will be considered here, and should any remain as a non temporary scenario their seriousness of consequence indices S_c must be high, and 5 is suggested if the ship is stationary.

It also follows that evidence of storm-induced hatch cover failures cannot help to distinguish which of these six other loss scenarios is most likely.

C8 Cargo Shift/Liquifaction—Evidence and Deductions:

- This scenario has two possible end events under beam seas: capsize or hatch cover failure. If the vessel had capsized all of the 14 hatch covers over the 7 laden holds (all except holds 2 and 6) would have been forced *outward* by the ore, and they would be easily recognised. Therefore, the positive evidence of inward initial failure of all hatch covers (para 5.8 page 1:120 of the main report) rules out capsize.
- No further deductions can be made from the survey evidence

Other Arguments:

- This scenario shows a very low incidence in casualty data over many years for bulkers over 20,000 DWT (see Table 1 in section 1.5). Of 4 that reported cargo shift, all sent distress messages, 3 were lost, 1 towed to harbour and all 4 crews were safely evacuated. This is mentioned in section 2.6 which reviewed the whole topic. The fact that no distress message was received or lifeboats launched is circumstantial evidence against this scenario.

Conclusion (C8):

- The scenario cannot be absolutely ruled out, so must remain at the lowest probability $P_i = 1$; because of the severity of typhoon ORCHID S_c is increased from 2 to 3.

C9 Propulsion Loss

- The engine and tail shaft could not be examined. No lifeboats were launched or distress message received, so with no new evidence Phase 1 conclusion remains at $P_i = 1$, $S_c = 5$.

C10 Rudder Loss/Steering Gear Failure

- The steering gear could not be seen but their high redundancy and reliability makes failure very unlikely. Also, no new evidence, no lifeboats launched or distress message received.

- Because the scenario cannot be absolutely ruled out Phase 1 conclusion remains at $P_i = 1$, $S_c = 5$.

C11 Explosion/Fire in Engine Room

- The machinery items mentioned in section 5.2 showed no signs of being damaged by explosion, fire or smoke. This is not conclusive, as the absence of charring after 17 years could be due to the actions of current, or even marine life.
- The possibility of nearly simultaneous explosions from hydrocarbon residues in the two slop tanks was ruled out on grounds of very low probability and no scorch or burn marks.
- No lifeboats launched or distress message received so P_i is reduced from 2 to 1, and S_c remains at 5.

C12 Pooping Actions from Forward Waves

- There is some evidence of pooping damage but not from forward waves. Retaining this always very improbable scenario is therefore unjustified and it is ruled out.

C13 Pooping Actions

As a preliminary comment, the official report seems to have limited its definition of Pooping to damage to the Winnel ventilators allowing water to enter and contaminate the fuel tanks and causing engine stoppage (BRAER type). This paper considers all damage from being pooped (waves over the stern) so the title of C13 has been generalised. It is assumed that, in the prevailing very confused multi-directional sea conditions, being pooped is *not* limited to running with the sea or to the associated involuntary course changes.

Evidence with Comments:

- The main deck plating between frames 15 to 40 over the port fuel tank is severely collapsed downwards showing clear upstanding ridges over the underdeck longitudinals, which are also bent downwards.
- A long split exists in the nearby shear strake which is bent inward at 3 deck level; its straightish line suggests brittle fracture.
- The transom deck aft of frame 23 is severely collapsed downward at the centre with diagonal hinges leading to the transom corners; bollard tops are missing (probably imploded) and one circular manhole cover (or 500 mm MV?) is missing
- The port corner of the transom is severely damaged and the deck roller fairleader is bent inboard.
- The Winnel vents to the fuel tanks appear to be undamaged, at frames 17 and 26.
- Various ventilators on the aft deck quarters are missing their mushroom heads; one (at least) has a wad of material pushed inside it as if to prevent water ingress (video still 131).
- All guard rails at the stern are missing.

Deductions from Evidence:

- The damage to fittings on the transom and port side deck and the two depressions in the deck suggest damage either from pooping or from the early stages of implosion arrested from flooding elsewhere.
- The Assessors also suggested the deck depression on the transom may have been caused by inertia forces as the stern struck the bottom, but this is not agreed as the safety factor should cope with 3 or 4 g forces which are inconceivable in the likely bottom contact circumstances.
- The extensive split and inward depression of the port side shear strake appears more likely to be caused by pooping wave actions (see the Appendix) which could also account for the damage to the fairleader and structure at the aft port corner of the transom.
- Any ventilators stuffed with wadding suggest damage from earlier pooping actions.
- The missing guard rails are likely to have been swept overboard at sea, or dislodged by shock loads from the various implosion-explosion actions on sinking.

Other Arguments and Data:

- The probability that some of the loss of watertight integrity damage seen could be due to pooping would imply that water ingress occurred into the space below the transom.
- A lifeboat was sighted shortly after the loss. It is thought to have come from the ship's starboard side and could have been lost as the Master attempted to alter course to port, the obvious way. The predominant sea would then have been on the ship's starboard side. The starboard lifeboat, only one deck up, would then be very vulnerable to the mountainous seas and might have been torn from its davits. It is very unlikely that it was lost before the last message received from the ship because this would surely have been reported then. This is, of course, speculative and circumstantial.
- It would also be very difficult to maintain a hove-to heading in the conditions prevailing and the ship could have fallen off wind and ended up more or less beam-on (FI, 1989). She would then certainly have been in very serious difficulty, with a greater risk of being pooped.
- At the time of *DERBYSHIRE*'s last position report (0300Z/9/80) the Chief Officer of the M.V. *ALRAI* sent a message (referred to in 1.6) in which he felt "that it should not be ruled out that the *DERBYSHIRE* broke down and broached to". The cause and need for this speculation is perhaps surprising and implies that the *DERBYSHIRE* might have been in following or quartering seas and in some difficulty. The FI appear to have ignored this strange message. Nor did they consider why the ship reduced speed on the 8th of September.
- The FI report (1989) points out that a later coded message (2000/9/80) was sent and received. The time was probably local time as the message refers to Tokyo, in which case this is 8 hours after *DERBYSHIRE*'s last position report. It would then just about coincide with the beginning of the first of the three conditionally unstable cyclonic loops (see 2.1 and Fig. 3). These intensifying conditions persisted over the next 24 hours as typhoon ORCHID recurved northwards.
- The wreck of the *DERBYSHIRE*, allowing for the earth's curvature, is estimated to be about 34 nautical miles (nm) NE × N from her last known position, at 0300Z Assuming a linear progression of the ship between these two positions, her tracks over 9 and 18 hour periods were plotted. These were then compared with a median plot of typhoon ORCHID's progress over the same 18 hour period, as reported from Guam, Tokyo and Hong Kong. Within an accuracy of (10 nm it was found that initially the *DERBYSHIRE* was about 100 nm from the typhoon's instantaneous position and after 18 hours about 135 nm from it.
- This assessor's approximate estimate of the radius of maximum rotating wind speed at that time was about 100 nm which agreed surprisingly well with an earlier DMI value of about 110 nm radius (Faulkner and Williams, 1996b). It therefore follows when these two sets of calculations are put together that the *DERBYSHIRE* during her last hours was very close to the most damaging radius of the dangerous

semi-circle as it progressed along the track of the typhoon, as Fig. 3 demonstrates.

- It is noted that because of low freeboard the life saving equipment on the *DERBYSHIRE* was extremely vulnerable to boarding seas. In particular, Richardson (1998) suggests such seas would trip the hydraulic releases of the liferafts which would be washed overboard.
- Among her many problems *KOWLOON BRIDGE* suffered pooping damage.

Conclusions (C13):

- The evidence suggests the likelihood of pooping damage, but is inconclusive.
- However, taken together with the external factors just mentioned, and noting the potential forces involved from Appendix A, it would seem probable rather than possible that pooping occurred and caused at least some of the damage seen. What cannot be said is that this was a consequence of the Master attempting to run with the sea or to veer away from the typhoon track. These must remain only as possibilities.
- As a consequence of all these considerations, P_i might reasonably be increased, and an increase in S_c might be considered due to the possibility of water ingress into the steering flat. However, the evidence is not firm so no change is proposed.

C14 Hatch Coaming Collapse

C14? was retained as an "unforeseen" scenario following the Lord Donaldson work because the sea often springs surprises. Three were considered, but only one retained for serious consideration. The other two were:

- Striking a semi-submerged object like a container. This had previously been suggested (DoT, 1986) and was re-examined because of the splits found in the sides of the bow. However, these splits were not felt to be consistent with striking a container. Moreover, such a container would surely have been smashed by the turbulent waves in typhoon ORCHID.
- A huge wave or sequence of waves, sweeping away the accommodation and bridge super-structure. This was suggested by the DoT because after Phase 1 very little super-structure could be seen on the stern. However, there is no casualty data on such an event, and calculations showed that although the accommodation block walls might be badly deformed, there is massive shear strength in the internal transverse bulkheads and deep frames to resist this scenario.

However, hatch coaming collapse remains even though there is no direct evidence for it from the surveys. Specifically, no. 1 hatch coaming is regarded as the most vulnerable and the consequence is certainly serious and is not adequately considered in design.

Other considerations:

- The casualty data mentioned in 2.4 under Hatch Coamings does suggest that coaming damage does occur, and this would lead to water ingress into the hold.
- It has been suggested (Richardson, 1998) that the dislodged starboard windlass could have been swept aft at some stage before it left the ship, and hit the forward coaming of no. 1 hatch severely damaging it.
- A more likely source of extensive damage and substantial water ingress is from a spilling breaking wave, as described in the Appendix. Calculations in 2.4 show that this coaming would be vulnerable even to high normal waves sweeping over the bow. But a spilling breaker, or a near-breaking steep elevated wave crest, has about 2.5 to 10 times more damaging potential, as eq(vi) in Appendix A demonstrates.
- Using an exceedance probability reduction factor of 0.4 as suggested by recent data (Eilersen et al, 1989) and applying the equations of 2.2, it can be shown that over a 12 hour period of typhoon ORCHID the notional probability of a spilling breaker occurring for different wave heights is:

H	(m)	25	27.5	30
p	(%)	40	30	11

The crest tops of lower or higher waves would miss the coaming. Although the results are notional and untested, they do indicate significant possibilities of a breaking or near-breaking wave sweeping over the windlasses and on to no. 1 hatch coaming.

- The sequence of events would then be a steady and substantial increase in bow trim as no. 1 hold filled up, followed by the collapse of the hatch covers for holds 1 and 2 and plunging by the bow.
- It is a scenario that can arise from head or beam seas, and is potentially terminal because of flooding which could worsen subsequently if the damaged hatch cover is lifted by continuing sea actions.
- The 1966 ICLL makes no provision for hatch coaming strength, and the classification society rules are also quite inadequate.

Conclusion (C14):

- In the absence of corroborative data a risk numeral 6 is suggested made up of $P_i = 2$ and $S_c = 3$. This new scenario is in the "ALARP" zone of the risk matrix and clearly needs to be examined further (Appendix A) as Rn could increase.

5.4 Updated Risk Matrix with Comments

Figure 18 shows the final risk matrix for the seven remaining loss scenarios C4, C7, C8, C9, C10, C11 and C13, the dotted lines showing their changes from the initial 1996 risk matrix. Also shown is the additional possible scenario C14 hatch coaming collapse.

The six scenarios which have been removed on the basis of evidence and/or other arguments and data are shown in the bottom left corner of their original position.. The cluster of C9, C10 and C11 in the right hand bottom corner very nearly also came into the ruled out category because they are extremely unlikely. But they are retained because of their maximum seriousness of consequence rating $S_c = 5$ as the ship would be stationary and very vulnerable if any of these events did occur.

This assessor has found this novel approach to evaluating risks to be very helpful for assessing and comparing the various loss possibilities. The numbers of course are notional, and other assessors will doubtless have different views. This does not really matter. What does matter is establishing the most probable cause for the loss (C4)and doing something about it and the "near miss" scenarios C7 and C13 which certainly require attention.

Although C1 has been ruled out, it initially had the second highest risk numeral. Improvements in the structural design of such connections should therefore be considered, as they also should be for hatch coamings (C14).

*5.5 **Initiating and Terminal Events***

As the conclusions are approached it is appropriate to clarify a common confusion which often distracts attention from the true *cause* of ship losses, as it does in the official report. The recent LR update (1998) has several examples.

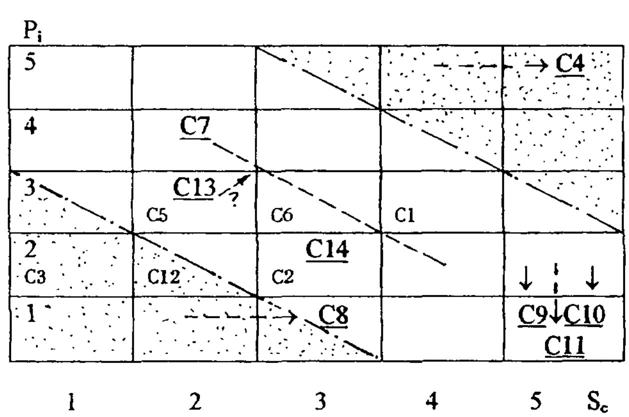
- *Lemma 5*—The true cause of the loss of a ship is not necessarily or even usually the *initiating event* in a chain of events. The true cause may be a *serious defect* which the chain of events revealed. The initiating chain of circumstances exposed the defect to a dangerous test, but it is the defect which is the *cause* of the loss.

An example is a large B-60 OBO ship in dense ore lost in a severe storm. The initiating event might have been shearing of vents to the fuel day tank, leading to salt-water in the fuel, causing main engine stoppage, leading to the ship coming beam-on to abnormal waves, which caused weak hatch covers to collapse, which led to loss of buoyancy and foundering. The true cause of the loss is not loss of vents, nor loss of power, but the deficiency in the hatch cover strength.

Of the 14 loss scenarios considered here for the M.V. *DERBYSHIRE*, 9 are *initiating* events only, and the remaining 5 are *terminal* events because their initiating event is inevitably final. That is, there are no other necessary ship events in the chain before the ship is lost. These 5 are 2 primary structure scenarios C1 and C2, and the 3 hatch related ones C4, C5 and C14.

6. CONCLUSIONS

One can be certain beyond reasonable doubt that the M.V. *DERBYSHIRE* was finally overwhelmed by typhoon ORCHID during the night or early morning of 9th/10th September 1980. To determine what event, or combination of events which, beyond reasonable doubt, caused her to sink, we turn first to the survey evidence.



	$P_i x S_c = R_n$
FE VULNERABILITY:	
C4 Hatch Cover Collapse	5 x 5 = 25
C7 Fore Peak Flooding	4 x 2 = 8
OTHER SCENARIOS:	
C8 Cargo Shift/Liquifaction	1 x 3 = 3
C9 Propulsion Loss	1 x 5 = 5
C10 Rudder Loss/Steering Gear Failure	1 x 5 = 5
C11 Explosion/Fire in Engine Room	1 x 5 = 5
C13 Pooping Actions	3 x 2 = 6
C14 Hatch Coaming Failure	2 x 3 = 6

Fig. 18 Final risk matrix for M.V. *DERBYSHIRE*

*6.1 **Deductions from the Underwater Survey***

The survey eliminates some scenarios: the three *Primary Structure* ones C1, C2 and C3 and two of the four *Fore End Vulnerability* scenarios C5 and C6. Of the remaining *Other* scenarios C9, C10 and C11 have had their notional probabilities reduced to $P_i = 1$ and are discounted. So also is C8 ($P_i = 1$ throughout). The improbable scenario C12 is subsumed in C13. These are major achievements.

Does the survey evidence lead to changes in the risk numerals? The consequence seriousness index is not influenced by the evidence, so only possible revisions to P_i are considered:

C4 Hatch Cover Collapse:

The survey leads to no firm conclusion but a $P_i = 3$ is suggested (medium likelihood) because the mosaic images show different failure modes, some of which may be caused by wave actions.

C7 Fore Peak Flooding:

Video images show damage to vents and the stores hatch which would cause slow flooding. P_i is raised from 2 to 4, but certainly no more as there is no evidence for the extent of flooding.

C13 Pooping Actions:

Circumstantial evidence suggests the likelihood that some transom deck and side damage was caused by pooping actions, but the evidence is inconclusive so P_i remains at 3.

It follows that the underwater survey does not by itself reveal the sequence of key events in the loss and hence it does not explain the loss with a reasonable level of certainty. Nevertheless, the two Assessors attempted to do so, but their description of the series of events is unproven and speculative. Note that the official report contains little numerical data, no relevant quantitative analysis, nor does it use FSA logic.

*6.2 **Deductions Based on Facts and Analyses***

Since the seabed evidence is inconclusive, it is essential to consult other evidence and analyses. For this reason these independent factors govern this assessment. The final values of P_i and S_c are given below and shown in Fig. 18.

C4 Hatch Cover Collapse:

Analyses of wave heights during typhoon ORCHID show, beyond reasonable doubt, that waves able to collapse the forward covers pass over the bow section of the ship. This is shown without including the effects of downward pitching into the oncoming waves. Pressure measurements at the DMI also confirm that a single steep elevated wave of height 23 m would burst no. 1 hatch cover. Casualty data for laden bulkers supports this scenario. P_i therefore remains at its original 5 and S_c is set at 5, so $R_n = 25$.

C7 Fore Peak Flooding:

C7 is linked to C4 because the same waves do the damage to both. However, there is a fundamental difference which is ignored by the two Assessors. In C4 a single elevated wave above 23 m high is terminal; in C7 about 2,000 wave passages are required to fill the fore peak ballast tanks and stores. In fact, C4 and C7 are in effect mutually exclusive because analysis of typhoon ORCHID's waves shows that C4 will happen long before C7 has lead to significant flooding. The probabilities for this are intolerably high. The Assessors' suggestion of flooding into the forward fuel oil tanks is dismissed (See 2.7 and 5.3).

Hence, it is concluded that the breaching of no. 1 hatch cover(s) does not depend on the prior flooding of fore peak spaces. P_i remains at 4 from the survey evidence but S_c is reduced from 4 to 2 because of the limited flooding.

C13 Pooping Actions:

The very confused, steep elevated 3-dimensional waves of typhoon ORCHID might suggest that S_c be increased from 2 to 3 because of the possibility of significant water ingress. However, it is left at 2 with a question mark, mainly because it is an initiating event, not a terminal one.

C14 Hatch Coaming Collapse:

This cause of loss was introduced because of suspected weakness of the hatch coamings (section 2.4) and because the analysis in Appendix A now quantifies the large forces caused by breaking waves over the bow or from the beam. It is also potentially terminal due to substantial water ingress which could worsen if the damaged hatch cover was also lifted or detached by the continuing sea actions. A cautious $P_i = 2$ and $S_c = 3$ is judged, but both could increase.

6.3 The Cause of the Loss

- Beyond any reasonable doubt, the direct cause of the loss of the M.V. *DERBYSHIRE* was the quite inadequate strength of her cargo hatch covers to withstand the forces of typhoon ORCHID. This weakness to resist substantial water ingress is gross when compared with other major elements of the watertight boundaries of the ship's hull.
- These hatch covers did meet the acceptable stress criterion of the 1966 ICLL. It then follows that the fundamental fault and cause of this tragic loss lies fairly and squarely in the altogether inadequate value and inappropriate nature of the loading and safety factor implicit in these Rules.
- It is not possible to say which of the eighteen covers failed first, or from which direction the waves came; but evidence and other arguments suggest that the no. 1 hatch covers were probably the first to yield, probably from waves over the bow with the ship hove-to.
- The prime conclusion does not depend on the likely extent of flooding of the bow spaces through damaged openings or the missing cover stores hatch cover.

6.4 Other Important Conclusions

- It will be apparent that this assessment differs in many details and in its prime conclusion from Williams and Torchio's official assessment. Their most likely cause of the loss (in Chapter 6) is almost pure fiction in places, full of assertions which are seldom backed by evidence and never by appropriate analyses. Most assertions are non sequitors. This is the clue to the fundamental difference between the two assessments.
- Nevertheless, this assessor agrees totally with their most sensible paragraph in the whole report (8.69 page 1:142): *"Regardless of the actual initiating event, the DERBYSHIRE case illustrates quite clearly how the hatch covers are a front line of defence against water ingress. Their failure inevitably would lead to the loss of such vessels and must be treated in the same manner as the main fabric of the hull structure".*
- However, and with respect, it should be understood that the hatch cover survey evidence is inconclusive, with a medium rating. It is only the quality of the DMI test data of 1986 and the conservative theory advanced in 1995 for Lord Donaldson's Assessment which, when matched together (Faulkner, Corlett and Romeling, 1996), provide the real justification and confidence for such statements which were made very clearly at the time.
- This is stressed simply to emphasise that advanced analytical thinking is an essential prerequisite for complex endeavours of this nature if a beyond reasonable doubt conclusion is to be reached. The independence of the survey and its deductions from sponsor interests is also vital once the objectives have been set.
- The question has been asked (Williams and Torchio, 1998a): *"Why did the DERBYSHIRE find herself in the most dangerous sector of typhoon ORCHID?"* The last para. In 1.6 touched on a common theme among master mariners who generally have little confidence in the safety aspects of weather routeing. It is also very clear from Appendix II of the FI report that Ocean Routes got it wrong as far as the plot of typhoon ORCHID was concerned. Had that been accurate Captain Underhill would have incurred little risk in attempting, as he did, to run ahead of the storm. But, had he been more influenced by the consistent median plot from Tokyo, Guam and Hong Kong, and allowed for the well known vagaries of typhoons and taken the approved avoidance action (The Mariners' Handbook, 1979), he would not have put his ship at such risk. But, he would also have been anxious to meet the Charter arrangements and would, no doubt, have confidence in the size and capability of his nearly new ship, especially before the more recent spate of bulk carrier losses were known.
- Section 2.3 describes TS simulations which suggest that high non-linear waves can give rise to wave induced bending moments which may be about 80% higher in sag than those given by the unified IACS standard (Nitta et al, 1992). This requires fuller investigations.
- The three remaining loss scenarios C7, C13 and C14 all have high enough risk numerals to suggest that they should be treated as "near misses," and methods to reduce these risks should be devised.
- Freak or abnormal waves do occur and have sunk many ships. They are not curious and unexplained quirks of nature. This assessment suggests that their occurrence can be predicted with sufficient accuracy for survival design as advocated recently by Faulkner and Buckley (1997) and others.
- The underwater technology now exists such that no ship need now remain unlocated or its loss not investigated if the will to look for it exists and the necessary resources are made available (Lang, 1998).

7. RECOMMENDATIONS

We should not only react to disasters, but design and operate to prevent them. The Assessors' recommendations, like their conclusions, cloud rather than clarify the main issues. Most have little if any link with the underwater survey evidence.

7.1 Prime Recommendations

- Revise substantially the 1966 Loadline Convention requirements as regards hatch cover strength for all covers. Detailed suggestions for this are given in the last two sections of 2.4 which also show the weight and cost penalties can be small. The analysis there also shows how important it is to abandon the present archaic allowable stress criterion based on ultimate stress. It should be replaced with a more logical and safer ultimate strength criterion as suggested.
- All Type B freeboard ships should have a raised forecastle head with high bulwarks and a substantial breakwater to protect the forward hatches and deck machinery and fittings.
- Consider an increase in freeboard and/or deck sheer forward. This is not necessary if the first two recommendations are adopted.
- Existing ships should have their covers replaced now. This breaks with tradition but the situation in lost lives is far too serious to delay.
- Review the present status and effectiveness of the ship safety aspects of weather routeing.

7.2 Other Recommendations

The following recommendations arise specifically from *DERBYSHIR*E related investigations, but are also thought to be important to consider for other ships.

- Designs for "near miss" scenarios C7, C13 and C14 should be improved. No rules exist for coamings and their collapse (C14) is terminal.
- The Frame 65 scenario (C1) initially had a high risk numeral. The design of such connections can and should be improved to eliminate cruciform "through the thickness" loading and alignment problems, and to reduce the direct and shear transfer loads.
- A *Survival Wave* approach to design (Faulkner and Buckley, 1997) should now be considered seriously as an addition to the normal design process. Section 2.2 introduces the topic and loss scenario C14 would be an excellent one for testing the method and to illustrate the first principles approach required. Also see Appendix A.
- The suggestion that ship bending moments from abnormal waves may substantially exceed the present IACS unified standard should be examined.
- The inelastic finite element calculations of partially loaded hatch cover responses to dynamic waves are worth repeating to see if failure modes corresponding to those seen in the survey can be explained. It would need an interactive well specified and monitored contract.
- The use of grade A mild steel clearly does promote brittle type fractures in structure and fittings under dynamic wave actions. Previous proposals that its use be abandoned for all hull and weather deck structures and fittings (Jubb, 1995) are suported.
- Dynamic impact of side shell from the mobility of saturated ore cargoes in holds should be considered in design of single hull bulkers.
- Because it is now evident that even large ships can sink very rapidly, the wider use of ramp mounted gravity launched lifeboats should be considered. Life saving equipment should not be vulnerable to pooping wave actions.
- The cargo hold flooding dangers are notably higher for ships laden in dense ore. This suggests that Floodability requirements may need to be revised.
- Fore peak spaces should be capable of being pumped out with controls operated from the Engine Room or Pump Room.
- The design and protection of weather deck ventilators and access hatch covers must be improved.
- The FSA approach should be beneficial when considering design and operational improvements.
- Guiding principles and practices for forensic analyses of shipwrecks should now be established. This must include other evidence and analyses.

Several more detailed recommendations arising from the *DERBYSHIRE* work can be found in Faulkner and Williams (1996a and b), in Faulkner and Buckley (1997) and in Faulkner (1998). These deal with environmental and oceanographic needs, design, construction and operation, and feedback of service experience.

ACKNOWLEDGMENTS

I am indebted to many people who have helped and encouraged me along the way. I will avoid the usual invidiousness by confining myself to just seven professionals from the "retired" brigade. But first, I dedicate this paper to the Derbyshire Family Association. Without their dogged perseverance and patience over 18 years the shipwreck would have remained an unexplored mystery. The magnificent seven are alphabetically:

- *Douglas Brown*, who has been an excellent devil's advocate on several aspects, including seamanship and feedback from operational experience
- *William Buckley*, whose interest in rogue waves of all types and whose single minded dedication to creating the survivability envelope and the associated first principles design concept over two decades is hopefully now about to pay off. It is appropriate here to acknowledge Bill's sponsors, the Ship Structure Committee and the US Coast Guard, for making their data for Fig. 5 available
- *John Donaldson*, Lord of the Realm, for his encouragement and inspiration through the early stages
- *Laurie Draper*, whose 1964 paper re-awakened my latent interest in freak waves. Laurie, it was Lord Donaldson who preferred "abnormal", but it doesn't matter what we call them as long as we design ships with some capability to survive them
- *Christopher Grigson*, another devil's advocate who has offered many helpful suggestions and whose experience and dedication to rigour and the truth has inspired and encouraged me
- *Neil Hogben*, for his helpful review of my development of the Abnormal Wave concept in my Annex to Lord Donaldson's report in 1995; this was the starting point for this paper and the many others in between
- *Jack Richardson*, Master Mariner, whose unrivalled wisdom drawn from years of varied command and operation, and whose continuing active pursuit of ship safety has kept me on an even keel throughout this long endeavour.

It is unusual, but I suggest justified, to include my wife Isobel, who many know as my secretary over the last 23 years, and amazingly still continues. She has a unique personal knowledge of our profession and is my greatest critic, editor and supporter through thick and thin.

Lastly, I acknowledge the support of the DETR for my involvement in this endeavour up to October 1997. The two wreckage photographs included in this paper are of course their property and this is acknowledged.

REFERENCES

AFTENPOSTEN, 1997. Videobilder av skipsvraket ga ingen svar, *article on survey of LEROS STRENGTH, Aftenposten, Oslo, 4 September.*

BACON, Sheldon, 1991. Ch. 31 Wind Waves, *in loc cit Coles, Adlard K.*

BAGNOLD, R.A., 1939. Interim Report on Wave Pressure Research, *Jnl ICE, vol. 12, London.*

BALES, S.L., 1982. Designing Ships to the Natural Environment, *Ship Performance Dept. Report, DTNSRDC, Bethesda, Md.*

BARLTROP, N., BROOKING, M. and WARREN, P., 1992. Bulk Carrier Losses: Are Tougher Steels Needed?, *The Naval Architect, Technical Note, p.E273, May.*

BISHOP, R.E.D., PRICE, W.G. and TEMAREL, P., 1991. A Theory on the Loss of the M.V. DERBYSHIRE, *Trans RINA, vol. 133.*

BRETSCHNEIDER, C.L., 1958. Selection of Design Wave for Offshore Structures, *Proc. ASCE, WW-2, vol. 84, March.*

BROWN, D., 1997. Rapid Failure, Rapid Sinking, *RINA Conf., Design and Operation for Abnormal Conditions, Glasgow, 21-22 October.*

BUCHNER, B., 1995. On the Impact of Green Water Loading on Ship and Offshore Design, *PRADS Intll Conf., Seoul, September.*

BUCKLEY, W.H., 1978. Hull Girder Structural Design—The Case for New Loading Conditions for extreme Waves, *Nav. Engrs. J., February.*

BUCKLEY, W.H., 1983. A Study of Extreme Waves and Their Effects on Ship Structure, *Ship Structure Committee Report SSC-320.*

BUCKLEY, W.H., 1988. Extreme and Climatic Wave Spectra for use in Structural Design of Ships, *Nav. Engrs. J., September.*

BUCKLEY, W.H., 1991. Analysis of Wave Characteristics in Extreme Seas, *Ship Structure Committee Report SSC-353.*

BUCKLEY, W.H., 1997. Critical Capsizing Conditions in Survivability Seaways, *loc cit Brown, 1997.*

BUREAU VERITAS, 1995. Special Issue on Bulk Carriers, *Bulletin Technique, no. 3.*

BYRNE, D., 1995. Hatch Covers: Maintenance and Operation with Reference to Failures in Service, *The ImarE, London, 18 April.*

CARDONE, V.J., 1987. Wave Hindcast of Typhoon ORCHID (1980) in connection with the loss of the M.V. DERBYSHIRE, *Final Report for LR, Nov. 10.*

CHAN, E.S., 1985. Deep Water Breaking Wave Forces on Structures, *ScD dissertation, Dept. of Civil Engineering, MIT, Cambridge Ma.*

CLAUSS, G., 1998. Task-Related Wave Groups for Seakeeping Tests and Simulation of Design Storm Waves, *Real Sea '98, Proc. Intl Workshop on Modelling of Ocean Environments in Wave and Current Basin, KRISOE, Taejon, Korea, February 3-4.*

COLES, K. Adlard, 1991. *Heavy Weather Sailing, 4th edn revised by Peter Bruce, Adlard Coles Nautical.*

DAHLE, E.A. and MYRHAUG, D., 1995. Risk Analysis Applied to Capsizing of Fishing Vessels, *Marine Technology, vol. 32, no. 4, SNAME, October.*

DENNY, D.F., 1951. Further Experiments on Wave Pressures, *Jnl ICE, vol. 35, London.*

DMI, 1985. Bulk Carrier Seakeeping Tests, *Report DMI 85226, SH9(1) vols 1 to X.*

DOMMERMUTH, D.G. et al, 1988. Deep-Water Plunging Breakers: A Comparison Between Potential Theory and Experiments, *Jnl Fluid Mech., vol. 189, pp 423-442.*

DONALDSON, Lord, 1995. Lord Donaldson's Assessment (DERBYSHIRE), *Cm 3128, London, HMSO, December, ISBN-0-10-131282-2.*

DoT, 1986. A report into the circumstances attending the loss of the M.V. DERBYSHIRE which foundered on or about 9 September 1980 in position approximately 25(30(North, 130(30(East with the loss of 44 lives, *DoT, March.*

DoT, 1989. M.V. DERBYSHIRE, Report of Court No. 8075, Formal Investigation, *HMSO, London, January, ISBN-0-11-550896-1.*

DRAKE, K.R., 1997. Wave Profiles Associated with Extreme Loading in Random Seas, *loc cit Brown, 1997.*

DRAPER, L., 1964. Freak Ocean Waves, *Oceanus, vol. 10, no. 4.*

EILERSEN, C., GUDMESTAD, O.T., OTTESEN, HANSEN, N.E. and JACOBSEN, V., 1989. Freak Waves and their Effect on Steel Jacket Platforms, *Report No. 3.12/156, Oil Industries Exploration and Production Forum, Paris.*

EVANS, J., MOTTE, R. and CALVERT, S., 1995. The Practical Application of Onboard Weather Routeing, *in Seakeeping and Weather, Proc. of RINA Conference, 28 February/1 March.*

FAULKNER, D., 1975. A Review of Effective Plating for Use in the Analysis of Stiffened Plating in Bending and Compression, *Jnl Ship Research, vol. 19, no. 1 March.*

FAULKNER, D., 1995a. Safety of Ships—Risk Assessment Based Design and Operation, *Greenwich and Hazards Fora Conference on Safety of Ships, Southampton, May.*

FAULKNER, D. 1995b. Design for Abnormal Ocean Waves, A Discussion Paper, *Annex to Lord Donaldson's Assessment (DERBYSHIRE).*

FAULKNER, D. 1995c. Ship Safety and Public Concern, *Presidential Address, Institution of Engineers and ShiPpbuilders in Scotland, 3 October, Trans IESIS, vol. 139, 1995-96.*

FAULKNER, D., 1997a. The Need for Survival Wave Design, *Keynote Address, Advances in Marine Structures III, DERA Conf., Dunfermline, 20-22 May.*

FAULKNER, D., 1997b. Hatch Covers—The Achilles' Heel of Bulkers?, *Lloyd's List, July 1.*

FAULKNER, D., 1997c. Implosion-Explosion Actions and Analyses, *Annex 2 of Faulkner 1998a (submitted to the DETR, May 1997).*

FAULKNER, D., 1997d. M.V. *DERBYSHIRE*—Hatch Cover Assessment, *Annex 3 of Faulkner 1998a (submitted to the DETR, June 1997).*

FAULKNER, D., 1997e. Flooding Through Fore Deck Openings in the M.V. *DERBYSHIRE* and the Resulting Risks. *Annex 3 of Faulkner 1998a.*

FAULKNER, D., 1997f. The Behaviour of Iron Ore Concentrates—Comments Relating to the M.V. *DERBYSHIRE, Annex 1 to Faulkner, 1998a, (submitted as a report to the DETR, November 1997).*

FAULKNER, D. 1998a. Lessons Learned from the Loss of the M.V. *DERBYSHIRE. Unpublished Report*

FAULKNER, D. 1998b. Review of the Bases for Relevant Ship Rules, *part of a study with AME Ltd. For Shell UK on Reliability Based Design and Assessment of FPSO Structures (commercial in confidence).*

FAULKNER, D., 1998c. Defining the Ocean Environment for the Save Design and Operation of Ships, *Keynote Address, COST Conference, Provision and Engineering/Operational Applications of Ocean Wave Spectra, Paris, 21–25 September.*

FAULKNER, D. and BUCKLEY, W.H., 1997. Critical Survival Conditions for Ship Design, *loc cit Brown.1997.*

FAULKNER, D., CORLETT, B.J. and ROMELING, J.U., 1996. Design of Hatch Covers and Coamings for Abnormal Waves, *RINA Conference: Watertight Integrity and Ship Survivability, London, 21–22 November.*

FAULKNER, D. and WILLIAMS, R.A. 1996a. Discussion of the Proceedings of the RINA Colloquium, M.V. DERBYSHIRE, The Search, Assessment and Survey, London, 15 March.

FAULKNER, D. and WILLIAMS, R.A. 1996b. Design for Abnormal Ocean Waves, *RINA Spring Meetings (with full discussion in RINA Trans. Part A, vol. 139, 1997).*

FAULKNER, D. and WILLIAMS, R.A. 1997. Formal Hazard Analysis Applied to the OBO Carrier DERBYSHIRE: A Technical Note, *The Naval Architect, RINA, November.*

FRIEZE et al, 1991. Report on Committee V.1, Applied Design, *in Proc. of the 11th ISSC, vol. 2, ed by P.H. Hsu and Y.S. Wu, Elsevier Applied Science.*

GARZKE, W.H., BROWN, D.K., SANDIFORD, A.D., WOODWARD, J. and HSU, P.K., 1996. The TITANIC and LUSITANIA: A Final Forensic Analysis, *Marine Technology, vol. 33, no. 4, SNAME, October.*

GAYTHWAITE, John, 1981. *The Marine Environment and Structural Design, van Nostrand Reinhold.*

GOLDMAN, J., 1978. How Big Can Waves Get?, *Ocean Industry Magazine, Houston, June.*

GRAHAM, R., 1988. Slamming Experiments with a Radio-Controlled SWATH Model, *RINA Intl Conf. SWATH Ships and Advanced Multi-Hulled Vessels II, London.*

GRIGSON, C.W.B., 1998. On the Contention that Bulkers and Tankers are too weak in storms, *Trans RINA, Part B, vol. 140.*

GRIGSON, C.W.B., 1998. *Derbyshire*: Revised Designs Required, *The Naval Architect, July/August, pp 30,32.*

HACKET, C.. and BEDFORD, J.G., 1996. The Sinking of the SS TITANIC—Investigated by Modern Techniques, *joint paper with The Institution of Engineers and Shipbuilders in Scotland and the RINA, Glasgow, December.*

HOGBEN, N., 1990. In *Long Term Wave Statistics, Ocean Engineering Science, vol. 9, Part A,. section 8, John Wiley and Sons.*

HOGBEN, N., 1997. Discussion of Faulkner and Williams 1996b, *RINA Trans, Part A, vol. 139.*

HOGBEN, N., DACUNHA, N.M.C. and OLLIVER, G.F., 1986. *Global Wave Statistics, Unwin Brothers.*

INTERCARGO, 1995. Analysis of Total Loss and Fatality Statistics Bulk Carriers, Ore Carriers and OBOs 1990-94, *Report of the International Association of Dry cargo Shipowners, March.*

ISBESTER, Capt. J., 1993. *Bulk Carrier Practice, The Nautical Institute, London, ISBN 1 870077 16 4.*

ITF Mission, 1994. Report of ITF Derbyshire Mission, *International Transport Workers Federation, London, July.*

JTWC, 1980. Data and Discussion of Typhoon Orchid, *in Annual Tropical Cyclone Report (1980), Joint Typhoon Warning Center, Guam.*

JONES, D.K. and ROE, N.P., 1991. Bulk Carrier Casualties—An Independent Consultant's View, *Intercargo/IBJ Seminar, Hong Kong, October.*

JUBB. J.E.M., 1995. Structural Failure of Bulk Carriers, *67th Thomas Low Gray Lecture, Institution of Mechanical Engineers, London, 5 January.*

KAWAKAI, M., 1969. On the Impact Strength of Ships Due to Shipping Green Seas, *J.S.N.A., vol. 125, June.*

KJELDSEN, S.P., 1984. Dangerous Wave Groups, *Norwegian Maritime Research, no. 2.*

KJELDSEN, S.P., TORUM, A. and DEAN, R.G., 1986. Wave Forces on Vertical Piles Caused by 2- and 3-Dimensional Breaking Waves, *Intl Conf. On Coastal Engineering, Taipei, Taiwan, 9-14 November.*

KOROBKIN, A., 1994. Water Impact Problems, *Chapter 7 in Marine Hydrodynamics, ed by M. Ohkusu, Computational Mechanics Publications.*

KRUSZEWSKI, A., 1992. Sliding Solid Bulk Cargoes: How to Avoid Them, *ICHCA Annual Review (based on IMO Sub-Committee on Containers and Cargoes, 32nd Session Paper BC22/318 submitted to IMO 13 November 1992.*

KVALSVOLD, J., FALTINSEN, O.M. and AARSNES, J.V., 1997. Effect of Structural Elasticity on Slamming Against Wetdecks of Multihull Vessels, *J.Ship & Ocean Technology, SNAK, Seoul, vol. 1, no. 1.*

LANG, Adm J., 1998. Accident Investigation An International Code. *Seaways, The Nautical Institute, August.*

Lloyd's List, 1995. Hurricane LUIS, *London, 16 September.*

Lloyd's List, 1996. Warning on Bulk Carrier Sinking Risk, *29 January.*

Lloyd's Register Report, 1982. TYNE BRIDGE—Examination of Fractured and Cracked Deck Plates, *Research Laboratory, Crawley, Report 62/9250/2018, June.*

Lloyd's Register Report, 1987. DERBYSHIRE—Report L9, *Prepared for the Formal Investigation into the loss of the DERBYSHIRE.*

Lloyd's Register, 1995. Bulk Carriers—An Update, *July.*

Lloyd's Register, 1998. Bulk Carriers—An Update, *March.*

LONGUET-HIGGINS, M.S., 1952. On the Statistical Distribution of the Heights of Sea Waves, *J.Marine Research, vol. 11, no. 3.*

LONGUET-HIGGINS, M.S., 1974. Breaking Waves in Deep or Shallow Water. *In Proc. 10th Symp. Naval Hydro., Cambirdge, MA (ed R.D. Cooper & S.W. Doroff) pp 597–605, Washington: Government Prining Office.*

LONGUET-HIGGINS, M.S., 1984. Parametric Solutions for Breaking Waves, *J. Fluid Mech. 121, 403–424.*

MAIB, 1997. Passenger Ship Suffers Damage in Hurricane, *Marine Accident Investigation Branch, Summary of Investigations, No. 1/97, DETR, UK.*

MARKS, L.P. and MARKS, A.P., 1979. *Standard Handbook for Mechanical Engineers, 1979 edition, McGraw-Hill.*

MASSEY, B.S., 1970. *Mechanics of Fluids, 2nd edition, Van Nostrand Reinhold Co.*

MEARNS, D.L.K., 1995. Search for the Bulk Carrier DERBYSHIRE: unlocking the Mystery of Bulk Carrier Shipping Disasters, *Proc. of Conf., Man Made Objects on the Sea Floor, Soc. Underwater Technology, London, February.*

MEYERHOFF, W.K. et al, 1994. Report of Committee I.2 Loads, *Proc. 12th ISSC, vol. 1, St. Johns, Newfoundland.*

MILLS & Co. 1995. The DERBYSHIRE, Lord Donaldson's Assessment—Observations, *Mills & Co., Newcastle upon Tyne, 26 April.*
MURRAY-SMITH, D.R., 1969. The 1966 International Conference on Load-Lines, *Trans RINA, vol. 111.*
MYRHAUG, D. and KJELDSEN, S.P., 1986. Steepness and Asymmetry of Extreme Waves and the Highest Waves in Deep Water, *Ocean Engineering, vol. 13, no. 6.*
NITTA, A. et al, 1992. Basis of IACS Unified Longitudinal Strength Standard, *J.Marine Structures, vol. 5, no. 1.*
OCHI, M.K., 1990. *Applied Probability and Stochastic Processes, Wiley Interscience.*
RAINEY, R.C.T., 1997. *Loc cit Hogben, 1997.*
RAMWELL, Dave and MADGE, Tim, 1992. *A Ship Too Far: The Mystery of the "Derbyshire", Hodder and Stoughton, ISBN 0-340-56997-2.*
RAPP, R.J., 1986. Laboratory Measurements of Deep Water Breaking Waves, *PhD thesis, MIT, Dept. of Ocean Engineeirng.*
RICHARDSON, Capt J., 1998. Derbyshire: New Forecastle Theories, *The Naval Architect, RINA, July/August, p 30 (see also Letter, in Seaways, The Nautical Institute, August).*
SKINNER, A.E., 1987. Cargo Movement Due to Forces Acting on it in a Seaway, *embodied as LR9.1 in Report LR9 by Lloyd's register, September.*
SPENCER, J.S., 1975. Structural Design of Aluminium Crew Boats, *Marine Technology, SNAME, vol. 12, no. 3, July.*
SPYROU, A.G., 1997. Bulk Carrier Losses—What have we Learned?, *paper to IMO Diplomatic Conference, London, 24-28 November.*
SUHARA, T., HIYAMA, H. and KOGA, Y., 1973. Pressure Due to Impact of Water Jet and Response of Elastic Plates, *Trans W. Japan SNA, no. 46.*
SUMPTER, J.D.G., BIRD, J., CLARKE, J.D. and CAUDREY, A.J., 1989. Fracture Toughness of Ship Steels, *Trans RINA, London, vol. 131.*
The Mariners' Handbook, 1979. *5th ed., published by The Hydrographer of the Navy, Taunton.*
THOMAS, G.O., 1968. An Extended Static Balance Approach to Longitudinal Strength, *Trans SNAME, vol. 76.*
Van DORN, W.G., 1993. *Oceanography and Seamanship, 2nd edn. Cornell Maritime Press.*
WILLIAMS, R.A. and FAULKNER, D., 1996. M.V. DERBYSHIRE—The Search, Assessment and Survey, *Paper Presented at the RINA Colloquium, London, 15 March.*
WILLIAMS, R.A. and TORCHIO, R. 1998a. M.V. Derbyshire Surveys, UK/EC Assessors' Report, *DETR Environment Transport Regions, March 1998, ISBN 1-85112-286-0.*
WILLIAMS, R.A. and TORCHIO, R. 1998b. M.V. Derbyshire Surveys, UK/EC Assessors' Report, A Summary, *DETR Environment Transport Regions, March 1998, ISBN 1-85112-075-0.*
ZHU, Ling, 1995. Structural Response of Ship Plates in Slamming—Drop Test Results and Analysis, *University of Glasgow Report NAOE-95-20, June.*

APPENDIX A

BREAKING WAVE IMPACT FORCES IN WIND DRIVEN SEAS

Adlard Coles (1991) describes the "supreme violence of breaking waves". These are not confined to shallow waters or shelving beaches. In open ocean extreme conditions, if the wind rapidly intensifies, younger steeper waves are generated (see Fig. 6 of Faulkner and Buckley, 1997). In the *overshoot* phase of wind wave growth some of these waves become oversteep (crest peak slopes $m > 0.58$) or unstable and their crest particle velocity (u_o) exceeds their celerity (c) and they dissipate their excess energy into breaking waves. There are two forms (Bacon, 1991):

- *Spilling Breakers* occur when the crest "topples" down the front face of the wave. It is assumed that the maximum impact velocities are at about $v = 2c = 2\lambda/T$ and that the maximum incident wave heights cannot exceed $H = 2.9\ H_s$ (Eilersen et al, 1989)
- *Plunging Breakers* are less common in open oceans, but they can occur when the wind wave growth has been so rapid that the overshoot energy is unusually high from ferocious winds, or, in multi-directional intensifying wind conditions which create 3-dimensional seas of *pyramidal* form whose crests can interact with each other creating what Adlard-Coles described as the "seething sea like a bubbling cauldron".

The energy from spilling breaker wave fronts has destroyed sea walls and dislodged and moved breakwaters. Figure 5 shows an elevated wave crest recorded during hurricane CAMILLE. Such waves are clearly important when considering wave forces sweeping along the upper deck of ships, or, even impacting on the topsides of ships holds. Present advice for vertical hatch coamings (Faulkner, 1995b) of taking relative impact velocity $v_i = (1.2c + \text{ship speed } v)$ when hove to, as in 2.4, should be reconsidered for a higher value for spilling breakers:

$$v_i = 2c + v \qquad \text{(i)}$$

used in conjunction with design pressures defined by eq(14) in section 2.4.

However, although rarer in deep water, the horizontal forces that can arise from the plunging breaker can be significantly higher. A *plunging jet* of water forms in front of the wave crest whose velocity can reach up to 3 or 4 times the wave speed (Bacon, 1991). This is thought to be due to the presence of air trapped under the curl of a plunging breaker (Bagnold, 1939). The initial relative horizontal water velocity would then be:

$$v_i = kc + v\cos\alpha\ ,\ 3 \le k \le 4 \qquad \text{(ii)}$$

where v is ship speed and α is heading angle relative to the predominant waves. Assuming a gravitational fall of the initially horizontal jet, and that v_i remains unchanged during the second or so before impact, it follows that for an initial height (h) of the jet above the impacted structure:

$$u = \sqrt{2gh} \quad , \quad t = \sqrt{2h/g} \qquad \text{(iii)}$$

$$v_{i\theta} = \sqrt{v_i^2 + 2gh} \qquad \text{(iv)}$$

$$\theta = \tan^{-1}\left(\frac{u}{v_i}\right) = \tan^{-1}\left(\sqrt{\frac{2gh}{v_i}}\right) \qquad \text{(v)}$$

where u is the vertical component of $v_{i\theta}$ the impact velocity, whose direction is angle θ to the horizon, and t is the fall time. For example, with $T_p = 13$ s, $\lambda = 260$ m, c = 20 m/s to correspond with the H = 30 m wave shown for the *DERBYSHIRE* in Fig. 8, and assuming v = 0, equations (ii) to (v) with k = 4 and (14) with $C_p = 1$ have been evaluated for varying heights (h) of the plunging breaker above the deck to derive $p_{i\sigma}$ the reflected wave impact pressure head of sea water acting on a flat surface normal to the jet (90° – θ to the deck):

h (m)	0	5	10	15
u (m/s)	0	9.90	14.01	17.15
$v_{i\theta}$ (m/s)	80	80.6	81.2	81.8
θ (deg)	0	7.1	9.8	11.8
$p_{i\theta}$ (≅m)	326	331	336	341

The corresponding much lower vertical pressure component acting on a horizontal surface under these assumptions is Cp 0.5 $pu^2 = C_p h$. However, in section 2.4 the C_p factor was ignored for green sea pressures on hatch covers.

These nearly horizontal *gifle* shock impact equivalent pressure heads may seem unbelievably high, but they are of the same order as those determined experimentally by Denny (1951):

$$p_m \cong 28\ H \quad , \quad p_e \cong 100\ H$$

where H is the incident wave height, p_m is the most frequently occurring instantaneous green sea impact pressure head and p_e is the maximum extreme pressure head. The duration of these gifle peaks was on the order of 0.01 seconds and these pressures are local—see Fig. 14b. Taking H = 30 m as for the *DERBYSHIRE* calculations gives:

$$p_m \cong 840\ \text{m} \quad , \quad p_e \cong 3000\ \text{m}$$

Dividing by the 0.5 $\rho v^2 = 326$ m for θ = 0° in the above calculations gives C_p values of *2.6* and *9.2* respectively. Although such comparisons can be fortuitous, it will be seen these values are very close to the $C_p = 3$ and *9* derived for design from more recent data in section 2.4 (Faulkner and Buckley, 1997).

For interest, it can be shown that ignoring ship speed the ratio (R) of the square of the horizontal water speeds at the crests of breaking and non-breaking waves having the same celerity c = λ/T is approximately:

$$R = \left[\frac{k}{1 + \pi H/\lambda}\right]^2 , \ 2 \le k \le 4 \qquad \text{(vi)}$$

Taking values of k = 2, for spilling breakers and3 and 4 for plunging breakers and a limiting steepness of H/λ = 0.14 from the *DERBYSHIRE* calculations leads respectively to R = 2.7, 6.1 and 10.9. This illustrates how much more damaging are the crest-induced forces from breaking waves than from linear waves. R values greater than 5 have been confirmed from water tank experiments on vertical piles (Kjeldsen et al, 1986).

In passing, it can be noted that whereas water particle motions execute *oscillatory* closed loops in linear waves, in higher order deep water waves they are *translatory* or *progressive* in nature and have higher forward particle velocities.

It is suggested that naval architects should design vertical surfaces and fittings to withstand breaking or near-breaking actions from *spilling* breakers, and leave the *plunging* breakers to coastal engineers. Load criteria should be derived using Buckley's First Principles Methodology (outlined in Buckley, 1997). Data from Eilersen et al (1989) suggests that the probability of encountering these breaking waves might be taken as 0.4 p_e(H) as derived, for example, in eq(9).

Further work is required. A good starting point for researchers is the following references: Longuet-Higgins (1974, 1982) and Dommermuth et al (1988) based on two excellent doctoral theses from MIT (Chan, 1985 and Rapp, 1986). For aerated seawater, density is less and the gifle decay is longer.

APPENDIX B

NOMENCLATURE

Ship dimensions, etc.:

B = maximum beam
C = coaming or opening height above deck
C_b = block coefficient
D = moulded depth
F = freeboard approx. 6.9 m
GM = transverse metacentric height
I_θ = longitudinal mass moment of inertial of ship and cargo
L = length between perpendiculars
L_m, L_t = mass, trim point distance to LCF
Mct = moment to change trim one centimetre (tonnes metres)
Tpc = tonnes per centimetre immersion
T = mean draught
t = change in trim
V_c = compartment volume
Δ = displacement
δ = parallel sinkage
ρ = sea water density

Structural strength:

A_s = stiffener cross-section area
a = spacing of transverse stiffeners

b	=	spacing of longitudinal stiffeners
C_p	=	water impact coefficient
E	=	Young's modulus
L	=	length of panel, hatch cover
M_p, M_u	=	plastic, ultimate bending moment
M_t	=	tripping moment of stiffener
M_w	=	wave-induced bending moment
p_d, p_i	=	design, water impact pressures
p_u	=	ultimate pressure load
s	=	plastic shape factor
t	=	plate thickness
W	=	width of panel, hatch cover
w_o	=	permanent deflection at plate centre
Z	=	stiffener, ship minimum section modulus
z_s	=	stiffener centroid above plate
α	=	a/b plate element aspect ratio
β	=	$(b/t)\ (E/\sigma_y)^{0.5}$ plate slenderness
a_e, b_e	=	effective plate widths
σ, σ_o	=	direct stress, direct yield stress (min)
τ, τ_o	=	shear stress, shear yield stress

Wave environment:

A_c	=	crest peak amplitude above SWL
a	=	crest profile amplitude above opening
c	=	λ/T wave celerity = $gT/2\pi$
D	=	period used in analyses during which stationary conditions prevail
F(H)	=	cumulative distribution function of waves
f(H)	=	probability density function of wave heights
H, H_s	=	wave height, significant wave height
H_m, H_e	=	most probable, extreme wave heights
h	=	crest peak height above opening
h_b	=	maximum mean pressure head of crest profile as it passes over no. 1 hatch cover
L_o	=	horizontal crest length of an abnormal wave which passes over a small opening
m_b	=	mean back slope of abnormal wave crest
m_f	=	mean front slope of abnormal wave crest
N	=	D/T_p number of waves passing
$p_e(H)$	=	wave height exceedence probability p_e
T, ω	=	wave period, frequency
T_z, T_p	=	wave upcrossing, modal periods
α	=	A_c/H crest amplitude ratio
ε	=	band width parameter
γ	=	$1nN\text{-}2(H/H_s)^2$ probability parameter
λ	=	$gT^2/(2()$ length of gravity waves
ζ	=	wave amplitude above SWL

Orifice flow theory:

A_o	=	orifice (opening) area
a	=	time varying water head above orifice
c_d	=	discharge coefficient = 0.6 assumed
v	=	mean downward velocity of water column entering the orifice
V_h	=	total volume of water entering orifice during passage of wave crest of local peak height h
V_{iD}	=	total ingress volume during period D
V_i	=	V_{iD}/D ingress flow rate appropriate to D

Acronyms:

ALARP	=	As Low As Reasonably Practical
COST	=	Cooperation Scientifique et Technologique
DETR	=	Department of Environment, Transport and the Regions (previously DoT)
DFA	=	Derbyshire Family Association
DMI	=	Danish Maritime Institute
DSL	=	Deep Submergence Laboratory
EC	=	European Commission
FI	=	Formal Investigation
FPSO	=	Floating Production, Storage and Offloading
FSA	=	Formal Safety Assessment
GMT	=	Greenwich Mean Time (denoted by Z)
GoM	=	Gulf of Mexico
IACS	=	Intl Association of Classification Societies
ICLL	=	Intl Convention on Load Lines
IMO	=	Intl Maritime Organization
ISSC	=	Intl Ship and Offshore Structures Congress
ITF	=	Intl Transport Workers' Federation
ITTC	=	Intl Towing Tank Committee
JTWC	=	Joint Typhoon Warning Centre
LR	=	Lloyd's Register of Shipping
MAIB	=	Marine Accident Investigation Branch
ROV	=	Remotely Operated Vehicle
RTS	=	Revolving Tropical Storm
SOC	=	Southampton Oceanographic Centre
TD,TS	=	Time Domain, Time Series
TNT	=	Trinitrotoluene
WBT	=	Wing Ballast Tanks (topsides)
WHOI	=	Woods Hole Oceanographic Institution

Discussion

Neil Hogben, Consultant, British Maritime Technology, Ltd.

This paper is the latest in a series of outstanding contributions by Prof. Faulkner to the investigation of the loss of the *Derbyshire*. I am honored that my involvement in reviewing an earlier paper is acknowledged and pleased to note a number of citations of my work in support of the arguments, on which I now offer some comments.

Particular mention is made on page 6 of the bringing together of independently derived wave data reported in Faulkner and Buckley (1997) forming the basis for the survivability and operability envelopes plotted in Fig. 4 of the present paper. The relevant section (pp. 9 and 10 of the above reference) contains a distillation of material from correspondence I had with Bill Buckley.

This showed that the lower part of the operability envelopes in Fig. 4 ($H_s \leq 10$m) are in remarkably close agreement with formulae on page 303 of the paper cited as Hogben (1990). It also noted the consensus of support for Equation (1) which is the basis for the lower part of the survivability envelope ($H_s \leq 14$m). It may be of interest to add here that, as mentioned in my correspondence with Bill Buckley and also noted on p. 317 of Hogben (1990), the steepness limit defined by Equation (1) corresponds closely to the condition

$$H_s/\lambda_p \leq 0.05$$

where $\lambda = (g/2\pi)T_p^2$. T_p^2 is the length of a wave with period T_p. Furthermore, using the common assumption that T_p is related to zero crossing period T_z by

$$T_p = 1.4\ T_z \text{ (open ocean)}$$

so that the corresponding wavelength $\lambda_z = \frac{1}{2}\lambda_p$, the condition may be expressed as:

$$H_s/\lambda_z \leq 0.1$$

This relation is widely accepted as defining an upper boundary for measured populations of H_s and T_z.

Regarding the upper part of Fig. 4, mention is made in Faulkner and Buckley (1997) of data from an extreme North Sea storm cited in Hogben and Tucker (1994) for which H_s = 13.6m and T_p = 13.44s (derived from T_z = 10.5s using limited fetch relation $T_p = 1.28\ T_z$). This storm is thought to be the severest ever recorded in the North Sea and it will be found that the above H_s and T_p values plot exactly on the survivability envelope at the point marked (a).

My final comment concerns the mention on page 7 of my support for Equation (4) of the present paper in my discussion of an earlier paper (cited here as Hogben 1997). In fact I offered support for the more general formula Equation (8) (Equation (15) of Hogben 1997) which as noted leads to Equation (4) when P_e = 1%. To avoid confusion, however, I should mention that due to a printing error my support was wrongly attributed to the formula, Equation (7) (Equation (14) of Hogben 1997).

Additional reference

Hogben, N. and Tucker, M.J. 1994. Sea State Development During Severe Storms: Assessment of Data and Case Histories. *Underwater Technology*, Vol. 20, No. 3.

John B. Caldwell, Member

This is a fascinating account of a remarkable piece of *post mortem* naval architecture. It reinforces the writer's view that more can be learned about safety through detailed studies of individual failures, than by the mere compilation of casualty statistics. It is only by identifying that chain of events which culminated in failure that remedies can be properly directed to the defective links, whether they be in design, construction, operation or management.

It is unfortunate that the three assessors could not finally agree on the event chain in this case, despite the formidable arguments and analyses presented by the author. The case for suspecting that overloading of the hatch covers led to the fatal flooding was first put forward, very convincingly, by Dr. E. Corlett about 13 years ago; but the obsession then with alleged structural weakness at frame 65, together with persuasive advocacy of other possible scenarios, seems to have distracted attention from the hatch problem. This paper has not only laid to rest many of these alternative speculations, but has refocused attention on a serious weakness in ship design.

In so doing, the author has also shown the futility of relying on acceptable stress (especially if related to UTS) as the criterion of structural acceptability. Our codes of practice *must* now recognize the superiority of limit state design, and the author shows well how this can be applied to hatch cover design. Such procedures must be adopted as a matter of urgency.

Classification societies may be less easily persuaded to the author's views on overall longitudinal strength, despite the rather alarming findings in Section 2.3 of this paper. The IACS standard S11 purports to take account, in its formulations of design conditions, of dynamic nonlinear response to waves of very low (10E-8) frequency. Moreover, because ship failures due to defective longitudinal strength appear to be so rare (as noted in Section 1.5 for bulkers), current standards do not appear unduly suspect. Had they been even 40%—let alone 80%—too low in their requirements for the section moduli of hulls, having shape factors rarely exceeding 1.4, there would surely have been more incidents of overall hull failure. Perhaps the author could elaborate his beliefs in this regard?

Space limits prevent further comment on this admirable paper, which, as a major contribution to safety at sea, will surely be much in demand. A long print run is recommended!

William H. Garzke, Jr., Member

We on the Marine Forensics Panel would like to commend Doug Faulkner for this paper on a very controversial subject because we know that assessing a ship loss is not an easy assignment. It takes many hours of painstaking research, examination of evidence and tests to determine the sequence of events that caused a vessel casualty. In this discussion, I would like to comment on those procedures and the brittle fracture references made by the author.

The analysis of a ship loss can be likened to the ship design spiral. One will close slowly toward the solution, but never actually have all the pieces of the puzzle because you are dealing with an indeterminate problem. Much of the evidence is circumstantial and needs confirmation as the pieces of the puzzle are slowly put together.

In many cases, particularly the current one, the three basic premises that the author outlines on page 21 of the paper are sound principles that govern a marine forensic analysis. Lemma one and two are most important and are clearly seen in the wreckages of the *Titanic* and the German battleship *Bismarck*.

The bow portion of the *Titanic* wreck looks like a ship because that portion of the ship took two hours and 40 minutes to fill with water. This is an example of Lemma one. The stern, on the other hand, had compartments that were tightly sealed and intact. When the stern was pulled under quickly these compartments sustained heavy implosion/explosion damage. The stern of the *Titanic* has the outline of a ship, but it resembles a junkpile to the observer. The latter is an example of Lemma two. The *Bismarck* wreck shows little explosion/implosion damage because the hull was almost filled with water before she made her final plunge to the bottom.

The analysis to date regarding Lemma three indicates that the bow and stern portions of the *Titanic* arrived on the seabed at different times due to dissimilar terminal velocities. The latter is important because little is known in naval architecture about terminal velocity of ship wrecks arriving at the seabed. Knowing the terminal velocity is important in separating the damage that caused the ship to sink from that caused by the sinking process. The only tests done on terminal velocity were accomplished in Germany in 1969-1970 when the German designers were concerned what would happen to the reactor vessel if the nuclear cargo ship *Otto Hahn* sank. This points to more testing of ship sinkings to determine the attitudes that a sinking ship may go through so there is a better understanding of the forces involved in the sinking process. However, all of this points out how a ship sinking of 86 years ago can be of assistance in understanding one that took place 68 years later.

The condition of the bow of the *Derbyshire* would indicate that it had filled with water before the ship sank because it shows no sign of explosion/implosion damage. The author proposes a different scenario of how the bow flooded than did the official assessor report. However, who is right? This is a dilemma faced by a marine forensics investigator. Several theories are plausible and the correct one, that is the actual sinking, cannot be seen. This leads to speculations that must be gleaned from a survey of the evidence, casualty and service data of the ship, and the application of theory and/or test data. This leads me to a question on simulations. Recently a large amplitude motions program has been developed to better assess ship loads and motions. In the author's opinion, would this have produced a better simulation of the ship responses than the use of the program SCORES?

Sinking of ships in waters less than 400 ft exhibit different properties than those in the deep oceans. The bows of the *Lusitania* and *Britannic* show heavy damage from a pivoting action on the seabed. They sank in 300 and 400 ft of water and were vessels larger than the depth of water in which they sank. Although the 500-ft cruise liner *Oceanos* that sank off East Africa in 1994 has yet to be examined, it is speculated that her bow sustained damage from the sinking process. She sank in 300 ft of water. The wreck of the *Edmund Fitzgerald* poses a challenge to a marine forensic analysis. The bow is upright and in good condition on the seabed, while the stern is upside down and intact. The center section shows extensive implosion/explosion damage. What could have happened? It appears that the stern section capsized during the sinking process due to the fact that 75 ft of her Spar Deck was still attached. The wreckage of the *Derbyshire* offers us another look at the loss of the *Edmund Fitzgerald* and what her last moments above the surface might have been.

Prof. Faulkner makes a very important recommendation in his paper concerning limit state design. Hatch covers are critical for the integrity of a ship, yet differ significantly from most other ship structure in that they are not part of a continuous redundant structure where failure of one member can be compensated for by neighboring members. Furthermore, the lack of continuity at the edges precludes the structure from developing an overload capability that membrane action provides to other structures, particularly bulkheads. The nominal design head of water used for hatch covers can be easily exceeded as Prof. Faulkner has demonstrated, but the designer should not rely on the use of conventional factors of safety to ensure structural integrity. The limit load should be determined for the actual structure and the design then based on an assessment of structural reliability.

Extensive use of structural reliability methods for the design of ship structure has been hampered by the lack of a reliability goal for overall ship structure. In the case of an isolated structure such as a hatch cover, there should not be such an impediment for several reasons.

- A little judgement on the consequences of failure should be able to produce reasonable target reliability. I would think that for an independent structure with high consequences of failure such as a hatch cover, a probability of failure of at least 10^{-7} should be achieved.
- The weight of major members should be relatively insensitive to the target reliability, if a reasonable level is reached.
- The instances of high loading on hatch covers are rare in the lifetime of a ship, and are therefore more amenable to reliability analysis than hull girder bending, which occurs continuously during ship operations.

An estimate of conditional probability of failure for redesigned hatch covers of 10^{-2} is given in the paper. This seems high, even considering 12 hours of storm loading is an extreme event. What would the impact be of a lower probability of failure, say 10^{-3} or 10^{-4}?

The study of reliability-based structural design has centered on primary hull structure, and little attention has been paid to secondary structures such as hatch covers. The U.S. Navy is now embarking on an ambitious multi-year effort to investigate the reliability of structural bulkheads. This is a very much-ignored subject, yet critical to the survival of a damaged ship. Can Prof. Faulkner provide any estimate of the probability of failure to transverse bulkhead 339 from hydrodynamic loading, excluding the possible impact from liquefied iron ore?

The recommendation on changes to steel selection practices made by Prof. Faulkner is not well supported by either his reasoning nor by the evidence presented from the investigation of this wreck. The principal finding seems to be the occasional appearance of straightline fractures. Such fracture surfaces can come from a variety of causes, and in general from any unstable crack growth. Unstable crack growth will occur in any steel as long as the material tearing modulus is exceeded by the applied tearing modulus, no mater how tough the material. The high stress loads associated with breakup of the ship as well as collapse of compartments under hydrostatic pressure can easily lead to rapid fracture that will produce straight crack fronts.

One of the primary points of evidence that Prof. Faulkner presents as supposed evidence of brittle failure is the horizontal crack in bulkhead 339. Such failure is most likely to occur from the presence of a stiff supporting member. What is the structural configuration at this point? Another likely cause of such a failure can be an improper weld Prof. Faulkner states that he believes that there is a horizontal weld seam at that point, but I would ask if the examination of the wreckage has been in sufficient detail to determine the actual location of the weld compared to the failure surface? Without the determination of structural configuration and the location of welds, there can be no support of any claim to brittle fracture unless the actual fracture surfaces are examined microscopically, an impossible task at this time because of corrosion to the fracture surfaces.

Prof. Faulkner should be careful in pointing to the failures in the steel plates as brittle fracture. There are tremendous forces developed in the implosion/explosion process. Further examination of the *Titanic* hull has caused a revision of thinking concerning brittle fracture failures in her plates since the bow wreck shows much ductile failures in terms of buckling even at low temperatures. Unless there are tests made to prove conclusively that the steel had brittle fracture tendency, we on the Panel would recommend refraining from such conclusions.

There is a significant difference between the grades of steel used for commercial and naval ship construction. The U.S. Navy only uses Grade D plating for hull structure, where IACS permits lower grades. There is even a greater difference in the toughness of steel selected for crack arrestor strakes; the U.S. Navy uses nothing other than HY-80 steel, not even permitting the very tough HSLA-80 steel in this critical application. The reasons for these differences are many, including a historical conservatism on the part of naval authorities. However, the science of fracture mechanics has not advanced sufficiently over the past 50 or more years that the Ship Structure Committee and other agencies have been diligently studying the problem to permit a true assessment of fracture for the tough materials used in ship construction. Contrary to Prof. Faulkner's contention, Grade A steel has a very high degree of toughness, so tough that assessment of toughness by such means as a valid compact tension for the critical stress intensity factor cannot be made. Could Prof. Faulkner please provide his definition of what constitutes a brittle material?

There seems to be much confusion in the paper between high loading rates on a structure and high strain rates of structural response. It is only high strain rates that can cause a change in material behavior. Water impact loading will lead to high loading rates, as Prof. Faulkner amply demonstrates, but because of the short duration of these impulses and their localized nature, they create significantly lower response at a much lower rate than the pressure pulse alone would imply. Prof. Faulkner also implies that the same phenomena of high initial pressure pulse occurs in the liquefaction of iron ore cargo. Can he please cite any reference to validate this assumption or provide any other reasons why he believes that a dense slurry would act the same as a liquid continuum?

The loss of the *Derbyshire* is an excellent example of the problems that have befallen bulk carriers in the past 20 years. During that period over 1500 lives have been lost and this situation has become so serious that the IMO issued new directives that took effect in April 1998. With the successive exploration of the *Derbyshire* wreck in early 1997 and the analysis that followed by Robin Williams, R. Torchio, and Doug Faulkner in separate publications, we are now beginning to recognize why these ships are being lost or damaged in significant numbers—insufficient bow freeboard in heavy seas and hatch covers that re not designed to take the hydrostatic pressures from boarding seas that result from the low freeboard.

The bulk carrier is a one-compartment ship. If one of their forward cargo holds that is empty of cargo due to alternate loading becomes flooded, they will be subject to adverse bow trim that makes boarding sea more likely. In addition, the flooding water in one of these cargo holds could create hull stresses that would be above their design limits. Computations of a vessel's longitudinal strength, involving the flooding water, are not required by classification societies nor are they routine calculations in naval ships that are designed to survive damage. The Marine Forensics Panel became aware of the abnormal stresses arising from flooding in our work on the *Titanic* that Doug Faulkner has cited credit.

This leads our Panel to a recommendation on bulk carrier design. We agree with the assessors' report on the *Derbyshire* that these ships be required to have forecastles that will protect the forward hatches from head seas. We would like to add that these ships could be two-compartment ships for those areas around the forecastle to insure survival if the two forward hatches fail and allow flooding of their cargo holds. We also recommend that it be required to have the strength of these ships checked with two-compartment flooding forward to ensure that the ship will survive from a structural viewpoint. We would appreciate Prof. Faulkner's comments on these proposals.

William O. Gray, Member

Prof. Faulkner has given us a classic tale of how to solve a mystery. It can clearly stand alongside the best work of Sir Arthur Conan Doyle. Only the *Derbyshire* tale truly proves again the old adage that truth is stranger than fiction. To me, Douglas Faulkner's paper is extremely important for three reasons:

- It convincingly solves the specific *Derbyshire* mystery.
- It has direct relevance to the tragic loss of bulkers generally.
- It argues rationally for improved design criteria for ships generally because of its convincing treatment of "freak" or abnormal waves and the extreme "local" pressures they can cause.

To comment more specifically on the "how to solve a mystery" aspects, one should study carefully Section 1.5 on "Risk Assessment of Loss Scenarios," Table 2 and Figs. 2 and 18 presenting preliminary and final risk matrixes. Equally important is Prof. Faulkner's use of "Lemma's" 1–4 as tests against which to measure the physical evidence and to make deductions regarding causes of the various damages observed. Finally on this aspect of the paper is the distinction drawn in Section 5.5 between "initiating" and "terminal" events (i.e., what is merely serious and what is truly fatal). I believe Faulkner's strict adherence to the combination of these disciplines is the reason that he concludes that major inadequacy in the design criteria for *Derbyshire*'s hatch covers *and* hatch coamings is the most likely cause of her loss. It must also be emphasized that the consequence of abnormal waves, as described in this paper and in the 1996 Faulkner, Corlett and Romeling paper, has been confirmed by model tests at the Danish Maritime Institute showing extremely high loadings on hatch covers and especially hatch coamings. These clearly justify the recommended several fold increase in design criteria and use of ultimate strength analysis as well as prescriptive yield strength design and FEM analysis. The 1966 ICLL criteria to which the *Derbyshire,* and *most existing* bulkers are designed are clearly inadequate.

By contrast, the other assessors in the final official report seemed more determined to find an explanation showing that "the design (of hatch covers) was in accordance with ICLL 1966" (which was true but irrelevant) thus ruling out hatch over *design* deficiency. They instead concluded that "the most likely cause of the loss of the *Derbyshire* was that the spaces forward of the collision bulkhead . . . became flooded over a period of time" . . . and "this flooding resulted in substantial reduction of freeboard . . . at the forward end" . . . and "As a consequence the forward hatch covers were subjected to considerably increased wave heights and dynamic pressures . . . in excess of design parameters, resulted in failure of the hatch covers and subsequent foundering of the vessel." Prof. Faulkner's analysis clearly demonstrates that fore end flooding was a secondary factor. It also provides a very plausible explanation for possible causes of fore end flooding (based on an anchor windlass being washed away), rather than the unsupported speculation in the official report regarding possible lack of good seamanship as regards an undogged stores hatch cover and ventilation of forward bunkers through uncovered manholes. These unsupported assertions by the official report must be highly offensive to the *Derbyshire* Families Association who lost 44 loved ones in the tragedy.

So what is the relevance of Prof. Faulkner's findings and recommendations? I'll only comment on a few of them, but all recommendations deserve urgent attention particularly by class societies and IACS. I strongly support that:

1. The criteria for designing hatch covers, and *coamings,* must be substantially improved (by several fold). Some points to note in justifying this are:

- Until this *Derbyshire* work, hatch covers and coamings have been paid little or no attention, despite nearly ten years of study of bulker losses looking at all other parts of their structure.
- On the positive side IACS has on Sept 11 of this year submitted proposals to IMO's MSC on forward hatch cover strength along Faulkner's lines, but no mention of coamings is made.

2. Something should be done about hatch covers of existing ships. As Faulkner has demonstrated, deficient hatch covers (and/or coamings) may be the leading cause of bulker total losses and lives in recent years (up to 30–35% and perhaps more).

3. The marine world as a whole should re-examine the issue of bow height and/or forecastles or raised fore decks. From my own experience of VLCC's in the late '60s the reduced freeboard permitted by ICLL 1966 (which produced T/D of 0.79–0.80 for large pre-SBT tankers) was a mistake. We had ships being swept clean on deck forward in just ordinary heavy weather without the masters' being aware of damage while it occurred. Of course, with SBT increasing tanker freeboard by about 50%, and with very small deck opening on tankers, this is much more an issue for bulkers now than tankers. In words which Faulkner describes as "their most sensible in the whole report" even the two official assessors said, "Regardless of the actual initiating event, the *Derbyshire* case illustrates quite clearly how the hatch covers are a front line of defense against water ingress. Their failure inevitably would lead to the loss of such vessels and must be treated in the same manner as the main fabric of the hull structure."

A closing observation on extreme waves may be in order. One often hears of ships "designed for this or that specific trade," and the LoadLine system assumes some areas are inherently more hazardous than others (i.e., winter North Atlantic). These are "good generalities, but lousy specifics." Much experience has shown that extreme conditions can be encountered just about anywhere (one of the "Queens" in the North Atlantic and many tankers/bulkers/liners in the Agulhas current off South Africa). The probability of extreme conditions is no doubt lower in "good weather" areas, but it's not low enough to discount the design criteria. And ships being mobile, as all are, seldom spend a lifetime in "the trade for which they were designed."

As I've watched this tragic *Derbyshire* story unfold, I was struck by a number of parallels in recent marine disaster reports wherein it seems to this outsider that there is a tendency to fit the data to a preconceived conclusion(s) rather than to objectively study *all* the data and only then decide what is the most plausible explanation. We surely will not improve matters at all to the extent that we seek mainly to justify existing practice.

I apologize to the author for neither asking any questions, or criticizing this work, or bringing any new data to my remarks as "legtimate" discussers are supposed to. He has covered the subject so thoroughly that I can only say "well done" and Q.E.D. I hope many take the time to read, and *act,* upon Prof. Faulkner's work.

C. W. B. Grigson, Visitor

Prof. Faulkner tells part of a singular history: that beyond reasonable doubt weakness of hatch covers sank the ill-starred *Derbyshire.* However, this is not agreed to by the IACS. Lloyd's Register (1998) states that research has identified the main problems and developed remedies for the bulk-carrier casualties; but that weakness of hatch covers is "speculation." Of the many bulkers in class since 1970, only seven cases of hatch damage out of 249 can be attributed to heavy weather. In the new unified IACS requirements, considerable reinforcement of bulkheads on old vessels is mandated, but their hatch covers need no strengthening. Nevertheless, Rule URS21 is to be applied to new bulkers and lays down strength increase for forward hatch covers by a factor of at least two. Again, the official report on the survey of the wreck (MV *Derbyshire* Surveys, 1998) disagrees with Prof. Faulkner. Flooding of tanks in the bow was the cause of the loss.

There is no analysis in Lloyd's Register (1998), nothing about effects of extreme waves. Nor is there any analysis in MV *Derbyshire* Surveys (1998), although an account of "the circumstance of the loss in more descriptive detail" is included. This is admittedly not fact but fiction. Yet the main author of that official report, R.A. Williams, wrote with Prof. Faulkner *Design for Abnormal Waves* (Faulkner & Williams 1996) in which our knowledge of structures and of storm weather was brought together and an analysis of loading caused by extreme seas is given. The sinking of the *Derbyshire* was discussed and already in 1996 it was shown that the cause of the sinking was collapse of hatches by the force of the waves. The statistics of storm waves are today well understood, and for the design of oil platforms the knowledge is accepted and applied. The storm which sank *Derbyshire* raged for 36 hours with significant height of the seas 14 meters. About 9600 waves swept over the ship; several of these in each hour were tall and heavy enough to smash the hatch covers, and it only has to be done once. The ship was in dense ore, ¾ of the volume of the holds empty. That paper also showed from experiments in the Danish tank, that designs like *Derbyshire* do not rise to, but bury their bows in the oncoming combers. The case for cover weakness as the root of the loss was made beyond reasonable doubt. Nevertheless, writing the official report in 1998 with R. Torchio, the assessor for the European Union, Mr. Williams has been persuaded that there was a loss of 7000 m^3 of buoyancy in the bow of a ship displacing 200 000 m^3, and that this was the cause of the sinking.

The earlier Faulkner and Williams analysis is so complete that no underwater survey of the remains was really necessary. However a scenario due to Bishop et al (1991) took hold. Founded on linear vibration theory, vast computations seemed to show that in storms serious weakness existed in parts of the hull and it was supposed that stern and deckhouse broke from the main hull at frame 65, and that this caused the sinking. For good measure, the authors claimed that their result was general and that *all* large bulkers were dangerously weak in similar regions in storms. In the discussion of the paper, Corlett pointed out that the correct structure of *Derbyshire* had not been used in the computations, but a single-skin one and not the much stronger double-skinned hull of the actual design. Such is the mesmerizing power of the supercomputer that this overriding objection to the Bishop et al contention was ignored. No explanation was given (or could be) in the reply to the discussion. Later the Bishop hypothesis was included in Lord Donaldson's Formal Safety Assessment with high probability, even though no such break-up of a very large all-aft ship had ever been recorded.

As Faulkner's new paper relates, the underwater survey, in which he himself took a principal part, was most valuable, not for determining the cause of the loss, but for proving as false many possible scenarios: for one, the hull did not break at frame 65 before sinking. But the survey could not determine which of the remaining possibilities was the cause of foundering, because the sequence of events at the surface which caused the sinking could not be decided from the shattered remains on the seabed. To ascertain the reason for the loss of a nearly-new very-strong double-skinned vessel, one must analyze the strengths and weaknesses of the design in relation to the forces in a storm lasting 36 hours with $H_s = 14$ m. If hatches fail under a load of 4 tonnes/m^2, and there is no dispute that this was the collapse load, Faulkner is definitive: no bulkship can remain watertight in such extreme conditions.

Faulkner's Lemma 5 is important, as it brings out a surprising logical error in the attribution of causes to casualties. In Lloyd's Register (1998, Table A4) 109 bulk, ore, O/O and O/B/O ships are listed which are thought to have suffered serious structural damage between Feb. 1990 and Feb. 1998. Forty-four of these were lost, including eight *large* ships which disappeared. The table says that in heavy weather one vessel displacing 90 000 tons sank (3, 1990) because a *ballast tank flooded;* another displacing 140 000 tons sank (3, 1992) because the *engine room flooded.* Williams and Torchio say the *Derbyshire* sank because *small bow spaces flooded.* Yet if the hatch covers had had adequate strength and remained watertight these large vessels would have been afloat when the sea calmed. The true cause of the sinking is cover weakness, dictated by the infamous 1966 ILLC Rule, which required elastic support for no more than 1.75Te/m^2.

Prof. Faulkner's independent assessment shows more comprehensively than the one in 1996, why, when bulkships in dense ore sail into a typhoon, the consequences are often terminal. He has done a great public service. Moreover this has been done in the teeth of an authority determined to silence him. Because in the words (Hansard 1997) of a Government Minister. Miss Glenda Jackson at the D.E.T.R.: ". . . Faulkner's active promotion of the theory that the *Derbyshire* sank when her hatch covers gave way *is a matter of dismay for the Department.*"

Additional references

Bishop et al. 1991. A Theory on the Loss of MV *Derbyshire. Trans. RINA.*

Faulkner, D. and Williams, R.A. 1997. Design for Abnormal Waves. *Trans. RINA.*

Hansard. 1997. Report of debate in the House of Lords, London, 3 Dec., p. 1458.

Lloyd's Register. 1998. Bulk Carriers, an Update, March.

MV *Derbyshire* Surveys. 1998. UK/EC Assessor's Report, A Summary, DETR, London.

Charles V. Betts, Visitor, UK Ministry of Defence

The loss of the *Derbyshire* has led to a greater level of enquiry and controversy in the United Kingdom than any other cargo ship casualty since 1980, apart from RO/RO ferries. Bulk carriers continue to be lost regularly and impressive papers such as this make an essential contribution to overcoming this near-scandalous situation.

Prof. Faulkner, as an international authority on ship and offshore structures, was an obvious choice to assist with the formal investigations and it is unfortunate that a difference of view appears to have arisen between him the UK/EC Assessors. On the other hand, the debate arising from such differences can often be productive in arriving at the truth.

I confess that I have not read the assessors' reports published this year by the DETR. With that proviso, I must say that I find the conclusions, and particularly the recommendations, arrived at by Prof. Faulkner as entirely persuasive. Above all, the case for a substantial and urgent improvement in hatch cover strength seems incontestable. Retrofitting of stronger hatch covers to existing bulk carriers should certainly follow, on moral as well as overall economic grounds.

As regards the loss of the *Derbyshire* herself, hatch cover collapse does appear to be the most probable direct cause. However, to be "beyond any reasonable doubt" (Section 6.3) is a very tough criterion. I do not follow the case for entirely "ruling out" cracking at Frame 65. Structural details in that area seem to have been poorly designed and build and in my view the analysis of Bishop et al, even if not wholly accurate, did demonstrate the threat posed to overall strength. The author argues that no other bulk carriers have broken in two (Section 1.5) yet a significant number have been lost without known cause. The fact that the bow and stern of the *Derbyshire* were found only 600 m apart could imply merely that separation took place immediately before they sank. The bow would probably be depressed as the ship broke in two making the hatch covers even more vulnerable to the sea. Implosion/explosion of the adjacent tanks (Section 5.3) would depend on how the breakage occurred: does not the fact that Bulkhead 65 is double-skinned and missing (Section 3.3) leave this question rather open? Whatever the answer, I am pleased that the author includes a recommendation to improve the type of detailed design found at Frame 65.

H. Inoue, Visitor, Overseas Shipbuilding Cooperation Centre

I would like to pay my respects to all of the people that promoted and achieved the investigation into the cause of the wreck of *Derbyshire.* Findings obtained in the light of advanced technologies are amazing. I believe that discussions on the findings will surely contribute to promote safety at sea.

In 1980, a Japanese bulk carrier, *Onomichi-maru,* also wrecked in December, about 1000 km off of Nojimazaki. In this case all the lives were saved fortunately, and the ship was afloat, though her forebody was lost soon. The Japanese Ministry of Transport attached importance to the wreck, and tried to tug her to Guam. However, she sank a few days before the date of her arrival, about two months after the wreck.

The Ministry of Transport organized a committee to investigate the cause. The committee was chaired by Prof. Yoshiyuki Yamamoto, and I was one of the members.

The first officer, who watched in the bridge, depicted the situation at the moment of the wreck in detail. Pictures of her forebody just after the wreck and many pictures taken during tugging were available. The officer's witness and many pictures were our start point.

It was obvious that she encountered an abnormal wave, and that she slammed to the wave and the deck around No. 1 cargo hold buckled. The committee worked for about half of a year from April in such fields as specific feature of the weather in the region, other cases of ship wreck in the region, wave load, hull strength, materials, etc. The committee report was published in November 1981. Many problems to be investigated were pointed out for explaining the case.

Many research works were devoted to the problems for the next five years. The main feature of the research work was the mechanism of slamming load and fracture mechanism of the forebody. Prof. Yamamoto explored a simulation program of slamming, and experiments on slamming were carried out at the Ship Research Institute. The mechanism of fracture of the forebody was investigated experimentally at the Ship Research Institute.

On the other hand, in the case of *Derbyshire*, the investigation had to start with circumferential evidences. In spite of this, it is amazing that 13 loss scenarios were written and one of them was supported by the findings of the EU/UK expedition.

In the course of the investigation of the *Onomichi-maru* case, I interviewed several masters to ask if they experienced bow slamming in laden condition. A master told me that he managed to avoid slamming by any means, but there had been a situation where slamming was unavoidable in passing a straight. His ship was a bulk carrier of about 50 000 dwt, not as large as the *Derbyshire*.

I now understand that the slamming was not the initial event from the findings by the Phase 2 Survey. However, would you tell me the reason why you ruled out the "slamming" at an early stage in writing the scenarios?

Some hatch covers were found folded outward, and that may be an evidence that the covers were not broken by the waves. I suspect that the hold might have flooded as the ship dived deeper, and when the pressure in the hold reached almost to the external pressure, the air escaped, blowing up the covers. I will be much obliged if you let me hear your opinion.

Douglas Brown, Visitor, Consultant Naval Architect, Inverclyde, U.K.

Referring to the underwater investigation, can the author clarify if any search was undertaken outward of the immediate wreck field, for instance, back along the probable track of the *Derbyshire* from her last reported position?

If so, were there any significant findings of interest?

Carl Arne Carlsen, Det Norske Veritas

[This discussion was prepared with assistance from Dr. H.O. Madsen, Dr. S. Valsgård, Mr. R. Loseth and Mr. W. Magelssen, all of DNV.]

We wish to commend Prof. Faulkner for a thorough study that promotes safer ships. The studies performed in the aftermath of the *Derbyshire* sinking and the site survey have created new knowledge, which no doubt will be implemented in international rules. The discussion is organized according to the recommendations offered in the paper.

The prime recommendation in the paper is a substantial revision of the 1966 International Load Line Convention (ILLC) requirements as regards hatch cover strength for all covers. We agree that hatch cover loads based on the ILLC leads to too weak designs. The consequence of this has been included in DNV rules already and later in unified IACS requirements. Following two tragic ship accidents in the 1970's, DNV, in 1976, introduced external hatch cover loads varying over the length of the ship and significantly increased requirements compared to the ILLC requirement, in particular, for the forward hatches. In its work for improved bulk carrier safety, IACS has introduced new unified requirements for hatch cover loads, which have been applied by IACS members since 1 July 1998 to new bulk carriers.

Following the studies by Prof. Faulkner about typhoon condition loads and abnormal waves, a working group in IACS has performed a careful comparison between such loads and the normal design loads based on North Atlantic conditions. This work was submitted to IMO, IACS (1998), and concludes that green sea effects from the North Atlantic design conditions are at least as severe as from the typhoon condition based on available data from the Typhoon Orchid. More work on this issue is in progress in IACS and DNV. The DNV work applies the SWAN programs, which at present are the most advanced nonlinear load programs available. In addition to evaluation of nonlinearities, the SWAN analyses also provide a full picture of the pressure distribution over the hull. The effect of weather routing and the status and effectiveness of weather routing systems is an important but difficult part to include in these studies.

The paper suggests that an allowable stress criterion does not represent a logical ultimate strength criterion. We agree to this, and in 1967 DNV therefore introduced buckling requirements to hatch cover plates. Neither IACS nor DNV has yet introduced a more complete ultimate strength criterion for hatch cover strength. Dynamic analysis to account for the time varying pressure can be performed, but elasto-plastic analysis will probably be sufficient for practical purposes.

The cost of increasing hatch cover strength is relatively small as also observed by Prof. Faulkner. A cost benefit analysis is appropriate to compare the additional cost of even stricter strength requirements versus the expected reduced losses from hatch cover failures. Different conclusions may be arrived at for new designs and existing ships.

The paper suggests that all Type B freeboard ships should have a raised forecastle head with high bulwarks and a substantial breakwater. This recommendation is under evaluation by IACS as part of a Failure Mode Effect Analysis of the watertight integrity of the fore end of bulk carriers.

The paper suggests that ship bending moments from abnormal waves may substantially exceed the present IACS unified standard. This suggestion is partly based on results of a study for a FPSO in the North Sea. This study was made by an ISSC committee as referenced in the paper. It is certainly the case that the design bending moment requirements for stationary FPSO's in the North Sea are stricter than for ships trading worldwide. A working group in IACS has compared the bending moment for the Typhoon Orchid condition with the IACS requirements. The conclusion is that the typhoon condition gives a smaller bending moment than the IACS North Atlantic design condition due to the very steep and short extreme typhoon-generated waves.

Prof. Faulkner rightly points to the need for further studies of the loads on hatch coamings even though hatch coaming failure was not the probable cause of the *Derbyshire* sinking. IACS has already initiated such work.

We support the recommendation of Prof. Faulkner about restricted use of grade A mild steel for hull and weather deck structures and fittings. Indeed, DNV makes a general check of fracture toughness of grade A mild steel in connection with its approval of manufacturers, although fracture toughness testing is not made for each batch.

Prof. Faulkner points to the need for consideration of dynamic impact from the mobility of saturated ore cargoes. We do not have damage experience suggesting this to be a major problem. We can nevertheless agree to the need for revisiting the IMO requirement to relative humidity versus the humidity level, which can cause liquefaction of the upper part of the cargo, as well as the need for reassessing the test method.

Prof. Faulkner briefly touches upon the possibility to design new efficient life saving equipment for situations where sinking takes place very rapidly. Ideas to this effect were proposed following the two accidents in the 1970's mentioned earlier. None of these ideas were implemented, but the actions were concentrated on increasing the design pressure on hatch covers. It is certainly worth reconsidering some of the suggestions made at that time—some of which were of completely novel nature.

Finally, we strongly support Prof. Faulkner in his recommendation of the use of Formal Safety Assessment in the rule-making process, both for ship design and operation. In the paper Prof. Faulkner has clearly demonstrated some of the benefits of a FSA not only in identifying the most probable cause of the *Derbyshire* sinking, but also in identifying "near misses." We also share his opinion that some guiding principles for forensic analysis of shipwrecks should be made in the light of the tremendous possibilities proved by the new survey methods.

Additional reference

IACS. 1998. "Bulk Carrier Safety," Comments on the Paper (MSC 69/2/1/Add.5) re *Derbyshire* as submitted by the United Kingdom to the 69th Session of the Marine Safety Committee. Submitted to IMO Marine Safety Committee, 70th Session.

Walter M. Maclean, Member

I would like first to thank the author for providing us with a most thorough and fascinating account of his assessment of the *Derbyshire*'s tragic loss. It is not often that such a comprehensive survey of a marine loss is undertaken and to have it assessed and so lucidly presented to our membership is an even more rare event. Although there are many aspects of this case that I would like to remark about, time will only permit me to address a couple of them.

First, I am delighted the author has pointed so clearly to the inadequacy of design loads and the philosophy for the forward hatch covers. Some months after the *Derbyshire* loss with all hands, another vessel was similarly lost in another ocean under Beaufort 11-12 conditions, the forward hatch covers being overcome by massive green seas. The vessel carried a cargo of steel resulting in a high hold permeability. With a flooded hold and fore deck awash, the master skillfully turned his vessel stern to the sea and headed back to port some 300 miles away. Accompanied by another vessel steaming a mile away, the vessel, with no more reserve buoyancy forward, plunged into a wave trough and disappeared in less than a minute, carrying all hands with it. No lifeboats were prepared for launching, no crew members were on deck in life jackets anticipating the disaster.

Two hatch cover segments, one from the No. 1 hold, floated ashore and were subjected to inspection, design load testing and structural analysis. Their condition was generally excellent and the tested segment sustained the design load with deflections closely as predicted. I believe the lessons to be learned from these two losses is not only that the hatch cover design criteria and philosophy were inadequate to the service requirement, but that the master and his seamen were poorly served by not being made adequately aware of the seriousness and tenuous nature of their position when such events occur. Whereas seamen are considered to be knowledgable and skilled, that is often not the case when serious conditions arise. In this later case, all of the crew came from the same community so their loss was doubly tragic.

My second aspect of interest has to do with the author's remarks concerning vessel routing services. In my mind, there is an unfortunate state of affairs in the maritime world, in that ship and cargo owners insure their risk in the marketplace, while the mariner insures his risk with his knowledge and skill. Whereas maritime education and training attempts to lower the mariner's level of risk, weather routing can do so as well to a certain extent while at the same time it is improving the ship and cargo owner's performance potential. During the time of the *Derbyshire* tragedy, at sea experiments were ongoing to assess the validity of weather and sea state forecasting in the Pacific as well as elsewhere. While major advances were being made in sea state forecasting, these experiments identified deficiencies in forecasting the energy levels and directional distributions. The propagation of energy, particularly from the southern hemisphere, and modeling limitations used in forecast models tended to cause underprediction of wave environments, and accordingly the resulting vessel motions. Over the past 15 years major improvements have been made in this field and the technology for utilization has advanced remarkably. I suggest we all look at Paper No. 4 to follow in the next session. Even in 1980, we were able to do a lot better than when I was at sea.

Thirdly, I would like to commend the author for his strong call for more research into heavy weather operations. He has done an excellent job in pointing to current inadequacies. One point that has long bothered me has not been discussed, however, and I suggest it may be worthy of consideration. That is the design of dry cargo vessel bulkheads for sustaining sloshing loads as when a hold becomes flooded. Some years ago, Prof. Yamamoto pointed to the inadequacy of bulkhead design for dry bulkers that end up having compartment flooding forward. I am unaware that this problem has been adequately served as yet. I would appreciate the author's remarks on this problem area.

Finally, thanks again for giving us such a fine paper on such an important matter.

Author's Closure

Dr. Neil Hogben: As the wave definitions and statistics are so important, Dr. Hogben's very supportive remarks are much appreciated, as is the clarification provided in his last paragraph. The confirmation of the proposed *survivability envelope* for future designs is very helpful, as is the additional reference he provides.

Prof. J. B. Caldwell: Contributions from Prof. Caldwell are always perceptive, to the point and welcome. However, his first assumption is understandably wrong. As it has been raised by others and is crucial to understanding. I will lift the curtain a little more (see also Dr. Grigson's last paragraph and my reply). It was because of the curious and badly judged conditions placed on me that there was no opportunity for me to influence the other two assessors so that the event chain leading to the loss might be agreed. Williams and Torchio chose to arrive at this from the final survey evidence alone, whereas I believe this to be quite impossible because of the implosion/explosion actions and because much of the evidence is circumstantial.

Sadly, the best example of this relates to hatch cover collapse. It is not possible from the survey evidence to positively distinguish between those which imploded inwards during sinking and those which may have collapsed from wave actions before the ship sank. Moreover, it is also impossible from the wreckage to determine if the hatch covers are inadequately strong and by how much. Advanced analyses, as have been attempted in this paper, are necessary to support or refute several loss scenarios.

In relation to Caldwell's surprise that the 1987-89 formal investigation did not pay much more attention to the vulnerability of hatch covers, he is correct in referring to the FI's obsession with the alleged weakness at frame 65. One of the investigators on the FI has said this occupied 40% of the time (and certainly created more than half of the supporting documents). Ironically, even though the frame 65 scenario could have been absolutely ruled out from wreckage evidence before the final survey was half-way through, it nevertheless continued to dominate the precious underwater time to the detriment of other likely scenarios.

In relation to the 40% to 80% increase in wave bending, from approximately ship length waves, Caldwell is correct in pointing to the low incidence of overall hull failure. However, I can state that the *Derbyshire* would have survived an 80% wave-induced overload with a small margin. I also point out that IACS S11 implies regular ship length waves no more than 10.75 m high (determined by the factor C and by LST analyses) which can hardly be said to be satisfactory for withstanding extreme cyclonic storms. All that is suggested in Section 2.3 of the paper is that it would seem unwise to ignore the results of the two sets of TS studies (one by the ISSC). Improved nonlinear dynamic analysis responses to a range of large amplitude asymmetric waves are surely required. Having said that, my opinion is that present design methods do seem to be adequate, but by an unknown margin. See also Dr. Carlsen's contribution and my reply.

William H. Garzke: It is a privilege to have a major contribution presented by Mr. Garzke on behalf of SNAME's Marine Forensic Panel which he chairs with such energy and distinction.

There can be no doubt that validated large amplitude motions programs would lead to more accurate ship loads and motions than the SCORES program can (as in my reply to Caldwell). Every encouragement should be given to their development.

Before answering the questions relating to hatch cover reliability, the basic assumptions should be understood. Because the uncertainties in hatch cover collapse are negligible compared with those in wave height prediction, it has been assumed that the probability of failure is simply the probability of a single wave exceeding that required to give an equivalent uniform pressure greater than the value $p_c = 4.0$ m required to collapse no. 1 hatch cover. That is, p_f is the *probability of exceedance* for the corresponding wave height. The notional probability of failure might in general be a little higher because the systematic and random uncertainties in hatch cover strength have been ignored.

With the proposed safety or load factor of 3.0 it can then be shown that p_c is approximately 0.01 using the equations in the paper. This design level follows the widely accepted advice from Ochi. Reducing this probability level to 10^{-3} and 10^{-4} would increase the wave loadings on no. 1 hatch cover to about 3.6 p_c and 4.2 p_c, respectively. A value of $p_f = 10^{-7}$ becomes meaningless and is wasteful in material and cost. Providing relevant *survivability conditions* are specified (as herein) the 10^{-2} level suggested is quite adequate for survival. It is approximately equivalent to the probability of meeting a 35 m extreme wave in 12 hours during Typhoon Orchid.

No estimate has been made of the probability of ductile collapse of bulkhead 339 under hydrodynamic loading, as this was not considered to be relevant. Because of the complex supports and stiffening a reliable estimate would require inelastic FE calculations preferably linked to a SORM reliability program. Regarding the long horizontal crack, it can definitely be said that it followed a weld line, and was also in the vicinity of a horizontal deep web stiffener on the forward side of the bulkhead.

Several opinions are given and questions raised in relation to brittle fracture, including challenging my recommendation to avoid Grade A mild steel. It is possible that our understanding differs substantially, and in view of the restriction on space to respond, I merely reiterate:

- While grade A mild steel has improved in quality in recent years it still has no specification for notch toughness. Perhaps Garzke is not referring to mild steel as used by most class societies? Dr. Carlsen's discussion from DNV supports my recommendation.
- *Derbyshire*'s wreckage provides a lot of evidence of crystalline brittle fracture as confirmed by Sumpter and Burdekin from macro-photographs of fracture surfaces.
- Tests reported by Sumpter et al showed the *stress* peaks with no more than about 5 millisecond rise time, as would occur from nearby slamming and other dynamic loads, can reduce toughness substantially. Much earlier, Pellini and others showed the same effect with very high *strain rates,* as Garzke states.

It would seem that brittle fracture in detail may be a subject on which views differ.

I know of no evidence which validates my implied assumptions from Equation (14) regarding the effects of impact from liquified ore. Although density is clearly important, internal friction (viscosity) must play a part and may attenuate the pressure. Because of this Section 2.7 emphasizes the high level of uncertainty regarding the level of pressure in the hypotheses I advanced. Research is suggested.

I must also advise some caution with the statement that the loss of the *Derbyshire* is an excellent example of the problems that have befallen bulk carriers in the past 20 years. Firstly, the *Derbyshire* was a double-skinned bulker, whereas the vast majority have single side shells whose weakness to prevent water ingress in later life has been conclusively shown to be the most important initiating cause of the majority of losses. Calculations and evidence convincingly ruled out this possibility for the *Derbyshire.* Secondly, the *Derbyshire* had double-skin transverse bulkheads more than strong enough to prevent bulkhead collapse and the progressive flooding which has so often been the final act in many bulkers. Thirdly, *Derbyshire* was only four years old, whereas the majority of bulkers lost were over 15 years old. However, the lessons from the *Derbyshire* of hatch cover weakness and vulnerability to flooding at the fore end and aft end is transferable to bulker design generally.

Finally, I agree with the MFP recommendation that these ships should be able to survive longitudinal bending in the flooded condition. In the case of the *Derbyshire* she would have, but this may not always be so, especially for older corroded ships.

William O. Gray: Because of their vast and relevant experience, and to create a more international team, I had hoped to include William Gray and two retired USCG Admirals, Robert Price and Eugene Henn, to help in the final survey of the *Derbyshire.* Regrettably, this was not approved.

It is therefore particularly pleasing to have such a considered and supportive contribution from William Gray which neatly summarizes the main historical design weaknesses and the shortcomings of the official report. As far as the official suggestion of crew negligence is concerned, based on the alleged "unsecured" stores hatch cover, it *is* highly offensive and untrue. The evidence, when properly interpreted, indicates ingenuity and good seamanship in preparing for rough weather (see Section 5.3 C7 under *Deductions From Evidence* 7th indent).

Gray also makes an important general point, with which I totally agree, that ships should not be designed for a specific trade and route as they seldom spend their lifetime in it. For this reason, the *survivability* and *operability* envelopes developed by Buckley (and finalized with him in a joint 1997 paper) represent *global* conditions for the design of unrestricted operation ships.

It is of course flattering to be compared with Conan Doyle. But Sherlock Holmes was fortunate in creating or finding proof that did not require long drawn out and adversarial court proceedings. I fear this may not be so during the next formal investigation which is expected to start early in 2000. Vested interests may still cloud the truth, as happens so often. However, I have been told (in July 1999) by the Attorney General's office that this paper and its discussion will be important evidence and that I will be a key witness. So I am now rather more hopeful.

Dr. C. W. B. Grigson: Christopher Grigson spent much of his life in the design, operation and service feedback of VLCCs and other large ships. His perceptive contribution is very relevant. Like that from Gray, it offers no criticism and raises no questions. But it prompts me to make three comments.

First, Lemma 5 is really not mine but Grigson's! He suggested it when he read the first draft of my Section 5.5 which distinguished between initiating and terminal events.

Grigson's last paragraph refers to a letter read in the House of Lords from Miss Glenda Jackson, the Shipping Minister, when the Government changed and the DoT became the DETR. I wish to record that the article, which is alleged to have given the DETR such displeasure (Faulkner 1997b), was written before undertaking the final survey of the *Derbyshire* and owes nothing to it. It responded to the tragic loss of the bulker *Leros Strength* in February 1997. Moreover, extracts quoted from the previous *Derbyshire* experience were from papers by myself and others published with DoT approval.

Finally, I would not and did not resign because of any displeasure I may have given to the DETR. The Department had denied me access to survey photographs and it became clear that they wanted me out of the way. The real reason for this became clear later.

Charles V. Betts: As Charles Betts was one of the brightest students it has been my privilege to teach, I welcome his more philosophical yet relevant contribution. I have answered his first point regarding my differing views from the other two assessors in my replies to Caldwell and Grigson.

Betts refers to *cracking* at frame 65. Pre-existing cracking was certainly not ruled out and indeed exists in the wreckage, together with evidence of bad workmanship in the vicinity. But it is any subsequent *separation* at frame 65 which Betts questions, and my brief response related to ruling this out is:

- In 5.3 the first bullet in C1 provides the evidence which, with *Lemma 1,* absolutely rules out separation before sinking. I am not sure I can explain this more fully, except perhaps by referring to the contributions by Garzke, Gray and Grigson.
- Betts is correct in supposing that the close proximity of the stern and bow sections on the seabed would indicate that both would have sunk more or less simultaneously. If they were separate there can be little doubt the stern would have sunk very quickly, but the remaining intact 230 m of the ship would stay afloat much longer before being overwhelmed, even with the modest bow flooding that is likely to have occurred. The behavior of the stricken sister ship *Kowloon Bridge* is an example, and there are others (see the Inoue discussion).
- Moreover, it would be likely that the bow section would almost certainly come beam on to the wind and not remain in the hove to position seen on the seabed.
- Betts is right in saying many ships are lost without known cause. But, as Caldwell points out, there is very little evidence of primary hull failure being the cause—even less for a separation at the stern. The explanation is much more likely to be rapid sinking once no. 1 hold is breached through weak hatches or sides.

However, the first reason is also used in the official report and is now widely regarded as sufficient to rule out the frame 65 scenario. The families appear to have accepted it. Incidentally, the official report shows that most of bulkhead 65 *was* found (about 85%) and that the line of deck fracture fore and aft of frame 65 jumped all over the place and was consistent with the sequence of implosion/explosion actions.

Finally, regarding the Bishop et al analysis, the "horns of stress" toward the ends of the ship have been shown to be almost entirely due to still water loading, and are not particularly high. However, as Betts implies, the Bishop et al 1991 RINA paper did demonstrate the threat arising from the likelihood of bad workmanship. Many ships have similar design faults which must surely be improved.

H. Inoue: Hajime Inoue is a former Director General of the Ship Research Institute, Tokyo. He provides useful additional information relating to the loss of the 50 000 dwt bulker *Onomichi-Maru* which lost its bow from slamming actions, also in 1980. The three reasons this scenario was not considered for the *Derbyshire* are:

- She was a much heavier fully laden deeper draft ship whose dynamic response showed very low likelihood of slamming.
- Nevertheless, wave impact calculations were undertaken during the Lord Donaldson Assessment (1995) which showed that, even allowing for possible deck corrosion (scenario C6), there was plenty of reserve strength against total separation of the bow; it was nevertheless accepted that local dynamic-induced cracking of shell plating might occur (and there is some inconclusive evidence for this in the official report).
- At that time it was already known from the 1994 ITF survey that the bow was close to a lot of the wreckage plus strong circumstantial evidence that the stern was only 600 m from the bow.

This last finding would not be expected if the bow broke away; there would also then be more chance of a distress signal being sent and received, and for lifeboats and rafts being launched. I apologize that this was not referred to, mainly because it appears in a limited distribution report (D. Faulkner and R. A. Williams, Lord Donaldson's Assessment *(Derbyshire)*, Report Findings of the Technical Assessors, September 1995).

Mr. Inoue's explanation as to why some of the hatch covers were found folded outward is essentially correct, the large escape of air from the imploded/exploded compartments would have blown out any covers which may have been lodged in the hatch opening. But it does *not* follow with certainty that such covers were not broken by the waves, as they too might have been jammed in the hatch opening.

Douglas Brown: Two related and extremely perceptive questions are asked. It was not part of the final survey plan to extend the search back along the probable track of the *Derbyshire* from her last reported position. However, had we not found all the hatch covers, for example, then a wider search along such a track would surely have been undertaken.

But, the survey plan did include examination of the "Anomalies" to the southwest. Sonar images from the ITF survey suggested that these might have been a small ship or parts of a ship. In the event these were viewed and found to be volcanic mounds and pillow lava streams. Fortuitously, the route to the Anomalies was more or less back along the probable track of the *Derbyshire.*

A subsequent examination of these particular records revealed a sprocket wheel which is attached to a hatch drive motor. It was found about 4 km away from the remaining wreckage which suggests that it became detached from the ship not less than 30 minutes and not more than 1 hour before it sank. This is not mentioned in the official report but is in keeping with my additional loss scenario C14. It may have been struck and detached by a breaking wave, or by the loose starboard bow windlass before it was swept overboard. This chance finding is regarded as being very significant as it implies substantial weather or mechanical damage to a hatch coaming.

Dr. Carle Arne Carlsen: Dr. Carlsen's very supportive and comprehensive contribution on behalf of his DNV colleagues is most welcome. It is perhaps the most important of the many excellent contributions. I am naturally pleased to learn that DNV in particular, but also IACS, have and are reacting positively to several of the findings.

The reference he quotes has been followed up. However, while the pressure heads quoted have been increased from the ILLC requirements by a factor of about 3 based on tank experiments, the stress based safety factor has been halved! Thus the hatch cover strengths are only increased by about 50%, which is far from adequate. This matter will be taken up with IACS. I would also reiterate my belief that elsewhere along the length of the ship hatch cover strength should be increased by a factor of at least 2.5. I am pleased to note work has started on hatch coamings.

The studies of ship bending moments from unusual large typhoon waves are most welcome. It is to be hoped that the IACS working group results for Typhoon Orchid will be more fully published than in the reference quoted. I believe that worse wave bending conditions may well be experienced in northern and southern latitudes away from the tropics when these cyclones migrate north and south and can draw in energy from other depressions. Steep, elevated ship length waves can be generated. The 1995 experience of the *QEII* is probably a good recent example. I agree entirely that more refined analyses are needed.

Support for the FSA risk matrix is welcome, but I am particularly pleased to find such strong support for formulating guiding principles for forensic analysis of shipwrecks. The SNAME Marine Forensic Panel is in a good position to undertake this, and I would gladly help in this.

Walter M. Maclean: Prof. Maclean's contributions are always welcome because he quotes relevant service experience, and has served at sea himself.

Although his first example ended in a loss with all hands I do believe the master took the right course of action in turning to run with the sea. The ship's alarmingly rapid disappearance "in less than a minute" is a characteristic of ships with serious fore end flooding (Brown, 1997). It is hoped that IACS and IMO put out a directive for bulk carriers to avoid serious storms until their hatch covers have been changed or substantially strengthened.

Walter Maclean's comments about improved weather forecasting are certainly encouraging, but it is the weather routing advice which may also need to be improved where safety in potentially extreme seas is at stake. Emphasis still seems to be on economics and time.

I do not know the answer to his third question regarding design of bulkheads to resist sloshing loads. Ten years or more ago it was not adequately treated in ship rules. The recent IACS strengthening requirements for bulk carriers may be adequate.

Verbal Discussion: There was unfortunately no time for discussion of the paper from the floor. In talking to people there appeared a common wish to see a more direct comparison of the notional probabilities of fore peak flooding and collapse of no. 1 hatch cover from bow waves. For the same assumptions this would provide valid comparisons to illustrate the difference in emphasis between this paper and the official report. Tables 3 and 4 help, but I now include Table 6 in which I use the same notional density function and mix of waves for the two phenomena.

It follows from Table 6 that allowing for trim changes from fore end flooding only increases the notional p_f for no. 1 cover by less than 5% in 3 hours (from 90% to 95%). For longer periods p_f is effectively 100% and bow freeboard reduction due to possible flooding is limited to 1.2 m, which is barely significant.

Some people do not like the word "Abnormal" applied to waves. Lord Donaldson disliked the more widely used "freak wave," as does W. H. Buckley who prefers *Episodic* waves. Several mariners regard such waves in extreme storms as "normal," in the sense that they certainly occur! However, I believe the words "normal" or "operational" are generally accepted as conditions which ships are presently designed for. My preference for exceptional seas is to use the words *survival waves* which require additional safety checks in design and operation (Faulkner and Buckley, 1997).

Finally, I thank all the discussers whose contributions have either provided new data or thoughts or have in other ways substantially enhanced the paper. The very high measure of support for its findings is particularly gratifying.

Table 6 Relative Probabilities for Flooding of Fore Peak Spaces and Collapse of No. 1 Hatch Cover ($p_f = p_c$) for Various Periods

Scenario	D=1Hr	D=3Hr	D=6Hr
%Fullness of FP Spaces:			
Ballast Tanks	7.4%	48%	100%
Bosun's Store	40.5%	100%	100%
Engineers' Store	30.2%	100%	100%
Freeboard Reduction at No. 1 Hatch:	16.8 cm	50.3 cm	117 cm
	6.6 in	27.7 in	46 in
HC Collapse Probabilities:			
Linear Waves Alone	26%	58%	82%
Nonlinear Waves Alone	99%	100%	100%
Mix of Waves	81%	90%	96%
Mix of Waves with Trim	82%	95%	100%