Transportation Safety Board of Canada

Bureau de la sécurité des transports du Canada

MARINE INVESTIGATION REPORT
M02L0021

HULL FRACTURE

BULK CARRIER *LAKE CARLING*
GULF OF ST. LAWRENCE, QUEBEC
19 MARCH 2002

Canada

Marine Investigation Report

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Report Number M02L0021

Summary

On 18 March 2002, the *Lake Carling* loaded a cargo of iron ore pellets at berth No. 2, Sept-Îles, Quebec, and departed the same day bound for Point Lisas, Trinidad. The next morning during scheduled rounds it was discovered that No. 4 hold was taking on water. Further inspection revealed that a six-metre fracture had developed on the port side shell. Sea ice thwarted attempts to keep a collision mat in place to stem water ingress and the bilge pumps were unable to keep up.

Additional pumps were brought on board from a Canadian Coast Guard vessel tasked to the area and these were sufficient to stabilize the situation. On 21 March 2002, the salvage tug *Ryan Leet* arrived on the scene. With the help of more powerful pumps and with the fracture partially plugged from the exterior, No. 4 hold was pumped dry. The vessel made its way to the protected waters of the Baie de Gaspé where more caulking work was done in way of the fracture. On 26 March 2002, the vessel weighed anchor for Québec, Quebec, for permanent repairs.

Ce rapport est également disponible en français.

Other Factual Information

	Lake Carling
Port of Registry	Majuro
Flag	Marshall Islands
IMO Number	8418758
Type	Bulk Carrier
Gross Tonnage[1]	17 464
Length	180 m
Draught	Forward: 9.7 m Aft: 10.08 m
Built	1992, Istanbul, Turkey
Propulsion	6680 kW Sulzer diesel, driving a single, fixed pitch propeller
Cargo	24 654 mt iron ore pellets
Number of Crew	19
Registered Owner	Bay Ocean Management Inc.

Description of the Vessel

The *Lake Carling* is a conventional "Handy-sized" bulk carrier with bridge, accommodations and engine room located aft of the five cargo holds. The vessel is of the gear-less type, i.e. without its own cargo handling equipment. The main engine drives a single right handed propeller.

History of the Voyage

On 14 March 2002, the *Lake Carling* arrived and anchored at Sept-Îles harbour to await loading. Some water ballast had frozen during the trip from Port Alfred, Quebec and, on 15 March 2002, the vessel berthed to complete the de-icing of No. 3 hold. By 17 March 2002, the loading berth was available and the vessel was ready, in all respects, to load. At 2330[2], the vessel was made fast at loading berth No. 2 of the Iron Ore Company of Canada (IOC).

Loading of 24 654 metric tonnes (mt) of iron ore pellets commenced at 0033 on 18 March 2002. Cargo was to be loaded in holds Nos 1, 3 and 5 according to the alternate hold loading plan in the vessel's loading manual. The loading and de-ballasting sequence was conducted to keep the bending moments and shear stresses below the harbour limits, as set out in the vessel's loading manual and the sequence was verified on the vessel's loading instrument. The chief mate had previously submitted the loading plan to IOC, and loading began with the first pour into No. 3 hold.

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1 Units of measurement in this report conform to International Maritime Organization standards or, where there is no such standard, are expressed in the International System of units.

2 All times are eastern daylight time (Coordinated Universal Time minus four hours).

The loading sequence, times and quantities are summarized in Appendix A.

Loading was stopped between 0415 and 0500 due to problems with the cargo handling equipment ashore. At 0550, loading was again interrupted, this time at the chief officer's request, to enable him to de-ballast the vessel. Loading resumed at 0853 and continued until final trimming out at 1231.

The draught survey, prepared by the chief mate after loading, found the vessel's draughts to be 9.7 metres (m) forward and 10.08 m aft. According to the loading instrument, the greatest seagoing Still Water Bending Moments (SWBM) were located at frame 85 in No. 4 hold (90% of approved maximum) and at frame 154 in No. 2 hold (86% of approved maximum). At 1350, two tugs were secured alongside and by 1400, the *Lake Carling* was underway.

The afternoon and evening of 18 March 2002, and early morning of 19 March 2002 were uneventful. The vessel was making approximately 13.5 knots while transiting the Gulf of St. Lawrence. Winds were generally from the north or northeast between 10 and 20 knots. At about 0800, the hatch cover of No. 4 hold was opened for routine maintenance, at which point the ship's personnel observed water ingress on the port side of the hold. The Master was informed. The ship's position at this time was 48˚16'48" north; 061˚21'30" west, approximately 38 nautical miles (nm) north of the Îles-de-la-Madeleine (position 1, Appendix C). Winds were from the north at 20 knots, air temperature was -6˚ C and water temperature was near 0˚ C. Sea state was not documented by the crew but, by all accounts, was unexceptional. Calculations and historical data support a wave height of between 1.5 and 2.5 m and a wavelength of approximately 56 m.

With the vessel stopped, emergency stations were sounded and the starboard lifeboat made ready. Information about the vessel's condition was transmitted to Halifax Search and Rescue (SAR), which directed other ocean-going vessels to the area as a precautionary measure. By 0900, the vessel *Berge* was on the scene. By 0925, a SAR aircraft was overhead and had dropped some additional immersion suits at the master's request.[3] The first drop missed the vessel and the suits were not recovered. A second drop of 10 immersion suits was recovered by the crew of the *Lake Carling*. By 1035, another vessel, the *Degero,* had arrived to assist as necessary.

During the afternoon, SAR aircraft dropped additional pumps. When the Canadian Coast Guard vessel *George R. Pearkes* arrived on the scene, both commercial vessels which had come to the assistance of the *Lake Carling* were released. The *Lake Carling's* crew had been attempting to apply a collision mat to the exterior of the vessel's hull to slow the water ingress, but because of the sea ice the operation was difficult. By 1925, the collision mat was in place. With bilge and salvage pumps operating, water ingress was controlled and water within No. 4 hold was maintained at about 3350 m^3. (the maximum volume of No. 4 hold is approximately 8900 m^3).

The next day, 20 March 2002, winds were shifting to the southeast. While awaiting the arrival of a salvage tug from Halifax, Nova Scotia, the decision was taken to seek some relative shelter to the northeast of the Îles-de-la-Madeleine. At 0908, the engine was put slow ahead and the vessel headed in a southwesterly direction under the escort of the *George R. Pearkes*. At about 1515 the *Lake Carling* anchored northwest of the Îles-de-la-Madeleine. Continuous pumping had stabilized the water level in No. 4 hold at about 3250 m^3.

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3 SOLAS requirements stipulate immersion suits be carried for each member of the rescue boat. In the case of the *Lake Carling*, each of the seven members of the rescue boat had an attributed immersion suit.

Photo 1. The *Lake Carling* stopped in ice, 22 March 2002 (assisting tug, the *Ryan Leet,* seen on the port side)

The following day, 21 March 2002, the salvage tug *Ryan Leet* arrived at 0750. Earlier that morning the collision mat had been destroyed by the floating sea ice. A large salvage pump from the *Ryan Leet* was brought onto the *Lake Carling* to pump No. 4 hold dry. By 1600, a diver was in the water and had began caulking the exterior fracture surface.

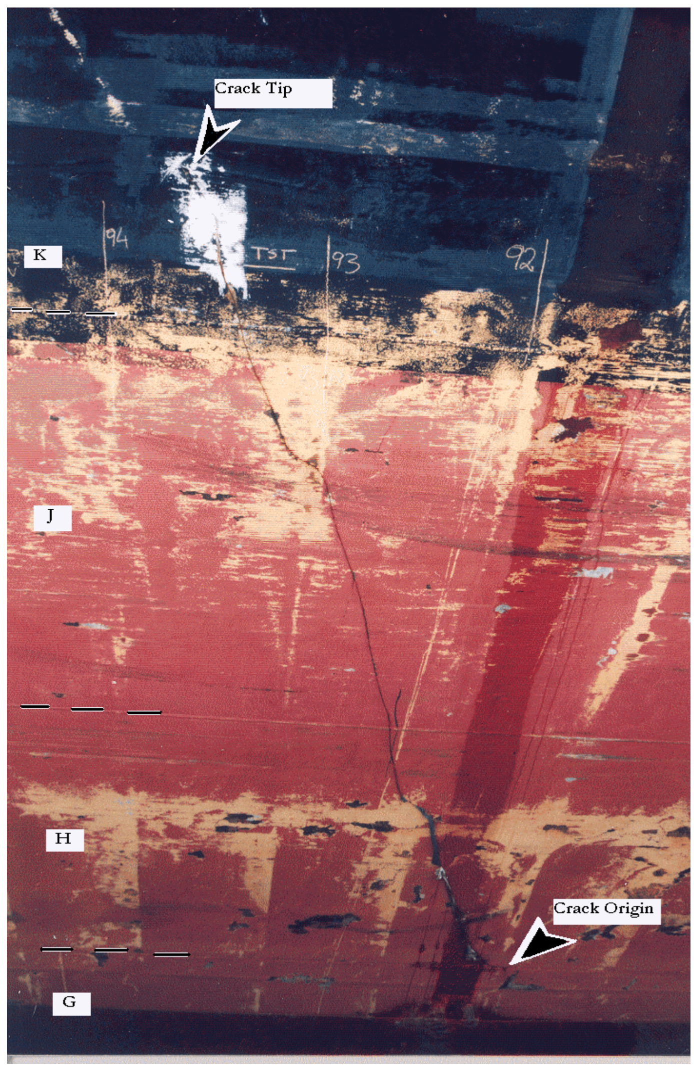

Photo 2. Principal fracture

By 0940 on 22 March 2002, the hold had been pumped dry and bracing work was being fitted to the inside of the fracture to reduce water ingress further. Later in the day winds shifted to the west southwest and increased to 40 knots, with 3 m swells. The decision was made to proceed to the Baie de Gaspé to seek temporary shelter. The manhole cover on the tank top of No. 4 hold had been removed thus giving the vessel's ballast pumps access to the hold. It was decided to allow some ballast water into the hold for the transit to the Baie de Gaspé as this would reduce the SWBM at the fracture location.

The transit to the Baie de Gaspé was not without risks, as freezing spray was causing ice accretion on the forward third of the vessel, thus increasing the SWBM. By the late afternoon of 23 March 2002, the *Lake Carling* arrived in calmer waters and was anchored in the Baie de Gaspé.

The fracture had not grown appreciably since the initial discovery, as a crack-arresting hole had been drilled at the crack tip to limit the growth of the fracture.

Unfavourable weather did not allow the *Lake Carling* to proceed before 26 March 2002, at which time the vessel weighed anchor and made way towards Québec to undergo permanent repairs. On 28 March 2002 the vessel tied up at Québec and offloaded a portion of its cargo. Floating repairs were carried out according to Det Norske Veritas (DNV) Classification specifications and, on 04 April 2002, the vessel was cleared to sail by port state inspectors and the DNV surveyor.

Side Shell Fracture

The principal side shell fracture was on the port side at frame 91, extending upwards and forward from the toe of the weld at the base of the side shell frame. The fracture traversed frames 92 and 93 through H and J strakes, terminating just short of frame 94 (K strake) in No. 4 upper water ballast tank, which was empty at the time. The shell fracture divided at the juncture of the ballast tank sloping plate; one branch continuing for 45 centimetres (cm) on the ballast tank sloping plate at approximately 90˚ from the juncture point—the other branch on the ship's side continuing up and forward for approximately 40 cm past the juncture point. The total length of the fracture at the ship's side was in the order of 6 m. Visual inspection and laboratory analysis indicates that the principal fracture originated at the base of frame 91 (at the toe of the weld).[4] The fracture origin was located 1.3 m below the neutral axis of the vessel's midship section modulus.

The principal fracture was the forward half of a crack manifestation that presented itself on either side of the base of the frame. Five similar crack manifestations were found in No. 4 hold; on the port side, at frames 89 and 93, and on the starboard side, at frames 85, 91 and 96. All crack manifestations appeared to originate near the base of the frame at the toe of the weld, and giving rise to two cracks, one forward and one aft of the frame, each some 75 millimetres (mm) in length and generally in a characteristic "V" formation. Some typical examples found on the port side are shown below (See Photos 3, 4 and 5). All of these cracks were rusted and appeared to have been present for some time.

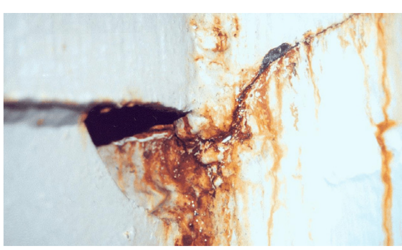

Photo 3. Frame 93

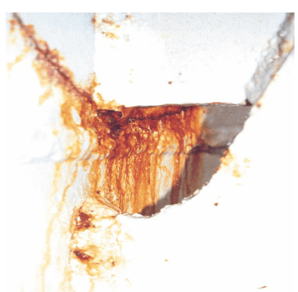

Photo 4. Frame 89

Photo 5. Frame 91 (aft)

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In No. 2 hold, four crack locations were also found; on the starboard side at frames 171½ (See Photo 6) and 172½, and on the port side at frames 144 and 145. In contrast to the cracks in No. 4 hold, all of the cracks in No. 2 hold had been covered with superficial weld repairs. The weld repairs had penetrated only a few millimetres into the thickness of the hull plate. It was not determined when, or by whom, these repairs were undertaken, nor is there any record held by DNV of these cracks or the repairs. In contrast to the crack manifestations in No. 4 hold, not all of these cracks were present both fore and aft of the frame, such as at frame 171½, where the crack was only forward of the frame.

Photo 6. Frame 171½ starboard

Fracture Toughness Requirements of Steel Used in Ship Construction

Historically, fracture toughness criteria for ship steel were initiated following some spectacular structural failures due to brittle fracture such as the Liberty ships and T-2 tankers during and subsequent to World War II.[5] The investigations and research that followed established the Charpy V-notch (CVN) impact test as the accepted fracture toughness standard for some steels used in welded ship construction.[6] In 1954, DNV became the first classification society to introduce the CVN impact test in order to qualify steel toughness.[7]

Throughout the 1950s, classification societies endeavoured to revise specifications to assure steel quality. In 1959, after numerous meetings, seven major classification societies published the Unified Requirements for Steel Ships. After much discussion, it was agreed that only class D and class E grades of steel were to have a CVN rating, which for grade D steel was set at 35 foot-pounds (ft-lbs) (47 Joules) at 0˚ C. Over the intervening decades, many other investigations with respect to the fracture toughness and fracture behaviour of ship plate materials have been conducted by several groups, including the Ship Structure Committee.[8]

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5 S.T. Rolfe, D.M. Rhea, B.O. Kuzmanovic. *Fracture-Control Guidelines For Welded Steel Ship Hulls*, Ship Structure Committee, SSC-244, 1974.

6 A.W. Pense. *Evaluation of Fracture Criteria for Ship Steels and Weldments*, Ship Structure Committee, SSC-307, 1981.

7 S.T. Rolfe, D.M. Rhea, B.O. Kuzmanovic. *Fracture-Control Guidelines For Welded Steel Ship Hulls*, Ship Structure Committee, SSC-244, 1974.

8 The Ship Structure Committee (U.S.A) was created in 1946. The stated mission of the Committee is to eliminate marine structural failures.

By 1974-75, standards had risen but brittle fractures in ships were still occurring even though ship design and crack arrester strategies, in addition to the fracture toughness of some (although not all) steel, had been adopted in an attempt to achieve fracture-safe performance. Accurate and reliable correlations between CVN energy and fracture toughness have been hard to establish.[9] It has been shown that nil-ductility transition (NDT) temperature combined with dynamic tear energy is an accurate indicator of fracture toughness, and a reasonable base point for comparison of structural steels. However, CVN is still the industry standard.

Currently, the International Association of Classification Societies (IACS) requirements describe four grades of normal strength steel.[10] In this respect, DNV requirements are identical to those of IACS. All grades are of the same yield and tensile strength, as well as elongation, but each grade must demonstrate a required CVN impact energy at different test temperatures. The table below summarizes the requirements for normal strength steel, 50 mm or less in thickness.

Grade	Temperature (˚C)	CVN (Joules) Longitudinal / Transverse	
A	none required	none required	
B	0	27[(a)]	20
D	-20	27	20
E	-40	27	20
(a) CVN tests are generally not required for grade B steel with a thickness of 25 mm or less.			

Although there is no set minimum CVN for grade A steel (or grade B steel 25 mm or less in thickness), IACS gives guidance on steel exposed to low service temperatures on the assumption that this steel will have a longitudinal CVN of 27 J at +10˚C.[11] Some classification societies, such as Lloyd's Register (LR), have introduced rules that require in-house checks by the steel manufacturer be made to ensure grade A steel achieves a minimum CVN of 27 J at +20˚C. Reportedly, DNV also has standards similar to LR for grade A steel, but these appear to be internal procedures as opposed to Rules.

In a recent review of the fracture properties of LR grade A ship steel, Lloyd's found that from a total of 39 samples coming from a variety of steelmakers word-wide, the lowest average CVN recorded was 49 J at 0˚C (from one sample), while the average value at this temperature amongst

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9 A.W. Pense. *Evaluation of Fracture Criteria for Ship Steels and Weldments*, Ship Structure Committee, SSC-307, 1981. T.L. Anderson. *Elastic-Plastic Fracture Mechanics*, Ship Structure Committee, SSC-345 (Part 1) 1990.

10 IACS *Requirements concerning Materials and Welding*, W11.6.2.

11 IACS *Guide for the use of hull structural steels for prolonged exposure to low service temperatures*, 1991.

all 39 samples was much higher, at 134 J.[12] Five samples, however, had fracture appearance transition temperatures (FATT) above 0˚C, and four other samples were between -6˚ C and -1˚ C.[13]

The American Society for Testing and Materials (ASTM) grain size of these samples ranged from 7.5 to 10, with over 97% of the samples (38 of 39) at 8 or greater.[14] The smaller the grain size, the more grain boundaries are present in a given sample. As grain boundaries are inherently tough, metals with smaller grain size usually demonstrate a better fracture resistance than those with a relatively larger grain size.

Lake Carling - Construction History

The *Lake Carling* was built in Turkey in 1992 to DNV 1A1 and Polish Registry specifications. The vessel was strengthened for carriage of heavy bulk cargoes and was DNV ice class 1C. Vessel specifications indicate that holds Nos 2 and 4 may be empty (alternate loading). Strakes H, J, and K are all grade A steel, 19 mm thick, with the rolling direction along the length of the ship. G strake, just below H, is similar in quality to the above-mentioned strakes but is 15 mm thick. In shipbuilding, grade A steel is often used in the majority of a hull structure, and this was the case for the *Lake Carling*. The shear strake (L strake) and strength deck were grade E steel 30 mm thick.

Hardness, tensile strength and microstructure of H strake near the fracture origin were examined and found to be within specifications, or, where no specifications exist, to be without defects. CVN impact tests were conducted on sample specimens and the results were as follows:[15]

Temperature (˚C)	CVN (Joules) Longitudinal / Transverse	
+20	33	29
+10	26	31[(a)]
0	18	15
-10	10	8
-20	7	7
(a) higher transverse CVN due to experimental scatter		

12 Lloyd's Register. *Review of the Fracture Properties of LR Grade A Ship Steel*, 1999.

13 FATT (as used in this report) is the temperature at which the Charpy fracture surface is 50% cleavage and 50% tearing.

14 An ASTM grain size of 1 is relatively large while a grain size of 10 is relatively small.

15 TSB Engineering Report LP 022/2002.

The *Lake Carling* metal samples demonstrated a FATT of 32˚ C. The ASTM grain size of the sample tested was found to be in the order of 5 to 6.

Lower Frame Renewal

In March of 2001, the *Lake Carling* was in dry-dock at Gdansk, Poland, for various repairs and a scheduled annual survey. At this time, the lower sections of 62 frames were renewed and close-up surveys were done in all the holds. Of the 10 frame locations, including the principal fracture, that were later found to have crack manifestations, four had their lower sections renewed during this dry-dock. These were: frame 171½ on the starboard side (No. 2 hold) and frames 89, 91 and 93 on the port side (No. 4 hold).

Past Loading History

Using the ship's records, all loading and unloading operations were examined from the time the vessel sailed from the shipyard in Gdansk on 26 March 2001, to the loading at Sept-Îles just prior to the hull failure. Most of the cargos handled during this period were either medium density bulk such as nepheline syenite (1.25 mt/m^3), sugar (0.9 mt/m^3) and potash (1 mt/m^3), or break bulk and steel coils, slabs or billets.

Only once in this period (before the Sept-Îles iron ore consignment) was a high density bulk cargo loaded, zinc/lead (2 mt/m^3). This cargo, taken at Belledune, New Brunswick, in October 2001, was loaded in all five holds at rates between 20 and 29 t/min, well within the vessel's ballast capacity. As far as could be determined, the vessel was loaded correctly at all times since leaving Gdansk with the possible exception of one trip -from Thunder Bay, Ontario, to Montréal, Quebec, in November/December 2001.

The *Lake Carling* left Hamilton on 26 November 2001 in ballast (with 6152 mt of ballast water in No. 3 hold) bound for Thunder Bay. Draughts were recorded in the Welland canal as 6.38 m forward and 6.85 m aft. The vessel encountered severe weather on Lakes Huron and Superior, with winds from the northeast at 30- 40 knots, and four-metre seas. The water temperature was cold—near 5˚ C. The vessel arrived at Thunder Bay on 29 November 2001 in the early morning and went to anchor. The TSB has been unable to acquire records with respect to exactly when No. 3 hold was de-ballasted in unprotected waters, enroute to Thunder Bay. However, the resulting seagoing SWBM would have been 107% of that allowable at frame 91. Later that day, the vessel was shifted to the loading terminal to load potash. Stowage plan and loading instrument entries show that the following was loaded:

Hold	Weight (mt)
1	4255
2	2818
3	6249
4	0
5	4688

The loading instrument printout (harbour condition) for this loading indicates an actual bending moment (BM) of 78 055 t-m occurring at frame 86. This is 79% of the permissible harbour BM of 99 375 t-m, but 103% of the seagoing limit of 75 900 t-m at this location. No loading instrument printout for the seagoing condition was available. The vessel sailed from Thunder Bay in this condition, with draughts of 7.99 m forward and 8 m aft. With the exception of this instance, all other departure conditions examined between 26 March 2001 and 16 March 2002 had been correctly entered (i.e., departure condition = seagoing condition of the loading instrument).

The vessel sailed on 30 November 2001 arriving at Montreal on 05 December 2001 to complete loading with 6000 mt of syenite in No. 4 hold. Once this cargo was loaded, the seagoing BMs were then reduced below the approved maximums for the vessel. The vessel left Montreal on 05 December 2001 and crossed the Atlantic, encountering severe weather for two days at mid-voyage with winds of 40-60 knots.

Sister ships

Two other vessels were constructed to the same plans and specifications as the *Lake Carling*, and at the same shipyard. Hull number 14 was constructed in 1990 and later became the *Lake Charles*. Hull number 15 was constructed in 1992 and later became the *Lake Champlain*. The *Lake Carling* was hull number 16. All three vessels were operated by Bay Ocean Inc. of New Jersey, United States of America.

The *Lake Charles* was inspected by TSB personnel at Sorel, Quebec, in March 2002. Special attention was paid to the bottoms of the side shell frames. No "V" crack manifestations were seen at these locations, however, in No. 4 hold, the ends of the frames were approximately 100 mm above the seam of the weld joining the G and H strakes. This compares to about 25 mm on the *Lake Carling*. The *Lake Champlain* was surveyed by company representatives while in dry dock in Poland in May 2002. No "V" crack manifestations were found, however the ends of the frames were, on average, approximately 90 mm above the shell plate seam.

Analysis

For a well-maintained ship, significant fractures are caused by one or more of the following;[16]

- Abnormal forces in or on the ship structure;
- Presence of flaws or notches in the structure where fractures originate; and
- Inadequate physical properties of the structural steel at service temperatures.

All three factors were involved in the side shell fracture of the *Lake Carling*. Minor cracks, as opposed to significant fractures, are a fact of life on bulk carriers, or any type of large vessel, for that matter. Of major importance is the vessel's damage tolerance, that is to say, the length to which a through thickness flaw or crack can grow before becoming critical. Assuming that loading and dynamic forces remain within design parameters, the fracture toughness of the metal is what will ultimately determine this length.

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[16] K.A. Stambaugh, W.A. Wood. *Ship Fracture Mechanisms*, Ship Structure Committee, SSC-337(part 2), 1990.

Side Shell Crack Initiation

The *Lake Carling* underwent a survey in dry dock approximately one year before the occurrence. Particular attention had been paid to the bottoms of the side shell frames due to the renewal of many of them, including frame 91 port. Since none of the six crack locations in No. 4 hold had been previously repaired, and the four in No. 2 hold had been repaired only superficially, it is highly unlikely that these cracks were present at the time of the dry docking.

Crack initiation may be due to any number of causes, including: improper deballasting during loading; insufficient draughts while transiting a seaway in ballast; asymmetrical loading; damage by unloading grabs during discharge; side shell striking while negotiating locks; or exceeding the approved seagoing SWBM. Unsatisfactory welding procedures and localized construction details can also cause or contribute to the initiation of such cracks. Once initiated, cracks will, depending on the operational environment of the vessel, usually enter a stage of slow, stable growth.

Superficially, similarities seem to exist amongst all ten crack locations, thus implying that they were created by the same mechanism, but some major differences are also evident between those in No. 4 hold and those in No. 2 hold. In No. 4 hold, all six of the crack locations, three to port and three to starboard, are concentrated in an area within eight frames, and at each location the cracks are roughly symmetrical fore and aft of the frame. All were unrepaired and three of the frames had been replaced during the Gdansk dry dock. In contrast, at the four crack locations in No. 2 hold, the cracks are not all symmetrical fore and aft of the frame, and in the case of frame 171½, there is no crack aft of the frame. Furthermore, they are not concentrated in a limited area of the hold; two are in the forward section and two in the aft section of the hold.

All four of the cracks in No. 2 hold were superficially repaired and only one frame had been replaced at the Gdansk drydock. Another major difference is one of construction detail. All of the frames of concern in No. 4 hold are of the separate bracket configuration while those in No. 2 hold are integral brackets. The stress concentration factors, such as the discontinuities caused by the scallop (cut-out) in the side frame and the proximity to the change in plate thickness at the shell plate seam weld, are not entirely similar.

Of the ten crack locations, four of the frames had been cropped and renewed at the bottom. There does not seem to be a strong correlation between frames replaced in dry dock and the crack locations, but the correlation cannot be discounted entirely. Half of the crack locations (3 of 6) in No. 4 hold were where frames had been cropped and renewed. Given the preceding, it is most likely that the cracks in No. 4 hold were created by the same mechanism at some time between the dry dock in Gdansk and the loading at Sept-Îles. Although the cracks in No. 2 hold were probably created during this same time frame, it is less certain that they were created by the same mechanism as those in No. 4 hold.

Several sources could have been responsible for the cracks in No. 4 hold. De-ballasting in unprotected waters, and/or the improper loading four months prior to the hull fracture, are possible causes of the crack initiation. For the de-ballasting scenario, the SWBM imposed on the hull girder at frame 91 would have been 107% of the approved maximum permissible. For the loading scenario, the SWBM at frame 86 was 103% of the approved seagoing allowable limit. Being farthest from the neutral axis maximum stresses would have been experienced in the deck and bottom shell. However, the combination of all global and localized stresses would still have been significant at the bottom of the side shell frames. The vessel sailed in this condition for 5 days, from Thunder Bay to Montréal, in water close to 5˚ C. After leaving Montréal, the vessel encountered very heavy weather in the North Atlantic. Had small cracks developed due to improper loading and cold water conditions between Thunder Bay and Montréal, they could have grown under such dynamic loading.

The restrained nature of the welded connections at the lower ends of the side shell frames made this area susceptible to the retention of residual stresses. The coincidence of several stress concentration factors, such as:

- the discontinuities caused by the scallop (cut-out) in the side frame;
- the proximity of the frames lower ends to the shell plate seam (possibly exacerbated when the frames were renewed at Gdansk);
- the change in plate thickness at the shell plate seam weld; and
- the presence of residual stresses;

created the conditions necessary, when subjected to high stresses and cold ambient temperatures, to cause small cracks to form at the base of the side shell frames between frames 85 and 96 in No. 4 hold.[17]

The intervening four months operation prior to the occurrence is a reasonable time frame in which these cracks could grow imperceptibly under the dynamic loading of the hull girder.

Side Shell Fracture

Properly loaded at Sept-Îles and in relatively calm seas, no relationship can be drawn between the fracture and these operational and environmental factors. Ultimately, the small crack at frame 91 went critical solely due to factors related to the physical properties of the steel and the ambient temperature.

The grade A steel used in the construction of the side shell of the *Lake Carling* was "within specifications" insofar as tensile strength is concerned, but as for minimum CVN, no specifications actually exist. The relatively low fracture toughness of the side shell plate when exposed to temperatures near 0˚ C allowed the forward crack at frame 91 (port) to grow to failure at a load well below the ultimate tensile strength of the material. The length of this crack at the time it became critical was not determined but calculations have shown it could have been as short as 10 cm.

According to the IACS Unified Rules, grade A steel less than 50 mm thick (and grade B 25 mm or less in thickness) does not have to demonstrate a minimum CVN. Under these rules this steel can be used for a ship's side shell. Some testing has shown that the average CVN of grade A steel available worldwide is often quite high and the grain size relatively small.[18] This, in effect, sets a defacto standard—ship owners, ship constructors, and classification societies all expect and depend upon grade A steel having a fracture toughness that is sufficient for all operational conditions. However, without actual standards, expectations are not always enough to ensure adequate fracture toughness and damage tolerance.

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17 TSB Engineering Lab Report LP 022/2002.

18 See appendix B for comparison of *Lake Carling* side shell plate with that of Lloyd's tests.

Although the relationship between CVN energy and fracture toughness is not necessarily straightforward, the system has been used with relative success by all of the major classification societies for many years by providing a qualitative estimate of material toughness. There are, however, no requirements to use steel of a given CVN energy at low operating temperatures in way of the ship's sides (which are usually grade A steel). Nonetheless, cargo vessels may often trade in zones where ambient temperatures are close to, or below, 0˚ C and these low temperatures generally tend to reduce the ability of the steel to resist crack growth.

The grain size and CVN impact energy, and thus the corresponding fracture toughness, of the grade A steel used in the construction of the *Lake Carling* was well below the defacto standard when compared to average values of grade A steels available worldwide. This steel performed below expectations and did not provide a reasonable damage tolerance in all operational conditions.

Steel Toughness Standards and Damage Tolerance

The *Lake Carling* was relatively new *and* had been recently inspected, yet a substantial fracture resulted from the existence of what should have been a tolerable crack (10 cm) in the ship's side. The *Lake Carling* occurrence, although seemingly rare, is most certainly not unique.

Historical data have revealed that nearly three quarters of all casualty-related fatalities on bulk carriers are attributable to structural failure.[19] Other data culled from Lloyd's casualty database indicate 23 bulk carriers foundered in cold water in a twenty-year period, yet the cause of the losses are undetermined.[20] Notable vessel losses in the TSB databank are as follows:

- *Jalamorari*, General Cargo, December 1982.
- *Charlie*, Bulk Carrier, January 1990.
- *Protektor*, Bulk Carrier, January 1991.
- *Marika*, Bulk Carrier, January 1994.
- *Salvadore Allende*, December 1994.
- *Leader L*, March 2000.

Albeit almost always in heavy weather, these losses were also all in cold temperatures. Due to a lack of forensic evidence, the true cause of these losses cannot be proven. Although the Enhanced Survey Program (ESP) and other initiatives more recently introduced to reduce risk for bulk carriers are continuing to increase safety, the *Lake Carling* can be viewed as an example of residual risk that remains in spite of these initiatives. A recent evaluation by IACS of risk control options (RCO) in respect of the side shell integrity of bulk carriers identified 15 RCOs, 11 of which were put forward for further investigation.[21] Although one option called for the requirement to use notch toughened steel and associated welding consumables for frame brackets, toughness of the metal used in the side shell was not addressed or identified as a RCO.

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19 IACS *Bulk Carrier Safety* Formal Safety Assessment, 2001.

20 1978-1998.

21 IMO MSC 76/INF.21, October 2002.

The appropriateness of using steel of unknown toughness in vessel construction has been raised in various reports and proceedings, including those concerning the loss of the *Derbyshire*, the brittle fractures of the *Tyne Bridge* and the breaking in two of the *Kurdistan*.[22] During the re-opened *Derbyshire* inquiry (under Justice Coleman ([U.K.]), the following quotation was restated:

> Depending on the properties of the steel float and/or weld, the ambient temperature and the location of the crack, a crack as small as 30 millimetres could be sufficient to initiate a fast-running brittle fracture.[23]

The steel toughness of the *Derbyshire* was not further investigated because no steel was actually taken from the wreck for testing. In his independent analysis of the *Derbyshire* sinking, the Professor Emeritus of Naval Architecture at the University of Glasgow, Scotland, D. Faulkner, stated his support for reviewing the use of metal of unknown fracture toughness in ship's hulls.[24]

Although the recent Lloyd's initiative to qualify the toughness of grade A steel may appear to be an improvement on existing standards, the required 27 Joules at 20˚ C is less than that demonstrated by the *Lake Carling*; and 20˚ C is certainly well above the temperature most vessels may expect to encounter at one time or another. Additionally, Lloyd's leaves it up to the manufacturer to report that the steel meets this requirement by way of "in-house" checks. This measure, although well intentioned, is less a tool for quality control than it is an indication that the toughness of grade A steel has been, and continues to be a cause for concern. It has been suggested that a FATT below 0˚ C is necessary to ensure sufficient fracture toughness for ship's hulls.[25] In the Lloyd's study of the fracture properties of grade A steel, 5 of 39 samples (nearly 13%) demonstrated a FATT above 0˚ C, while a further four samples (10%) were at -6˚ C or above. For the *Lake Carling*, the FATT was determined to be 32˚ C. In other industries, such as electric power generation, risks due to brittle fracture are reduced by ensuring that operating pressures are only permitted at component temperatures approaching or exceeding the component's FATT.[26]

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22 The *Kurdistan* shell plates, almost entirely of grade A steel, were found to have 27 Joule Charpy transition temperatures of between 5˚ and 20˚C. The vessel broke in two on March 15 1979 in the cold waters of the Cabot Strait (Canada), six years after its construction.

23 Dr. Timothy J. Baker, *Derbyshire* Formal Investigation transcripts, 4 May 2000.

24 D. Faulkner, *An Analytical Assessment of the Sinking of the M.V. Derbyshire*, The Royal Institution of Naval Architects, RINA Transactions, 2001.

25 J.D.Sumpter, A.J.Caudrey, *Recommended Fracture Toughness for Ship Hull Steel and Weld*, Marine Structures 8, 1995.

26 J.R. Foulds, P.J. Woytowitz, T.K. Parnell, C.W. Jewett, *Fracture Toughness by Small Punch Testing*, Journal of Testing and Evaluation, Vol 23, No1, 1995.

A recent study found, after a review of the available data, a significant variability in the fracture initiation toughness of grade A plates.[27] Other studies have found similar results and have advocated the use of a prescribed minimum toughness standard for all metal and welds used in ship hulls.[28] In fact, 40 J at -40˚ C has been the standard for Canadian ships of war for over 40 years, while 100 J at -20˚ C has also been suggested as a minimum to ensure adequate damage tolerance and protection against brittle fracture.[29] In a major review of a vast amount of available literature concerning the fracture properties of grade A ship plate, it was concluded that "...the crack arrest ability of grade A plate is poor and probably inadequate for most ship applications".[30] Nonetheless, it would appear that, notwithstanding the average high toughness and quality of most steels, some grade A and B steels that are not suitable in all conditions are still being produced and used in ship's hulls.

In the marine industry, standards evolve over time, usually in reaction to a high profile disaster or event. Because of the nature of the trade, bulk carriers are prone to side shell flexing, and the side shell is more at risk from crack damage than any other area of the vessel.[31] When ships are lost without a trace or are inaccessible, it is not possible to analyse the relationship between material toughness and the cause of the vessel's loss.

The *Lake Carling* had loaded iron ore in the port of Sept-Îles and the fracture was discovered when the vessel was close offshore in the Gulf of St. Lawrence. This provided the TSB with an opportunity to closely examine the fractures and conduct an in-depth analysis of all aspects of the occurrence, including: the circumstances leading to the occurrence, the cause of the fracture and the inherent mechanical properties of the steel.

One certainty remains—all ships, especially bulk carriers, operating in cold waters and having their side shell of metal with characteristics similar to those of the *Lake Carling*, are at risk. The damage tolerance could be less than adequate and cracks could remain unnoticed or discounted as insignificant, yet they would still pose a significant risk when exposed to low temperatures. Given the uncertainties and variability of fracture toughness for some grade A and B steels, it would appear that residual risks for unstable brittle fracture are still present in vessels with hulls constructed with these steels, especially when operating in colder climates.

Unreported repairs

The cracks in No. 2 hold were repaired in a substandard fashion and were not reported to the classification society. In its report into the structural failure and sinking of the bulk carrier *Leader L*, the Polish Classification Society concluded:

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27 British Steel Limited, *Offshore Technology Report - OTO 2000 001*, 2000.

28 J.D.Sumpter, A.J.Caudrey, *Recommended Fracture Toughness for Ship Hull Steel and Weld*, Marine Structures 8, 1995.

29 Dr. J. Matthews, Defence R&D Canada - Atlantic.

30 British Steel Limited, *Offshore Technology Report - OTH 95 489, Literature Review of the Fracture Properties of Grade A Ship Plate*, 1997.

31 D.J. Ghose, N.S. Nappi, C.J. Wiernicki. *Residual Strength of Damaged Marine Structures*, SSC-381 1995.

> To assure its local strength, the structure should also be continuously supervised. This requires close co-operation of the classification society, shipowner and crew (to record noticed damages and defects), which not always is the case.[32]

One of the major risk reduction measures implemented in the 1990s addressing structural failures in bulk carriers has been the ESP. It has been shown in one study that the ESP has had a general effectiveness in the order of 19% for these vessels within this category of casualty.[33]

Notwithstanding being under the ESP regime, some cracks in the *Lake Carling* hull went unnoticed and unrepaired. Those cracks that were repaired were not executed to classification society specifications nor were they reported. This omission increased risks to the vessel and crew.

Immersion Suits

Although the *Lake Carling* was carrying the required minimum number of immersion suits—one for each member of the rescue boat crew—in the first hours that followed the discovery of the fracture the master requested that additional suits be dropped by SAR aircraft. This was a prudent decision even though, in the end, they were not used. Because SAR resources and the extra suits were readily available, the drop was possible.

Since their introduction into the marine industry, immersion suits have proven to be an efficient and reliable defence against death by hypothermia. On Canadian vessels the carriage of immersion suits for all crew members has been mandatory since 1983.[34] The TSB has recorded numerous instances where immersion suits have saved lives:

- December 1990, a crew member of a fishing vessel rescued after seven hours in cold water;
- January 1993, a crew member of a fishing vessel was recovered after approximately five hours in the frigid sea;
- February 1995, a crew member of a fishing vessel was rescued after over two hours in cold water;
- December 2001, of a four man crew, both persons wearing immersion suits survived while, of the other two (not wearing immersion suits), only one survived.

In 2001, subsequent to the *Flare* investigation, Canada submitted a proposal to the 74th session of the IMO Maritime Safety Committee (MSC).[35] In 2002, the MSC Sub-Committee on Ship Design and Equipment (DE) considered the carriage of immersion suits for all persons on board cargo

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32 Polski Rejestr Statkow, *Report into the loss of the Bulk Carrier Leader L*, 2000.

33 IACS, *Bulk Carrier Safety - Formal Safety Assessment - Fore End Watertight Integrity*, 2001.

34 Vessels over 15 tons gross tonnage.

35 Proposal MSC 74/21/3.

vessels should be made mandatory, particularly in cases where casualties occurred in cold climates. In certain circumstances, individuals involved may then have a better chance for survival and rescue.

The DE Sub-Committee meeting in March 2003 further considered the issue and subject to, *inter alia*, a geographical definition of "warm climates" where carriage of immersion suits would not be required, developed and submitted to MSC a draft of proposed amendments to SOLAS regulation III/32.3, (*Personal Life-saving Appliances*).

The TSB has found that some residual risks appear to remain, even when carrying immersion suits for 100% of the crew, particularly with respect to the maintenance of the zippers. Past investigations have shown that poor zipper maintenance can nullify the advantages of having an immersion suit. Hand in hand with any new requirements for more widespread carriage of immersion suits should be provisions for training and proper maintenance of this equipment. The DE Sub-Committee is presently developing guidelines for periodic testing of immersion (and anti-exposure) suit seams and closures for consideration by MSC.

The TSB commends these initiatives.

Conclusions

Findings as to Causes and Contributing Factors

1. The restrained nature of the welded connections at the lower ends of the side shell frames made this area susceptible to the creation of residual stresses.

2. Conditions were created for small initial cracks to form at the lower ends of some side frames between frames 85 and 96 in No. 4 hold due to:

    - service loads greater than those approved for the vessel;
    - probable presence of residual stress;
    - stress concentration factors due to discontinuity caused by scallop (cut-out) in the side frame;
    - the proximity of the frame end to the shell plate seam weld; and
    - the change in plate thickness at the shell plate.

3. The relatively low fracture toughness of the side shell plate when exposed to near 0˚ C temperatures allowed the forward crack at frame 91 (port) to grow to failure at a load well below the ultimate tensile strength of the material. The length of this crack at the time it became critical was not determined but could have been as short as 10 cm.

4. Approximately four months before this occurrence, the *Lake Carling* was subjected to service loads that exceeded the maximum approved seagoing bending moment.

Findings as to Risk

1. There are no Unified Requirements to use steel of a certified toughness or minimum FATT in way of the ship's sides for cargo vessels which may often trade in zones where ambient temperatures are close to, or below, 0˚ C.

2. Given the variability and unqualified fracture toughness for some grade A and B steels, it would appear that residual risks for unstable brittle fractures are present in vessels with hulls constructed with these steels, especially when operating in colder climates.

3. The large grain size and low CVN impact energy of the *Lake Carling*'s side shell plate resulted in a corresponding fracture toughness that is below expectations and does not permit a reasonable damage tolerance in all operational conditions.

4. Cracks at the bases of four side frames in No. 2 hold had been observed and repairs had been made. These cracks and subsequent repairs were not documented or reported to the Classification society, nor were they completed in accordance to the Classification society's specifications.

5. The *Lake Carling* complied with SOLAS minimum requirements for the carriage of immersion suits. However, although the vessel often operated in areas of sub- zero weather, immersion suits were not carried for all crew members - nor are they currently required to be carried.

6. Several side shell frames were repaired in Gdansk a year before the side shell failure. Although there does not appear to be a strong correlation between the principal fracture (and other cracks discovered at the base of the frames) and these repairs, it cannot be discounted entirely.

Other Findings

1. Although built to specifications that allowed alternate cargo hold loading, the *Lake Carling* was rarely loaded in this manner. Greater SWBMs are imposed on the structure when alternate hold loading is adopted.

Safety Action

Action Taken

Although not specifically related to events of the *Lake Carling* fracture, discussions at IMO have addressed alternate hold loading; specifically the possible benefits deriving from banning alternate hold loading of heavy cargoes in the full load condition, and in particular the resulting reduction in shear forces and bending moments when loading homogeneously in all holds.[36] Further meetings of the Maritime Safety Committee (MSC) agreed that the Design and Equipment (DE) sub-committee develop draft amendments to SOLAS chapter XII along the following lines:

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[36] MSC - 76th session, 2-13 December 2002.

> Bulk carriers in the full load condition (90% of the ship's deadweight at the relevant freeboard) of single-side skin construction and 150 m in length and over, constructed before 1 July 1999, after reaching 10 years of age, or constructed after 1 July 1999 if not in compliance with SOLAS chapter XII and IACS UR S12 Rev 2.1, shall be banned from sailing with any hold empty. The ban shall not apply to ships constructed before 1 July 1999 if they comply with SOLAS chapter XII and IACS UR S12 Rev 2.1.[37]

The proposal will be further discussed at the 2004 DE 47 sub-committee meeting.

Safety Concern

The use of grade A and grade B steel of unknown toughness or fracture appearance transition temperature (FATT) in way of ships' side shells has, in the past and to this day, allowed some vessels to be constructed of steel that is less than adequate for all ambient conditions. Because a vessel's side shell, particularly bulk carriers, is prone to flexing, the side shell is more at risk to crack damage than any other area of the vessel. Crack initiation is the first step towards a major fracture. Once a crack has initiated, only the material's damage tolerance stands between a nuisance defect and disaster. The material's damage tolerance is intimately related to its inherent toughness—a quality that can change dramatically for the worse in temperatures at or near 0° C if certain characteristics of the steel, such as carbon content or grain size are less than optimal.

Over the past 50 years, the debate amongst and between the various Classification Societies and other materials experts has been divided. On the one hand, the status quo is touted as sufficient and ample defence against brittle fracture. The status quo, however, is a moving target. The standards of today are more rigorous than in 1950—thanks, in no small measure, to some well documented disasters. On the other hand, objective evidence and a review of the pertinent literature has indicated, and eminent world leaders in the field have emphasized, the lack of toughness standards for this aspect of ship construction.

In a recent review of statistics over the period 1988-1998, of ships over 500 gt, close to 50 percent of all the causes of the total loss of a vessel were attributable to either "weather" or "various".[38] It is conceivable that somewhere within those statistics are other instances of structural failure. Without doubt, a considerable portion of these losses could be due to structural failure—and many of those structural failures could be attributed to brittle fracture. Because most of the wrecks can not be sufficiently investigated, the causes are attributed to "weather" or "various". However, the use of "weather" as a cause, although it may have contributed to the occurrence, is not considered appropriate as a criterion in some cases since modern vessels are built to withstand weather.

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[37] MSC-77th session, June 2003.

[38] International Underwriting Association, *Marine and Casualty Statistics*, 1999.

Although the average Charpy V-Notch (CVN) energy of today's grade A and B steel can generally be expected to be relatively high, 33% of the samples tested by Lloyd's had a fracture appearance transition temperature (FATT) greater than -10˚ C. Furthermore, five of the 39 samples (12.8%) had a FATT greater than 0˚ C. Any reasonable assessment of these results should conclude the existence of less than adequate toughness. By any definition, even requiring 27J at 20˚ C is a low standard—but it is a standard. The very fact that grade A steel is, by definition, a steel without a toughness standard should raise concerns.

Such action as identifying cargo hold water level detectors as a reasonable defence and risk reduction factor is not without merit, but this is a defence that is reactive rather than proactive.

The Board is encouraged with the International Association of Classification Societies' (IACS) intention to carry out critical crack length calculations taking into account the actual material characteristics included in this report. Based on the results of this analysis, IACS will apparently consider whether (or not) to introduce a screening of the material properties of shell plating in way of the single skin areas of the cargo and machinery region in ships with ice strengthening. The Board is also encouraged with the work of IMO involving restrictions on alternate hold loading and their proposal for "Goal-based new ship construction standards".

The Board is concerned, however, that even if a standard is agreed upon, too low a standard would cause unwanted and necessary constraints with a questionable safety benefit. Furthermore, until such time that restrictions or regulations are put into effect, existing bulk carriers and their crews continue to be at risk. Additionally, even vessels without ice strengthening are regularly called upon to trade in waters with sea temperatures at or near 0˚ C. By limiting any possible modifications of the IACS UR S6 (Use of steel grades for various hull members) to ice-strengthened vessels, other vessels would continue to be exposed to unacceptable residual risks.

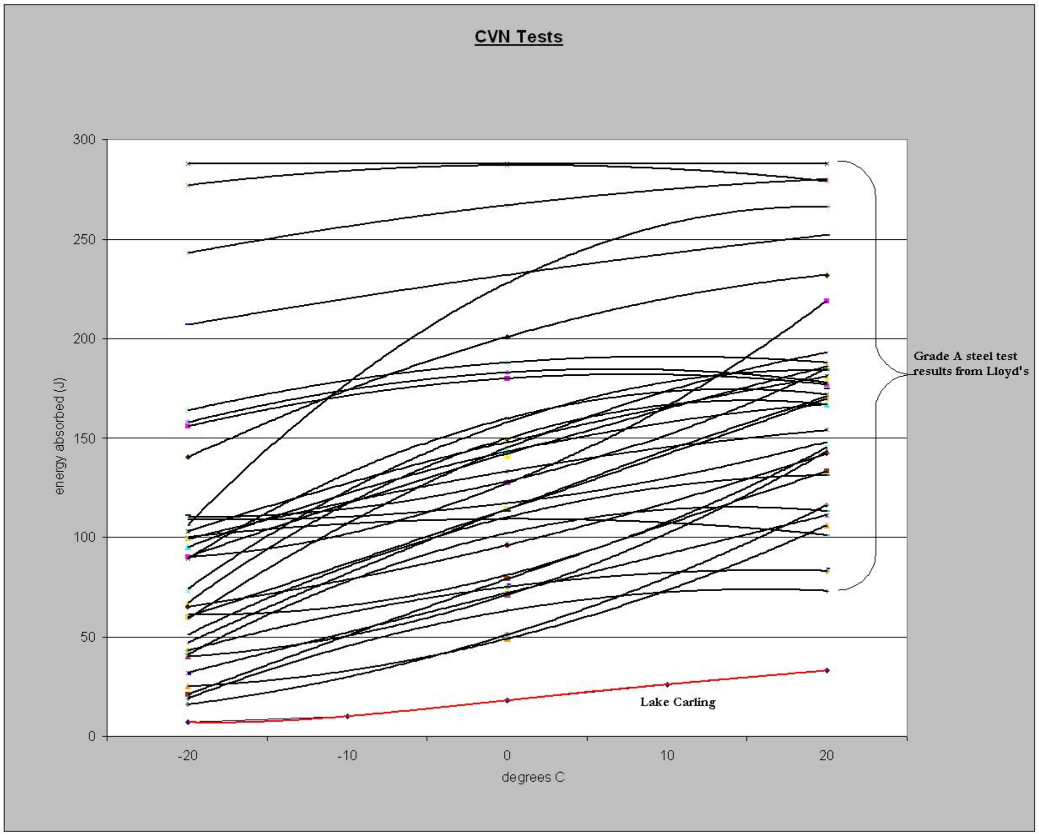
The Board will continue to monitor this safety issue.

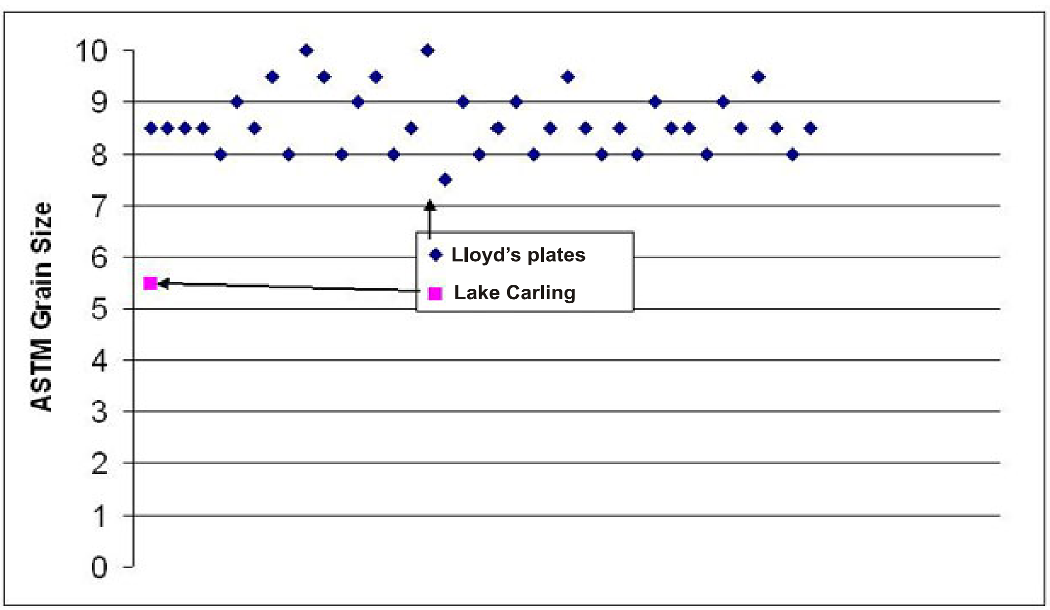
This report concludes the Transportation Safety Board's investigation into this occurrence. Consequently, the Board authorized the release of this report on 08 October 2003.

Appendix A - Loading at Sept-Îles

Time start / stop		Hold	Weight (Mt)	Rate (Mt/min)
33	234	3	6002	496
304	355	1	3429	672
410	536	5	3159	367
545	550	5	339	678
853	1029	3	4663	486
1035	1103	1	1991	711
1111	1159	5	3601	75
1210	1231	1	1400	666

Appendix B - CVN and Grain Size Comparison





Appendix C - General Area Chart