Report on the investigation of

an explosion on board

fv Fleur de Lys

which then foundered

18 miles south-east of Portland Bill

on 16 April 2000

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First Floor, Carlton House
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Southampton
United Kingdom
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Regulations 1999

The fundamental purpose of investigating an accident under these Regulations is to determine its circumstances and the cause with the aim of improving the safety of life at sea and the avoidance of accidents in the future. It is not the purpose to apportion liability, nor, except so far as is necessary to achieve the fundamental purpose, to apportion blame.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ac	:	alternating current (electricity)
BST	:	British summer time
DETR	:	Department of Environment Transport and Regions
DF	:	Direction finding
EPIRB	:	Emergency position indicating radio beacon
ETA	:	Estimated time of arrival
HRU	:	Hydrostatic release unit
kW	:	kilowatt
LSA		lifesaving appliance
m	:	metre
MCA	:	Maritime and Coastguard Agency
MRSC	:	Maritime Rescue Sub-Centre
UTC	:	Universal co-ordinated time
v	:	volt
VHF	:	Very high frequency (radio)

Operating pressure	:	The design maximum output from the pressure reducing valve.
Maximum working pressure	:	The maximum pressure to which the storage cylinder will be subjected in normal operation, which is at least 0.5bar less than the maximum design pressure.
Maximum design pressure	:	The pressure at which the expansion valve is set to open
Thermal cut-out	:	A device that during abnormal operating conditions, limits the temperature of the stored water by automatically interrupting the energy supply. It is constructed so that its temperature setting cannot be altered by the user and requires either replacement, or operation by hand, to restore the heat supply.

SYNOPSIS

An explosion in the engine room of the 16.45m UK-registered fishing vessel *Fleur de Lys,* DH7, sank the vessel rapidly. The accident occurred during fine weather, on Sunday afternoon, 16 April 2000, 18 miles south-east of Portland Bill, en route to Weymouth from fishing grounds off the coast of Alderney.

Although the vessel sank within a few minutes of the explosion, the skipper was able to send a VHF radio "Mayday" call before abandoning ship. This was received by the coastguard at Portland, which dispatched a rescue helicopter to the scene. The helicopter arrived within 16 minutes of the "Mayday" call and picked up all four crewmen from the sea. All were wearing lifejackets.

The lifejackets had been stored in an accessible position: in a locker on the open deck. The radio batteries were positioned high up in the engine room, so withstood the initial stage of flooding. The location of both the lifejackets and radio batteries increased the fishermen's chances of survival significantly.

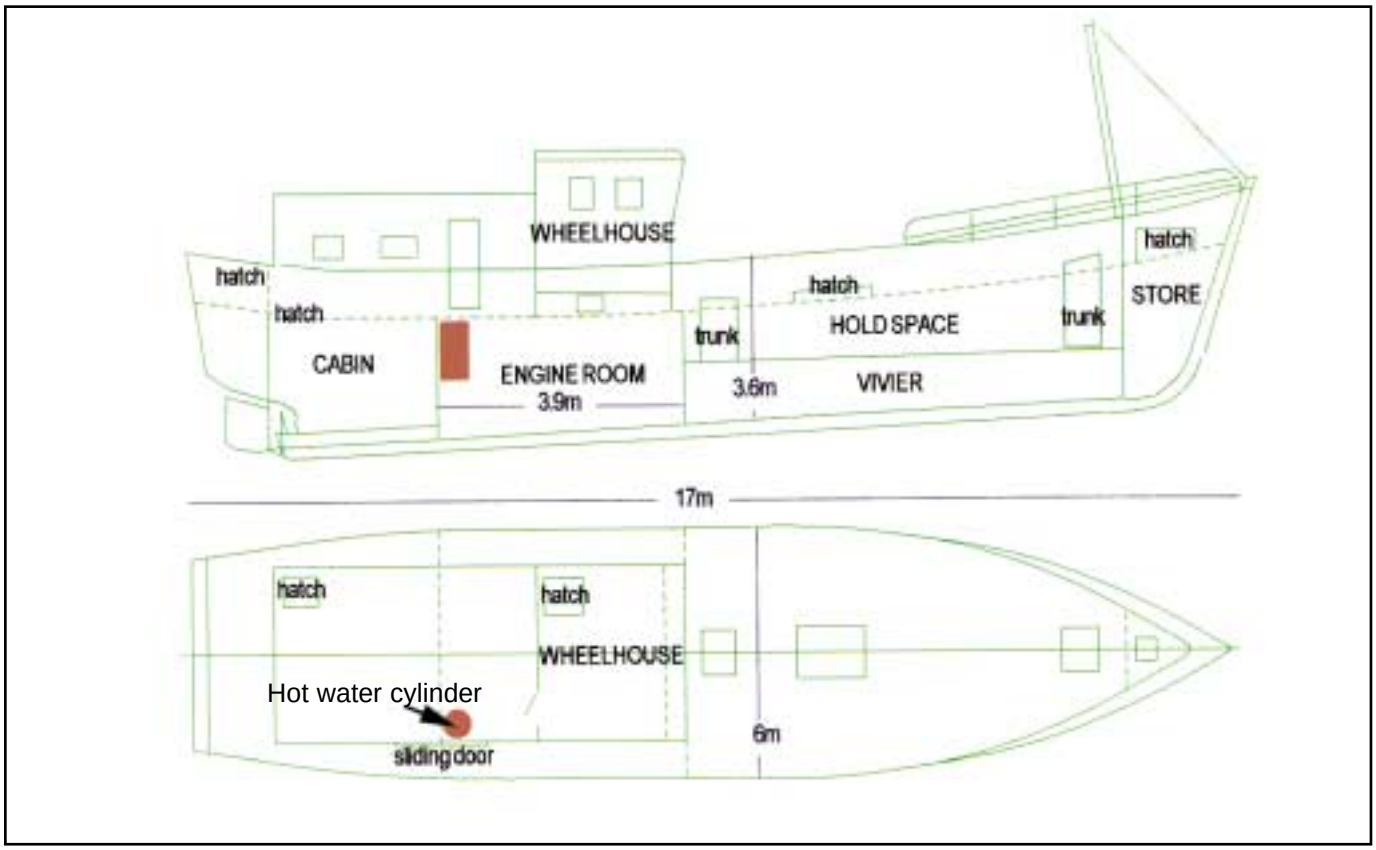
Fleur de Lys sank because her hull was damaged by violent rupture of the hot water storage cylinder of the unvented hot water system. The water in the cylinder had overheated and generated steam. This resulted in overpressure which, in turn, led to it rupturing. The cylinder overheated probably because its immersion heater thermostat failed to shut off the electrical supply to the heater. There were no safety devices fitted to prevent overheating and overpressure in case of thermostat failure.

The hot water system had a history of burst cylinder and pipes because of overheating due to thermostat failure. During the week before the accident, steam discharged from hot water taps. However, because the crew and owner had inadequate technical knowledge of the hot water storage system, they were unaware of the danger of overheating and the safety actions necessary to avoid an explosion.

The then Department of Environment, Transport and the Regions (DETR) provided regulation and guidance for United Kingdom land-based national standards of design, construction, and installation of hot water storage systems. These systems are equipped with safety devices designed to prevent incidents of storage cylinder overheating, overpressure and explosion such as occurred on board *Fleur de Lys.* No such regulation and guidance is provided to fishing vessels.

The Maritime and Coastguard Agency (MCA) is recommended to introduce suitable standards for the hot water systems on fishing vessels. It is also recommended to make known to the fishing industry the value of stowing lifejackets so they are accessible from the open deck.

Fleur de Lys



General arrangement

SECTION 1 - FACTUAL INFORMATION

1.1 PARTICULARS OF VESSEL AND ACCIDENT

Vessel details

Name	:	*Fleur de Lys*
Fishing No	:	DH7
Registered owner	:	Mr N Prust, 12 Sandown Road, Roselands, Paignton
Port of registry	:	Dartmouth
Flag	:	United Kingdom
Type	:	Inshore crabber
Built	:	1969 in Brittany, France
Construction	:	Wood – oak on oak
Length	:	16.42m
Gross tonnage	:	44.98
Engine power and/or type	:	Baudouin 164kW, auxiliary generator type Cummins 37kW Two banks of batteries, each with capacity of 180 ampere hours. One set for starting, the second set for radio and lights

Accident details

Time and date	:	1512 UTC, 16 April 2000
Location of incident	:	50° 17.6'N 002° 07.9'W 18 miles south-east of Portland Bill
Persons on board	:	4
Injuries	:	4
Damage	:	Vessel sank, structural damage

1.2 BACKGROUND

Fleur de Lys was owned by Nick Prust, an experienced skipper, who bought the vessel in 1989. At the time of the accident, he was working on a project with a Dutch stand-by vessel in the English Channel. From this vessel, he was in radio contact with the skipper whom he hired to take out the vessel.

Fleur de Lys left Brixham on the night of Saturday 8 April at 2000 and started fishing at 0200 on the Sunday morning around Alderney. The vessel expected to be away from its home port for seven days. With the exception of Tuesday, she fished every day, staying overnight in Alderney. She did not fish on Tuesday because of bad weather.

During the week, there were problems with the domestic hot water system on board. Since the Monday, the hot water taps had not been used because they discharged steam. When the taps were turned on, they first discharged hot water, then steam, followed by hot water.

The crew had no previous experience of steam coming from the taps. The skipper was unsure what to do, so he called the vessel's owner. He advised the skipper to shut off the electrical power to the hot water cylinder immersion heater and told him where the isolation switch was. He also said that if the skipper had any concerns, he should seek a qualified plumber when in Alderney, or on the vessel's return to Brixham. Meanwhile, the problem should be recorded on the repair list.

The skipper rang his father-in-law in Alderney who was a plumber. He advised that the hot water system should be all right because the pressure relief valve should lift. During the week, the skipper released the steam pressure from time to time by opening the hot water taps. The water supply pump was kept running to maintain a continuous water supply to the cold water taps.

1.3 NARRATIVE

Note: All times quoted are UTC (BST-1hour)

During the afternoon of Sunday 16 April 2000, *Fleur de Lys* was returning to Brixham from fishing grounds around Alderney, the Channel Islands. The skipper, Scott Duncan-Borthwick and crewman Jonathan (John) Jeune were resting in their bunks. Crewman Fraser McEndry was on watch in the wheelhouse with the other crewman, Darren Flannigan, keeping him company.

At 1500, Portland Maritime Rescue Sub-Centre (MRSC) received a very faint "Mayday" voice call on Channel 16 VHF. The word "Mayday" was spoken twice, but no position or other information was given. An 'open' microphone, thought to be on a vessel off Swanage, was causing interference and effectively disabling the MRSC's direction finding (DF) facility. Further investigation resulted in the conclusion that this "Mayday" call was a hoax.

Meanwhile, McEndry sat in the wheelhouse chair of *Fleur de Lys* and put his feet up on to the console. Flannigan was standing to his left. Because the trip was coming to its end, both men were in high spirits. At about 1512, there was a large explosion. Momentarily McEndry thought that they had collided with another vessel. The interior of the wheelhouse became very misty within 2 or 3 seconds. Steam was also seen coming from below. Having escaped from the wheelhouse, one crewman walked forward and looked aft. He saw that the wheelhouse had lifted from its mountings and that the mast was at a strange angle.

The two men resting in their bunks also heard the loud bang. The cabin filled with steam, and naturally both men wanted to escape. Water started to enter the cabin. Both men made for the ladder leading up to the hatchway into the galley, but debris prevented them from getting out. Flannigan helped them shift some of the debris from above before they were able to escape on to the deck. As he made his escape, Jeune looked back into the cabin and saw water filling the space.

All on board realised the vessel was sinking. The skipper was able to broadcast a “Mayday” on Channel 16 VHF. This “Mayday” was received at 1512 by Portland MRSC and identified as coming from the fishing vessel *Fleur de Lys*.It gave its position in latitude and longitude as 50° 17.596'N 002° 07.4'W and stated that the four crew members were abandoning the vessel.

The “Mayday” was acknowledged, and a “Mayday Relay” broadcast. At the same time, the Portland Coastguard rescue helicopter Whisky Bravo (R-WB) was scrambled.

Several vessels responded to the “Mayday Relay”. The fast ferry *Condor Express* proceeded at some 40 knots, giving an estimated time of arrival (ETA) of 30 minutes. The Weymouth all-weather lifeboat was requested to launch. The position given by *Fleur de Lys* was plotted and a search plan prepared.

Meanwhile the four men were on the deck of *Fleur de Lys* with water up to their waistlines. One man jumped on top of the galley and pulled the lifejackets from the their storage box. All four put them on.

The liferaft had been blown from its cradle mounted on top of the galley on to the deck between the port side of the wheelhouse and the guardrails. The vessel was going down by the stern. A smoke flare from the port side of the wheelhouse was set off. This ignited and issued red smoke for 3 to 4 minutes. With their feet on the gunwale and water up to their chests, two of the men tried to lift the liferaft clear of the guardrails.

With the liferaft lifted clear of the vessel and debris, one man, now in the sea but hanging on to the guardrails, tried to pull the painter to inflate the liferaft. By this time the sinking vessel was nearly vertical, with her bows out of the water.

Using the vessel as a climbing frame one man was able to locate the knife normally attached to the gunwale on the starboard side amidships. This was normally used to free snagged lines when fishing. The knife was then used to cut the two bursting straps around the liferaft's casing. The liferaft did not inflate.

All four men were in the water, wearing lifejackets but without the jacket straps tied. Some rope had wrapped around the skipper's arm and was becoming tighter. Afraid that he was going to be dragged down with the vessel, he used the knife to cut the rope free.

All shouted to each other to stay together and encouraged each other to talk. They were surrounded by fish boxes and wood. As they trod water their movements started to slow down as they became cold.

At 1528, sixteen minutes after the "Mayday" broadcast, helicopter R-WB reported on the scene that wreckage was visible, but there was no sign of *Fleur de Lys*. At 1535, R-WB reported that all four crew members had been recovered from the water, cold, but with minor injuries.

Dorset ambulance control was alerted, and the helicopter landing site in Dorchester was secured. All vessels were stood down after R-WB confirmed there was no large wreckage on the surface, only small items such as fish boxes etc. The four casualties were landed at Dorchester at 1550 and taken to hospital.

No transmissions from the vessel's emergency position indicating radio beacon (EPIRB) were reported to the coastguard.

1.4 ENVIRONMENT AND POSITION OF SINKING

The coastguard reported that the vessel sank at 1512 in position 50°17.6'N, 002°07.9'W.

Wind was east-north-east force 6. The sea was moderate, visibility good, and the sky was overcast.

1.5 LIFESAVING APPLIANCES (LSA)

1.5.1 LSA on board *Fleur de Lys*

The vessel was surveyed in March 1997 for the purpose of renewal of the United Kingdom Fishing Vessel Certificate. The certificate was valid until 9 March 2001. The record of particulars, annexed to the certificate, records the following LSA particulars.

Lifejackets:

Six Duncan lifejackets, each fitted with a light and retro-reflective tapes, were stowed in a cabinet, outside, on the galley top.

Lifebuoys:

Perry buoys outside on the port side of the wheelhouse.

Pyrotechnic signals:

Pains Wessex smoke markers dated 11/95 to 11/98.

Line-throwing appliance:

Two Pains Wessex type line-throwing appliances. Date of manufacture of rockets and cartridges were 8/95 & 8/98 respectively.

Parachute distress signals:

Twelve Pains Wessex parachute signals dated 2/96 to 2/99. The owner has stated that the pyrotechnics described above have been renewed since the 1999 survey. The ones on board at the time of survey were within the mandatory serviceable period.

EPIRB:

Jotron type 800, serial number 17184 or 800406. Date of expiry 10/2000.

The EPIRB was fitted to the radar mast. Batteries were renewed in 1997.

The EPIRB hydrostatic release unit (HRU) was of the Hammar disposable type, and was 3 years old at the time of the accident; one year beyond the expiry of its 2 year recommended life.

Falmouth Coastguard EPIRB registration section found no records in its database matching the serial numbers 17184 and 800406. There was no reference to *Fleur de Lys* in its records.

EPIRB registration has been mandatory since 1 June 2000, six weeks after the date of the accident.

Liferaft:

The vessel's owner hired the liferaft from Cosalt, Plymouth.

RFD Surviva 6-man serial number 300346 was new in September 1997. It was located in a cradle fixed to the galley roof **(Frontispiece)**.

It was last serviced by Cosalt in Plymouth in July 1999. The owner fitted the liferaft to the vessel.

The HRU was of the Hammar disposable type, and was supplied by Cosalt when the liferaft was serviced in July 1999. The accident occurred within the HRU's serviceability period.

1.5.2 Recovery of the liferaft

The liferaft did not deploy, but sank with the vessel. On 19 April 2000 the sailing charter yacht, *Anegada,* recovered *Fleur de Lys*' liferaft in position 50° 34.6N, 001°13.8W.

The yacht's skipper reported that the liferaft was found fully inflated, with its drogue and painter tangled. The liferaft contained the emergency pack. The stability bags were full of water, and the canopy was erect with its door open.

Because the yacht's crew were unable to haul the fully inflated liferaft on board, they deflated the liferaft by slashing the buoyancy chambers to exhaust the inflation gas. It was landed ashore a few days later and placed into custody of the yacht charterer at Hamble, before being transported to the Cosalt depot in Southampton for inspection.

There, it was confirmed that the inflation gas cylinder was empty, and that the cylinder gas valve had been activated to inflate the liferaft.

1.6 THE HOT WATER STORAGE SYSTEM

The present owner bought *Fleur de Lys* in 1989. At that time the vessel did not have a hot water system. In 1990 she underwent a £31,594 refit, which involved the fitting of a new wheelhouse, hull and deck repairs, extensive electrical rewiring and installation of a generator and switch gear.

The refit also included the installation of an unvented hot water storage system for domestic purposes. The work was contracted to shipwrights Cann and Pender of Paignton, Devon.

The unvented hot water storage system supplied hot water to the shower and galley of *Fleur de Lys*. As the name of the system implies, it is not open to atmosphere when all outlets such as taps and shower valves are closed. Such systems are fitted ashore in domestic premises and commercial buildings, as well as in fishing vessels and leisure craft.

1.6.1 The hot water storage system on *Fleur de Lys*

The following description is based on witness evidence given by the owner, the crew, the plumbers who repaired the system, and documentary evidence of repair specifications.

Description of the system

The hot water system at the time of the vessel's loss was an unvented system based on an insulated storage cylinder, situated on the aft starboard side of the engine room. It was used solely for the domestic needs of the crew, supplying hot water to sinks, shower and galley.

Principal components of the system were: a 120 litre, 900 x 450mm diameter hot water storage cylinder and immersion heater with thermostat; 240V electric motor-driven water supply pump; 5 litre expansion tank.

Electrical power to the pump and immersion heater was supplied by an auxiliary diesel engine-driven 240 volt ac generator fitted in the vessel's forepeak compartment. Power distribution to the system was through a distribution board and circuit breakers situated in the same compartment.

The pump supplied cold water from the vessel's fresh water tank to the hot water storage cylinder, as well as to the cold water taps. Fitted on the cold water inlet side to the cylinder was a combined pressure gauge/pressure reducing valve and pressure relief valve.

The reducing valve was a type manufactured by Altenic of Hixon Staffordshire, with an operating range of 1 to 6bar.

A pressure-activated switch started the pump when a water tap or the shower outlet was opened.

The hot water cylinder was manufactured by Albion Water Heaters of Halesowen, West Midlands, a leading manufacturer of domestic, industrial and marine hot water storage system components.

The cylinder was a conventional British Standard copper cylinder used in vented systems. Its specification was as follows:

- Direct type, 900mm x 450mm, 120 litre capacity, heated by an immersion heater of 3kW;
- Constructed of copper to BS 699:1984, classified as a Grade 4 cylinder for 6m maximum working head;
- Foam insulated to BS1566 Part 1: 1984;

- Heat loss from the cylinder is no more than 1watt /litre water capacity at normal working temperature of 60°C;

- The longitudinal seam was butt-welded and the two ends brazed to the cylindrical shell. The top was convex and the bottom concave.

The immersion heater was made by Red Ring Immersion Heaters. It was of a type often found in domestic hot water cylinders. It had a 3kW heating element, was 686mm (27inches) long and fitted with a Sunvic VKL, 2201 16amp 240 volt thermostat.

1.6.2 Maintenance history of system

Repairs to the hot water storage system were undertaken by AA Heating & Plumbing Services of Wadebridge in Cornwall. The company undertakes extensive work in Devon and Cornwall, installing unvented hot water systems in domestic premises.

The following defects to the system on *Fleur de Lys* were reported to, and were addressed by, this company.

30.09.98 Burst copper pipe and blown immersion heater. Immersion heater, thermostat and pipe replaced. Pipe tested.

Type of fault: immersion heater faulty, causing boiling of water and burst pipe.

10.10.98 Emergency call out to *Fleur de Lys* because of burst hot water cylinder pipe. Pipe replaced, tested and left working.

10.10.99 Bank holiday weekend 1999:

AA heating plumbers drained and removed the hot water storage cylinder, a grade 4 direct type, 900mm x 450mm, 120 litre capacity normally used in domestic open vented hot water systems. They found that the old cylinder was secured only by its pipe connections, and supported at its base by a car tyre.

The lagging had broken away from the cylinder which had imploded around its top seam and was leaking steam. Before removing the old cylinder, the plumbers isolated the power supply to the immersion heater and electric water pump at the distribution board, shut off the water supply and drained the water from the cylinder.

The replacement cylinder was similar to the one it replaced, an Albion grade 4 direct type, 900mm x 450mm, 120 litre capacity, heated by a 3kW immersion heater. The plumbers secured the cylinder to the ship's structure with steel straps, and connected it to the system using flexible pipes.

About one week later AA heating plumbers returned to the vessel to renew the thermostat.

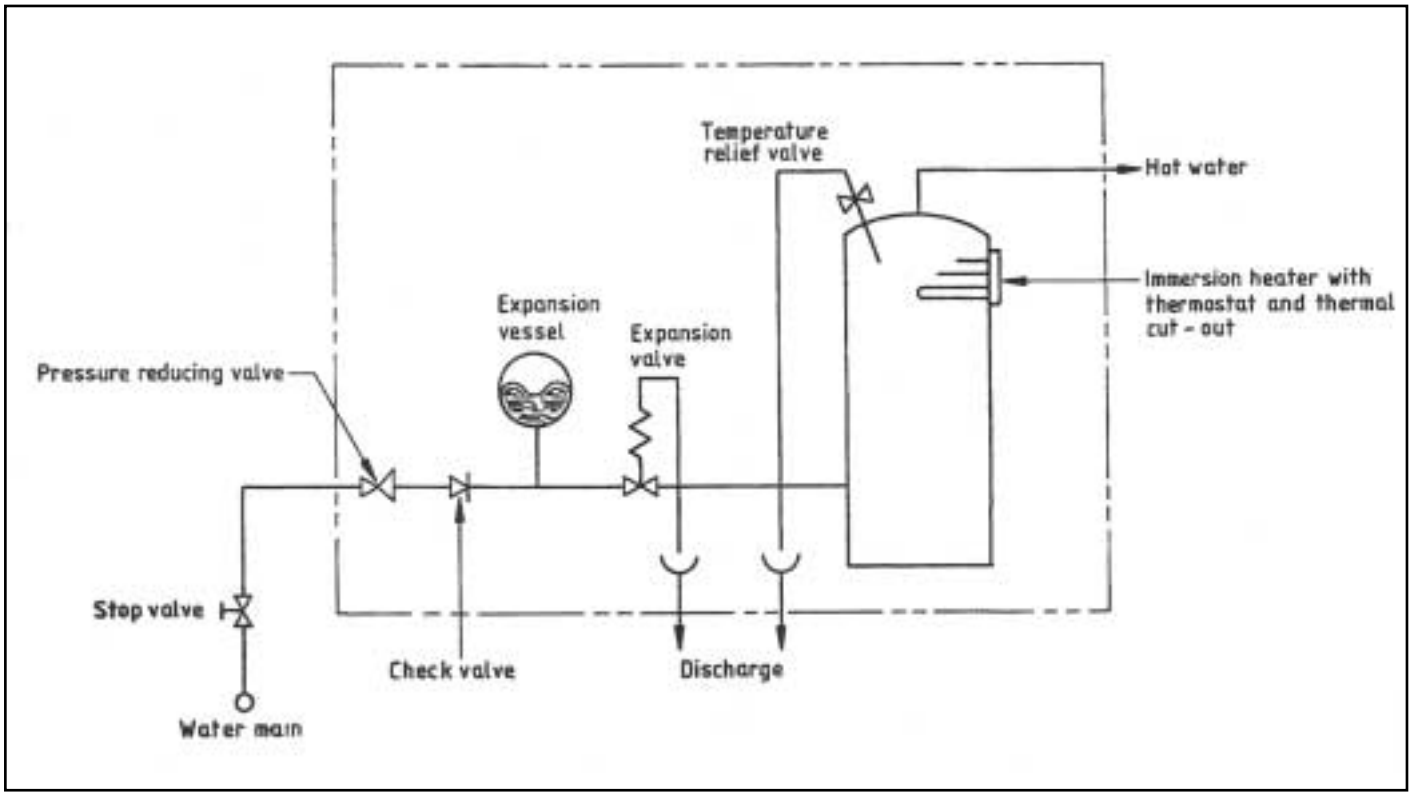
1.6.3 National standards for unvented hot water storage systems

In the United Kingdom, shore-based systems must be designed, constructed and installed to national standards. These standards are given in the Building Standards Regulations, British Standards Institute requirements, the Water Supply (Water Fittings) Regulations and European Directives. There are no similar standards and regulatory provision for marine installations.

The standards aim to prevent the possibility of scalding, overheating, overpressure and explosion. The systems must be installed by suitably trained people.

A typical unvented system, directly heated by an electric immersion heater, is shown in **(Figure 1)**.

Figure 1



Typical arrangement of an unvented hot water system

The system operates above atmospheric pressure. The pressure is regulated by the pressure-reducing valve in the water supply line.

The expansion valve (pressure relief valve) is designed to prevent overpressure of the storage cylinder, and is set to lift within the cylinder's maximum design pressure. The lifting pressure is normally between 2.5 and 6.5bar, depending on the body diameter and shell thickness of the cylinder.

Storage cylinders with a capacity of greater than 15 litres, up to and including 400 litres with a minimum operating pressure of 1 atmosphere, must be fitted with safety devices to prevent the water temperature exceeding 100°C. These must be factory fitted by the manufacturer.

The electrical supply to the immersion heater is interrupted by a thermostatic on/off switch to maintain a water temperature of around 55°C.

In case the thermostat fails, a thermal cut-out is fitted to limit the temperature of the stored water automatically to between 90 and 95°C, by interrupting the electrical (energy) supply. It must be constructed so that the user cannot alter its temperature setting, and it requires either replacement or operation by hand to restore the energy supply.

Should both thermostatic controls fail to interrupt the electrical supply to the immersion heater, without any other control device, there is nothing to prevent the temperature of the stored water from rising. The immersion heater continues to heat the water and generate steam. Because there is no vent through which steam can escape, the pressure inside the cylinder rises.

The pressure will build up to least 2.5bar before the pressure relief valve opens. At any pressure above atmospheric, steam will discharge from taps and shower heads, and, if opened, cause injury by scalding.

To prevent such a situation, a combined pressure/temperature relief valve is fitted at the top of the cylinder. The valve is pre-set to a temperature below 100°C to prevent the water boiling, and allow it to discharge at normal atmospheric pressure. The relief valve prevents internal build-up of steam pressure, and discharge of scalding water and steam when taps are opened.

1.6.4 Instruction manuals

The British standard 7206:1990 requires that each unvented hot water storage system shall be supplied with a comprehensive guide to installation and operation which shall include the following information:

- Name and address of the manufacturer;
- Set opening pressure and temperature of the temperature/pressure valve;

- Recommended maintenance;
- Results of test required by the Standard;
- Advice on correct installation and commissioning of the system;
- Details of the immersion heater, thermostat and thermal cut-out with an instruction not to fit immersion heaters without thermal cut-out;
- How to drain the system;
- Checklist of system components.

1.7 SALVAGE AND SURVEY OF THE WRECK

The P&I Club, interested in the loss of *Fleur de Lys*, made an unsuccessful attempt to raise her in an effort to gather material which would explain why she sank. It also commissioned an underwater video survey of the vessel.

The wheelhouse, galley and most other parts above deck level were missing, probably having been fouled by fishing gear from another vessel. Structural damage to the stern, bows and in way of the engine room was also found. It was concluded that the vessel probably sank because of the hull damage. Neither of the projects established why this structural damage occurred.

During these salvage operations, the wreck was towed across Swanage Bay on passage to Poole. However, salvors were forced to abandon the wreck at the northern end of Swanage Bay and lower it to the seabed in position 50° 37.4'N 001° 56'W. These operations were then abandoned.

The MAIB later commissioned a diving operation to survey the wreck and establish the cause of the structural damage to the hull. A particular objective was the retrieval of the hot water storage cylinder to establish whether it had ruptured. This was completed during May 2001.

1.7.1 The MAIB diving project

The condition of the wreck was as found during the earlier salvage operations. However, it was 45° from the upright to starboard, making any inspection of the starboard side of the hull impossible. No part of the wheelhouse or galley structure remained. Most of the bulwarks were missing. The stem was seriously damaged, with much of this area missing. The stern was split vertically from deck level to the keel just to port of centre. A complete length of planking was missing from the port side of the hull, in way of the engine room, below the vessel's normal water line. Another plank slightly below this had sprung at its forward end. The cabin and engine room were exposed but were filled with debris, much of which was bedding, parts of engine room to cabin division, and unidentified artefacts.

Divers spent several hours removing this debris. Once the engine room had been emptied of items of significant size, it was clear that the hot water cylinder, in its original form, was not in the engine room. The search continued in the lower reaches of the engine room for items smaller than an intact hot water cylinder.

During the late morning of the second day of this work, the base of the hot water cylinder was found. This was at the port side of the engine room, level with the floor plates, about 400mm forward of the aft engine room/cabin division. Shortly afterwards, the top of the cylinder, complete with immersion heater element, was found slightly forward of this position.

Further searching resulted in the cylinder's cylindrical wrapper plate being found beside the starboard side of the main engine, partially below floor plate level, and about 2m forward of the engine room/cabin division. A smaller piece was close by. The wrapper plate was noted to be embossed with the manufacturer's mark, M4469 **(Figures 2, 3 & 4)**.

These three items were all seriously distorted, and no thermal insulation remained on their surfaces. The cylinder bottom showed signs of failure of the circumferential brazed joint to the wrapper plate. Many other failure surfaces were of virgin material some distance from any brazed or welded seam.

1.8 MANNING

Fleur de Lys had a four-man crew. None were required to hold a certificate of competency.

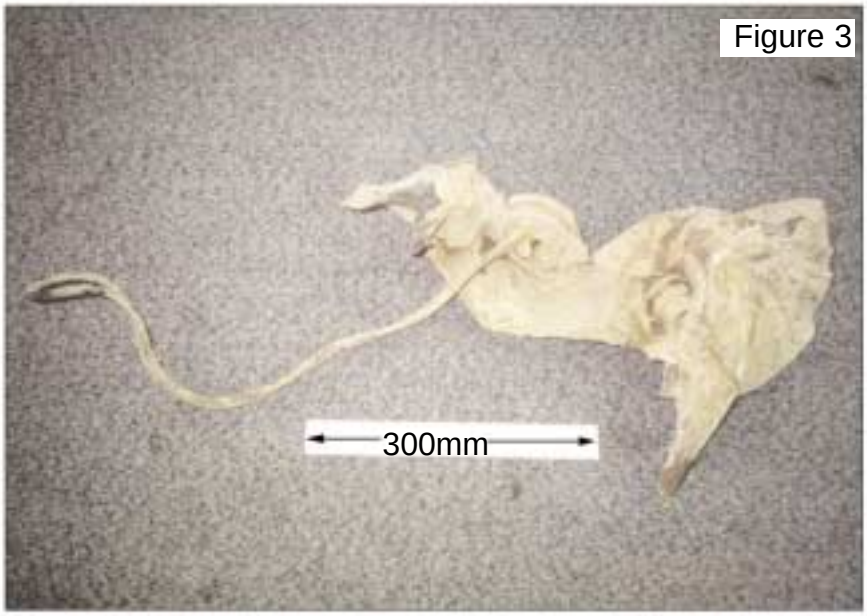
Scott Duncan-Borthwick, skipper aged 29. He had 14 years experience on fishing vessels and held first-aid, fire fighting and sea survival certificates.

Jonathan Abraham Jeune, aged 42, had been fishing at sea for 20 years. He completed three sea survival training courses in Jersey during that time.

J Fraser McEndry, aged 34, had been crab fishing at sea for 15 years. He completed sea survival, fire fighting and lifeboat handling courses.

Darren Flannigan, aged 28, had been fishing at sea for about 12 months. He had not attended a sea survival course.

Base of hot water cylinder



Cylinder top, with element of immersion heater

Wrapper plate of cylinder

SECTION 2 - ANALYSIS

The purpose of this analysis is to determine the circumstances and contributory factors of the accident, as a basis for making recommendations to prevent similar accidents in the future.

Evidence from the crew, all of whom survived, and underwater inspections were consistent with the *Fleur de Lys* sinking due to structural damage.

Further, it is reasonable to conclude that the damage was the result of the violent rupture of the hot water storage cylinder. The reasons for this conclusion are discussed below.

2.1 SINKING OF *FLEUR DE LYS*

One crewman in the wheelhouse first thought there had been a collision. However, after the initial shock of being thrown from his seat, and seeing the damage to the wheelhouse structure, he quickly realised there had been some kind of explosion. The other three crewmen were equally convinced that an explosion had taken place.

Although collision was a possibility, there was good reason not to dispute their observations that an explosion took place.

It is reasonable to expect that the force of impact of a collision, with say a larger ship, could have caused the extent of damage described by the survivors, and found during the surveys of the wreck. The damage was such that *Fleur de Lys* flooded very quickly, and within a few minutes sank by her stern without listing.

However, the factors giving credence to the probability of an explosion in the engine room outweigh those indicating the possibility of a collision.

The crewmen described the explosion as centred on the engine room. The wheelhouse was immediately above that space, so an explosion of sufficient magnitude could have forced the wheelhouse off its mountings in the way described by a crewman. Such an explosion would also explain why he was thrown upwards, banging his head on the wheelhouse deckhead.

A collision probably would have caused *Fleur de Lys* to roll to one side on impact. This did not seem to happen

Since there was no report of any heat or smoke generated, nor even any odours associated with burning oil, the possibility of an explosion caused by ignition of fuel, or lubricating oil, is dismissed. Instead of smoke, which would have resulted from an explosion of hydrocarbons, the wheelhouse and accommodation space were filled with steam.

The only likely source of such a large volume of steam was the hot water storage cylinder. This was installed in the engine room, on the bulkhead dividing the engine room from the cabin, and directly beneath the wheelhouse which felt the full effects of the blast. This bulkhead was also seriously affected.

Given the damage described, and the presence of steam, the possibility that the explosion was due to overpressure of the cylinder, resulting in serious structural damage leading to the sinking, was therefore investigated.

2.1.1 Possibility of explosion of hot water cylinder

A few days before the incident, the crew reported that steam, then water, followed again by steam, had discharged from the domestic hot water taps. Although the crew had opened taps from time to time to vent off the accumulating steam, electrical power to the cylinder immersion heater was not switched off.

The hot water cylinder immersion heater thermostat was meant to limit water temperature to a safe level, so that the hot water could comfortably be used. Clearly, the thermostat failed. Previous incidents of burst cylinder and pipes indicated that the immersion heater thermostat had failed before. However, in each case, there had been insufficient pressure to cause violent rupture of the cylinder.

The manufacturer, Sunvic, has stated that thermostat switches can fail in the closed position. Such a condition would result in a continuous electrical supply to the immersion heater and uncontrolled heating of the cylinder water.

In the absence of a temperature/pressure relief valve and thermostatic cut-out switch, overheating, steam generation and overpressure were likely. If these safety devices had been fitted, and working it is most likely that the explosion would not have happened.

A pressure relief valve, would probably have been set at a lift pressure of no less than 2.5bar. None of the crew reported any steam discharge in the area of the storage cylinder. If there had been such a discharge, this would have indicated the possibility that the valve was lifting under the pressure head of steam.

The MAIB appointed Information Search & Analysis Consultants (IS&AC), of London to evaluate the potential hazard of an exploding hot water cylinder and its potential to damage and sink the vessel **(Annex 1)**. The consultants argued that, given the significant heat input by the immersion heater compared with the heat loss rate, the grade 4 cylinder probably failed at its failure pressure of 3.4bar. The inspector’s view is that if the cylinder failed at this pressure then the pressure relief valve, must have been set at this pressure or higher, or it was seized in the closed position.

The latter possibility could have been due to scale and sludge, which could accumulate naturally at the base of the cylinder and in the water inlet pipe where the valve was fitted.

2.1.2 Likely effects of explosion

The MAIB consultants considered two grades of cylinder construction. A grade 4 domestic hot water cylinder, as fitted on board *Fleur de Lys* and a marine grade cylinder of similar size with their immersion heaters switched on continuously. The copper plate thicknesses of the cylinders are described in Section 1, the marine grade having the bigger shell thickness.

The consultants confirmed that both cylinders would have burst due to excess internal pressure if the immersion heaters were left on for an extended period with no means of venting off pressure. Significant damage to the vessel's hull could have occurred as a result of the blast wave produced by the explosion. The full report submitted to the MAIB is in **Annex 1**.

The water cylinder body would form a missile as a result of the explosion. The missile velocities calculated were such that the missile would have been expected to breach the hull in both cases.

The consultants' overall conclusion was that an explosion with either grade of cylinder would have damaged the vessel sufficiently for her to flood and sink.

2.2 SUITABILITY OF THE HOT WATER SYSTEM ON *FLEUR DE LYS*

2.2.1 The copper cylinder

The grade 4 cylinder fitted to *Fleur de Lys* was one of four grades and 16 sizes of copper hot water storage cylinders specified by British Standards 699: 1989 for domestic purposes.

The grade numbers relate to the maximum allowable working head. Grades 1, 2 & 3 indicate a maximum head of 25, 15 & 10 metres respectively. (2.5,1.5 & 1.0bar gauge pressure respectively). The head is the distance from the base of the cylinder to the top of the water level in the cistern feed tank. A grade 4 cylinder has the lowest maximum allowable working head of 6 metres and the lowest test pressure requirement.

These test pressures requirements are:

Grade 1 - 3.65bar
Grade 2 - 2.2bar
Grade 3 - 1.45bar
Grade 4 - 1.0bar

Grades 3 and 4 are normally used in open vented systems found in domestic premises.

2.2.2 The grade 4 hot water storage heater

The suitability of a grade 4 cylinder for use in an unvented system, such as that fitted on *Fleur de Lys*, is considered below.

In England and Wales, building regulations require unvented hot water systems to comply with British Standard 7206 specifications for unvented hot water storage units and packages. With regard to a hot water storage cylinder of the size fitted to *Fleur de Lys*, (900 x 450mm diameter), for an unvented system the cylinder metal thickness is tabulated below:

Copper cylinders for unvented systems - Nominal thickness of body and minimum thickness after forming ends (mm)									
Body diameter - **450 mm**									
Expansion relief valve setting, (bar)	**2.5**	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
Thickness (mm)	**0.9**	1.2	1.4	1.6	1.8	2.0	2.2	2.5	2.6

Grade 4 copper cylinder - Minimum nominal thickness of copper sheet before forming. (mm)			
Test pressure (gauge): 1.0bar Maximum working pressure (gauge): 0.6bar			
	Body	top	bottom
Thickness (mm)	0.55	0.6	0.9

The tables above indicate that the minimum thickness of the shell body of a 450mm diameter cylinder, used in an unvented system, is 0.9mm for an expansion valve setting of 2.5bar. This compares with the shell body thickness of 0.55mm of the grade 4 cylinder which is clearly not intended to withstand a minimum design pressure of 2.5bar, as required of a storage cylinder used in an unvented system.

2.2.3 Temperature and pressure control

The standards required of unvented hot water storage systems used ashore, were discussed in the previous section of this report.

To summarise, unvented hot water storage systems require safeguards to prevent overpressure and scalding. These safeguards are:

- cylinder working pressure maintained within limits which are dependent of cylinder's strength and
- water temperature limited to 100°C.

On the first point, the British Standard requires that a pressure relief valve (expansion valve) is installed in the cold water feed to the cylinder from the water supply pump. As far as the AA Plumbing and Heating plumbers could recall, such a pressure relief valve had been fitted because they used it to relieve the pressure on the system before replacing the damaged cylinder.

On the second point, the standard requires that the system must have factory-fitted devices to prevent overpressure due to temperature rise of the water. To achieve this, a temperature controlled electrical supply cut-out switch must be located on the storage cylinder. The cut-out can only be reset manually rather than automatically. In addition to this, a temperature/pressure relief valve must be fitted to prevent boiling and steam discharge from taps.

By shore installation standards applicable to unvented hot water systems, the system fitted to *Fleur de Lys* was not suitable for the purpose intended because:

- The storage cylinder shell thickness was too thin and unsuitable for an unvented system operating above atmospheric pressure – the cylinder's maximum working pressure was 0.6bar and its test pressure 1.0bar.
- A temperature electrical cut-out switch and temperature/pressure relief valve were not fitted.
- The pressure relief valve fitted would have been suitable for a lifting pressure range between 2.5 and 6.5bar, which was above the working pressure and test pressure of the storage cylinder installed.

2.3 FACTORS CONTRIBUTING TO THE ACCIDENT

2.3.1 Actions of the crew

During the few days before *Fleur de Lys* sank the crew became aware that something was wrong with the hot water system when steam discharged from the taps. They were naturally concerned, but were unaware of the danger of explosion. Their main concern was the risk of scalding and the loss of hot water on board. This loss was compensated by the availability of showers in the marina at Alderney, where the vessel berthed each evening.

They made some effort to work out what was wrong, but were at some disadvantage. They had no idea how an unvented hot water system worked;

there were no instructions or guidance notes to help them, and they were oblivious of what safety devices ought to have been fitted to prevent overpressure and overheating.

Any training and experience the crew might have had contributed little to their ability to diagnose the fault.

The other crew members had little interest in the engine room except to help in topping up engine oil sumps and cooling water tanks, and changing engine oil filters from time to time.

One crewman had some knowledge of engineering systems. He knew, for example, how to change marine engines' belts and engine oil. He had also owned a motor cycle, which he maintained. However, his enthusiasm for the mechanical systems of a motorcycle did not extend to those of the vessel's engine room.

Other crewmen also had no interest in the vessel's engineering. None of the four men had any formal training in the operation and maintenance of fishing vessel engineering systems.

A fishing vessel having propulsive power greater than 750kW is required to have certificated crew on board satisfying the requirements of The Fishing Vessels (Certification of Deck Officers and Engineer Officer) Regulations 1984. Fishing vessels of lower propulsive power, such as *Fleur de Lys* (164kW) are not required to have any crew on board with engineering knowledge or qualifications.

The skipper had little understanding of the hot water system. His view was that if faults were found with machinery etc, then it was the owner's responsibility to ensure that it was put right before the vessel left port. The skipper's main function was to ensure a good catch of fish. He was of the view that he should not have to spend time sorting out machinery faults. Despite this view he did try to sort out the problem, albeit unsuccessfully.

In his effort to find out what was wrong, the skipper examined the hot water storage cylinder. Because of the way the pressure gauge on the unit was facing, he explained that he was unable to see what pressure was in the tank. He checked the fresh water level tank gauge, thinking that the tank might have been empty. It was not. As a precaution against scalding, he told the crew not to open the hot water taps.

After seeking advice ashore from the owner and his father-in-law, who was a plumber, he was content to vent off the steam pressure regularly through taps, and arranged for the system to be repaired on the vessel's return to England a few days later.

Steam generation in the hot water system could have been stopped by simply switching off the electrical supply to the immersion heater; the switch was on the distribution board in the forecastle.The water in the storage cylinder would have cooled to ambient temperature, and cold water would then have discharged from both hot and cold taps. The owner, on advising the skipper to shut off the electrical supply to the immersion heater, was content for the skipper to solve the problem by consulting a plumber either in Alderney, or in England, when the vessel returned.

2.3.2 Action of the owner of *Fleur de Lys*

The skipper warned the owner of the problem experienced with the hot water system. The owner was content to wait until the vessel arrived in England before the problem was resolved.

He had the hot water system installed ten years before the accident, during an extensive refit undertaken by shipwright contractors Cann and Pender.

Accounts of what was fitted at the time differ. Mr Cann of Cann and Pender, explained that a 15 litre Cleghorn water storage heater and fittings were fitted to the vessel. He explained to the MAIB inspector that the storage heater was fastened to the bulkhead with stainless steel straps supplied by the maker. Mr Cann's recollection conflicted with that of the owner who recalled that a 120 litre storage cylinder was fitted but could not recall what type. There is no documentation available to verify what in fact was fitted at the time.

If indeed these were Cleghorn components, they would have been supplied by Cleghorn Waring of Letchworth, England. The company is a leading manufacturer of unvented hot water systems, which comply with United Kingdom national shoreside standards. These standards are described in Section 1 of this report.

Cleghorn supplies systems to the leisure craft and fishing industries. There have been many such systems expertly fitted to fishing vessels which comply with these standards. This has been done voluntarily, because there are no marine standards for hot water storage systems.

If it was a Cleghorn system which had been fitted to *Fleur de Lys* in 1990, the water storage cylinder and heater would have been supplied with a thermostatic cut-out switch to prevent overheating in case the immersion heater thermostat failed. A pressure relief expansion valve would have also been fitted. A temperature/pressure relief valve would not have been fitted to the Cleghorn system at the time of installation by Cleghorn in 1990 since this safety device was only introduced in 1991.

Neither the owner, nor Mr Cann, can recall if any of these safety devices were fitted.

To help in the MAIB's investigation, the owner kindly arranged to accompany the inspector on a visit to a fishing vessel fitted with a Cleghorn system. The vessel was fv *Keristun* which was moored alongside at Dartmouth, Devon. The inspector examined the system and found a neat and well engineered installation, with safety devices described in the standard. The owner of *Fleur de Lys* expressed surprise at the quality of the installation, and exclaimed that it seemed to be a different system to that fitted on his vessel.

The owner seemed to have little knowledge of what safety standard ought to be applicable to hot water systems. His lack of knowledge of the dangers of hot water storage systems was borne out by the fact that he did not consider reasons for, or safety implications of, the earlier burst pipes and cylinder. Also, he was content to have fitted a substandard storage cylinder without the necessary safety devices.

As for the cylinder, economic considerations might also have influenced his decision. A 120 litre grade 4 storage cylinder for use in vented systems, like the one fitted to *Fleur de Lys*, retailed at about £80. Its counterpart, fitted with standard safety devices needed for an unvented system, cost about £400.

2.3.3 Action of AA Heating & Plumbing Services

Until their work on *Fleur de Lys*'s hot water system, the plumbers had not worked on ships before. However, they were experienced installers and repairers of unvented hot water systems shoreside.

The owner of the plumbing company, and the men who carried out the work on *Fleur de Lys*, were very helpful to the inspector. They showed him a recently installed domestic unvented hot water system, and explained the essential safety devices and other components in the system. They were rightly very proud of their knowledge of the system and their workmanship in fitting it. The impression given to the inspector was that they were competent and knowledgeable installers.

One plumber was a designated trainer of new recruits into the company. Another had many years' experience fitting these systems in new building projects, such as those in Canary Wharf, in the East-end of London. Both were employed to install and maintain unvented hot water systems.

Yet despite this experience and safety awareness, they did not offer any warnings to the owner of *Fleur de Lys* about the consequences of fitting a substandard storage cylinder without standard safety devices. Working on a fishing vessel was a new experience to them. They told the inspector that they disliked working in the cramped, noisy and oily conditions of the engine room. One plumber said that he had to take time off work to recover.

Unlike shoreside installations, there is no legal provision to install marine systems to a recognised safety standard. However, acceptable safety standards were well known to AA Heating and Plumbing Services. The company was mistaken to install substandard equipment for an owner, whose possible motivation was to find the cheapest option to solve his problems.

2.3.4 Actions of the Department of Transport, Environment and Regions, (DETR) and Maritime Coastguard Agency

The DETR required stringent requirements for domestic and industrial buildings, to guard against overpressure and scalding from hot-water systems. The requirements evolved from experience of grim and fatal accidents ashore.

The DETR, whose jurisdiction covered both buildings and ships, did not place any value in terms of regulation and standards to ensure the safety of unvented hot water storage systems on board fishing vessels. There is, therefore, no requirement for these systems to be approved or surveyed by the department's MCA. Thus, when *Fleur de Lys* was surveyed and assigned a safety certificate there would have been no reference made to its hot water system.

Mandatory requirements alone do not guarantee an acceptable level of safety on fishing vessels. Owners and crews have a responsibility to ensure that their vessels are safe. However, as the domestic shoreside sector has learned, mandatory safety standards for unvented hot water systems result in a significant decrease in risk of scalding and explosion.

A similar level of safety is needed in fishing vessels. To achieve this, MCA should provide a similar safety standard and advice for fishing vessels as that provided for the building industry ashore.

2.4 THE ABANDONMENT OF THE VESSEL

The explosion was sudden and unexpected. *Fleur de Lys* sank within the 16 minutes between the "Mayday" call and the arrival of the helicopter at the scene of the accident. Until they saw the helicopter, the four seafarers believed they were in mortal danger.

The skipper and the crewman had little time to escape from the accommodation, which quickly filled with water. The only exit from the space was restricted by the clutter of damaged furniture and the jammed door leading into the galley. They were able to escape because of their determination to survive and because of the quick action of another crewman, who had the presence of mind to remove the damaged door obstructing the exit.

Fortunately, the radio batteries were unaffected by the explosion and the initial stages of flooding. A lesson to be learned from this accident is that storing batteries high up in an engine room increases a crew's chances of survival of

flooding. Because of this and the skipper's sharp response a "Mayday" was sent only a few minutes after the incident, and just before the vessel sank.

The crew knew that the vessel was flooding rapidly and would sink very quickly. Their chances of survival depended on the immediate availability of lifejackets. The owner had heeded advice from local fishermen and stowed them on deck where they were easily retrieved in an emergency. Lifejackets are usually stored inside the vessel, where access is difficult, and sometimes impossible if the vessel is on fire or sinking.

The four men of *Fleur de Lys* were thankful that the owner made such a wise decision. Had the lifejackets been stored inside the vessel, it is probable that they would not have retrieved them before the vessel filled with water. Some of them stated that in the 16 or so minutes they were in the water, they became cold and were unable to feel their legs. Without lifejackets their chances of survival would have greatly diminished.

Once in the water, the crew were full of despondency that they had failed in their efforts to inflate the liferaft, that it had not resurfaced after the vessel sank and that the smoke marker apparently failed to operate effectively. Why the latter failed is unknown. The smoke marker probably did not work properly because its working life had expired. Its expiry date was November 1998, nearly two years out of date.

Three of the crew believed that having experience of the basic sea survival course helped them. Once in the water and after the vessel had sunk, they ensured that their lifejackets were properly secured. As the four trod water they had the sense to group together to help each other maintain morale by talking, and encouraging each other to believe that help would soon be on hand.

All were very disappointed that the liferaft went down with the vessel. It had been serviced within the mandatory service period. To deploy it, they would have needed to extract the painter from the liferaft casing until they were able to operate the gas release mechanism on the bottle. The crew complained that they had been unable to deploy the liferaft by pulling the painter. The task had been made difficult, if not impossible, because both the casing, and the person trying to deploy the raft, were floating in the water, so there was no solid foundation from which to get a firm hold.

The liferaft did not surface in time to be of any value to the seafarers. When it did surface inflated, the crew had already been rescued and been landed ashore safely.

It is possible that the liferaft did not surface immediately because the HRU had been fitted incorrectly. Seafish has reported that out of 23 liferafts fitted to small fishing vessels, such as *Fleur de Lys*, only two HRUs were found to have been

fitted correctly to allow automatic release of the liferaft once the vessel had submerged. The MAIB has also found a significant number of HRUs have failed to operate because of incorrect installation.

In this case, however, the weak link of the HRU must have broken and released the liferaft, since it was later found floating and fully inflated. One explanation why it did not release and inflate sooner is this: because the casing had been partially opened in the attempt to inflate the liferaft, the casing filled with water, lost buoyancy and became caught up in the sinking vessel temporarily. Eventually, the liferaft disentangled itself from the wreckage, surfaced and inflated, because it still had sufficient buoyancy to do so.

The crew hoped that the coastguard had heeded the “Mayday” message, and that the EPIRB had activated its emergency signal. In fact, the EPIRB did not activate. It is possible that the HRU was incorrectly installed or had malfunctioned. It is also possible the out-of-date HRU unit did not function and failed to release the EPIRB from its mountings, or that it had been damaged by the shock of the explosion. However, the search and rescue efforts of both the coastguard, and the helicopter crew, were rapid and effective.

2.5 THE “MAYDAY”

Ten minutes before receiving the “Mayday” from *Fleur de Lys*, Portland MRSC had received another “Mayday” which was, eventually, classified as a hoax. It was certainly not sent by *Fleur de Lys.* However, the effective disabling of the MRSC’s DF system, by an ‘open’ microphone on the VHF set of another vessel, was still generating a nuisance.

Fortunately the skipper of *Fleur de Lys* was able to give an accurate position when he sent his message. Had he not done so, locating the survivors without the DF system would have been much more difficult.

This incident highlights the importance of giving a position in any “Mayday“ call, since the coastguard’s DF system might, for reasons beyond its control, not be fully functional. It also highlights the responsibility of all who use VHF radios tuned to Channel 16; the channel must be kept clear for essential traffic, and must not have its efficacy upset by unwanted transmissions, even silent ones from sets where transmit buttons are inadvertently depressed.

SECTION 3 - CONCLUSIONS

3.1 FINDINGS

1. *Fleur de Lys* sank 16 minutes after the “Mayday” call and before the helicopter arrived. [1.3]

2. All four crewmembers were rescued by helicopter from the sea. [1.3]

3. A “Mayday” was sent out by *Fleur de Lys* within minutes of an explosion in the engine room. [1.3]

4. The vessel sank by the stern without any noticeable list. [1.3]

5. The vessel sank in position 50^{o} 17.6’N 002^{o} 07.9’W. [1.4]

6. The radio batteries survived the explosion and flooding. They survived the flooding because they had been installed high up in the engine room. [1.3, 2.4]

7. The crew’s immediate chance of survival was enhanced significantly because the lifejackets were stored on deck. Had the lifejackets been located inside the vessel, it is unlikely that the crew would have been able to retrieve them before the vessel sank. [1.3, 2.4]

8. The experience of attending the basic sea survival course helped the crew react effectively during their ordeal in the water. [2.4]

9. The crew had been unsuccessful in attempting to launch the liferaft. [2.4]

10. The liferaft sank with the vessel and did not resurface in time to be of any help to the crew. [2.4]

11. The liferaft was later found adrift, fully inflated and equipped. [1.5]

12. The liferaft had been serviced within its mandatory service date. [1.5]

13. The smoke markers did not operate effectively. The reason why it failed is unknown. [1.5,2.5]

14. The EPIRB did not operate. [2.4]

15. The renewal date for the EPIRB HRU had expired. [1.5]

16. The EPIRB batteries were renewed three years before the accident. [1.5]

17. Falmouth Coastguard could not find any record in its database of the serial numbers marked on the EPIRB fitted to the vessel, nor of any reference to *Fleur de Lys*. [1.5]

18. EPIRB registration was made mandatory on 1 June 2000, six weeks after the accident. [1.5]

19. The vessel was fitted with an unvented hot water storage system. [1.6]

20. A hot water storage cylinder of insufficient strength was fitted to this system. [2.2]

21. Steam persistently discharged from the hot water taps on board the vessel in the few days leading up to the explosion. [1.2,2.1]

22. The burst hot water storage cylinder and pipes, which happened in the months leading up to the explosion, highlighted the possibility that an explosion could occur - a danger signal that remained unheeded by the owner of *Fleur de Lys* and AA Heating & Plumbing Services. [2.2]

23. A replacement hot water cylinder, of the same type and grade, was fitted about six months before the accident. [1.6]

24. The replacement hot water cylinder was found, catastrophically damaged, in three discrete parts in the engine room of the wreck. [1.7]

25. The sudden release of energy contained in the hot water cylinder under pressure was sufficient to cause serious structural damage to the vessel. [2.1]

26. The MCA had surveyed and issued a United Kingdom Fishing Vessel Certificate to *Fleur de Lys*. [2.3]

27. There was no mandatory requirement for the MCA to inspect *Fleur de Lys*'s hot water storage system. [2.3]

28. The DETR provided regulation and guidance for United Kingdom land-based national standards of design, construction, and installation of hot water storage systems. There is no similar provision for fishing vessels. [2.3]

3.2 CAUSES

The explosion

The hot water storage cylinder ruptured because the water in it overheated and steam generated, causing overpressure. The rupture of the cylinder probably occurred at about 3.4bar, four times working pressure of the cylinder. The pressure relief valve must have been set at this pressure or above, or it was seized in the closed position.

The cylinder probably overheated when the immersion heater thermostat failed to shut off the electrical supply to the heater. There were no safety devices fitted to the system to prevent overheating and overpressure as a result of thermostat failure.

The sinking

The vessel sank because of damage to her hull caused by the violent rupture of the hot water storage cylinder.

3.3 FACTORS CONTRIBUTING TO THE EXPLOSION

1. The crew and owner had inadequate technical knowledge of the hot water storage system, so were unaware of the danger of overheating and the safety actions necessary to avoid an explosion.

2. Regulations and guidance do not provide adequate standards for the construction, installation and maintenance of unvented hot water systems in fishing vessels.

SECTION 4 - RECOMMENDATIONS

The Maritime and Coastguard Agency is recommended to:

1. Provide standards and guidance for United Kingdom registered fishing vessels for standards of design, construction, and installation of hot water storage systems. These systems should be equipped and maintained with safety devices designed to prevent incidents of storage cylinder overheating, overpressure and explosion such as occurred on *Fleur de Lys*.

2. Promulgate to the fishing industry the wisdom of stowing lifejackets on the open deck for easy access.

Marine Accident Investigation Branch
October 2001

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Fishing Vessel 'FLEUR de LYS'

Evaluation of Possible Explosion

Study for Marine Accident Investigation Branch

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Contents

1 INTRODUCTION

1.1 BACKGROUND

This work has been performed to assist the client, The Marine Accident Investigation Branch, establish the cause of the sinking of the fishing vessel Fleur de Lys while she was at sea.

The vessel's crew who escaped before she sank reported an explosion centered on the engine room area immediately preceding the flooding which took place rapidly from the aft. Mention is also made of the wheelhouse being lifted from its mountings.

A hot water system was installed about 10 years ago. In the few days before the vessel sank the crew reported problems with the hot water system. The system included a storage cylinder in which water was heated by an immersion heater. There was no atmospheric vent to the hot water cylinder or the system and the system was classified as closed or unvented.

There is the possibility that the hot water storage cylinder failed explosively under loads from the internal pressure of steam. This work provides a quantitative basis for evaluating whether or not the release of energy from the rupture of the cylinder could lead to sufficient damage to the vessel to cause it to flood and sink.

1.2 DATABASE.

1.2.1 Data has been provided by the client in the form of drawings, text descriptions, construction and other standards and a manufacturer's data sheet as follows:

Doc.1 Sketch A of the fishing vessel Fleur de Lys showing profile and plan views

Doc.2 Sketch B of the Wheelhouse of the fishing vessel Fleur de Lys showing plan and two elevation views and details of fixings

Doc.3 "Rules for the construction of wooden fishing vessels" published by White Fish Authority/Herring Industry Board (1975)

Doc.4 BS 699:1984 "Copper direct cylinders for domestic purposes".

Doc.5 Fact File 009: "Albion Marine Calorifiers" - Manufacturer's Data Sheet.

1.2.2 Other sources, including technical data and calculation procedures are as follows:

Ref.1 "Guidelines for Evaluating the Characteristics of Vapour Cloud Explosions, Flash Fires and BLEVEs" published by The Center for Chemical Process Safety of the American Institute of Chemical Engineers, (1994)

Ref.2 "Explosion Hazards and Evaluation" by WE Baker, PA Cox, PS Westine, JJ Kulesz and RA Strehlow, published by Elsevier Scientific Publishing Company in 1983

Ref.3 "Explosive Shocks in Air" by GF Kinney published by MacMillan Company, (1963).

Ref.4 Kempe's Engineers Year Book 1988 Edited by Carill Sharpe published by Morgan-Grampian Book Publishing Co.

Ref.5 "Chemical Engineering" by JM Coulson and JF Richardson, published by Pergamon Press, (1956).

1.3 SCOPE

This report provides the essentials for evaluating the potential hazard of an exploding heated water container and its potential to damage the structure of the fishing vessel bringing about flooding and subsequent sinking.

The next two chapters set out the information on which the assessment has been made, detailing the relevant features and quantitative details of the hot water cylinder in Chapter 2 and the ships construction in Chapter 3.

Chapter 4 describes the calculations and presents the results. It is divided into three sections: an Introduction and a Section for each of the

two cases. Each Section is also subdivided into subsections numbered 1 to 4 dealing in turn with the failure of the water cylinder, the calculation of the explosion forces, the evaluation of how these forces develop loads on the ships structure and the details of the attempt to determine the possible consequences of these loads on the complex structure of the vessel's timbers and the steel deck.

The conclusions are set out in Chapter 5.

2 THE HOT WATER CYLINDER

2.1 INTRODUCTION

Two cylinder constructions are to be considered:

A Grade 4 water cylinder when its immersion heater is continually on
A marine grade cylinder similar to the Grade 4 water cylinder under the same circumstances.

The two cylinders are described separately below

2.2 GRADE 4 WATER CYLINDER

The cylinder under consideration is constructed of copper, has height of 900mm and a diameter of 450mm. The cylinder has a convex hemispherical top end and a concave domed bottom. According to the appropriate British Standard its maximum storage capacity is 120 litre.

The maximum working pressure is defined as a head of 6m of water (approximately 0.6 bar gauge) and the test pressure is 1 bar gauge.

The cylinder is insulated against the loss of heat so that such losses are restricted to 120 W for this cylinder at a temperature difference between ambient and the water in the cylinder of 50°C.

The vessel mass is estimated at about 30 kg.

2.3 MARINE GRADE WATER CYLINDER

The cylinder in this instance is constructed of copper with a thickness of 1.8mm throughout, has height of 900mm and a diameter of 450mm. The cylinder has a convex hemispherical top end and a convex hemispherical bottom and its storage capacity is 106 litre.

The maximum working pressure is defined as a head of 6m of water (approximately 0.6 bar gauge) and the test pressure is 5.17 bar gauge.

The cylinder is insulated against the loss of heat so that such losses are

restricted to 106 W for this cylinder at a working temperature of 60°C representing a difference between ambient and the water in the cylinder of about 45°C.

The manufacturer's experience is that the cylinder will fail along its longitudinal seam when tested hydrostatically but they have no information on the likely failure mode due to overpressure when containing gas or vapour.

The vessel mass is estimated at about 30 kg.

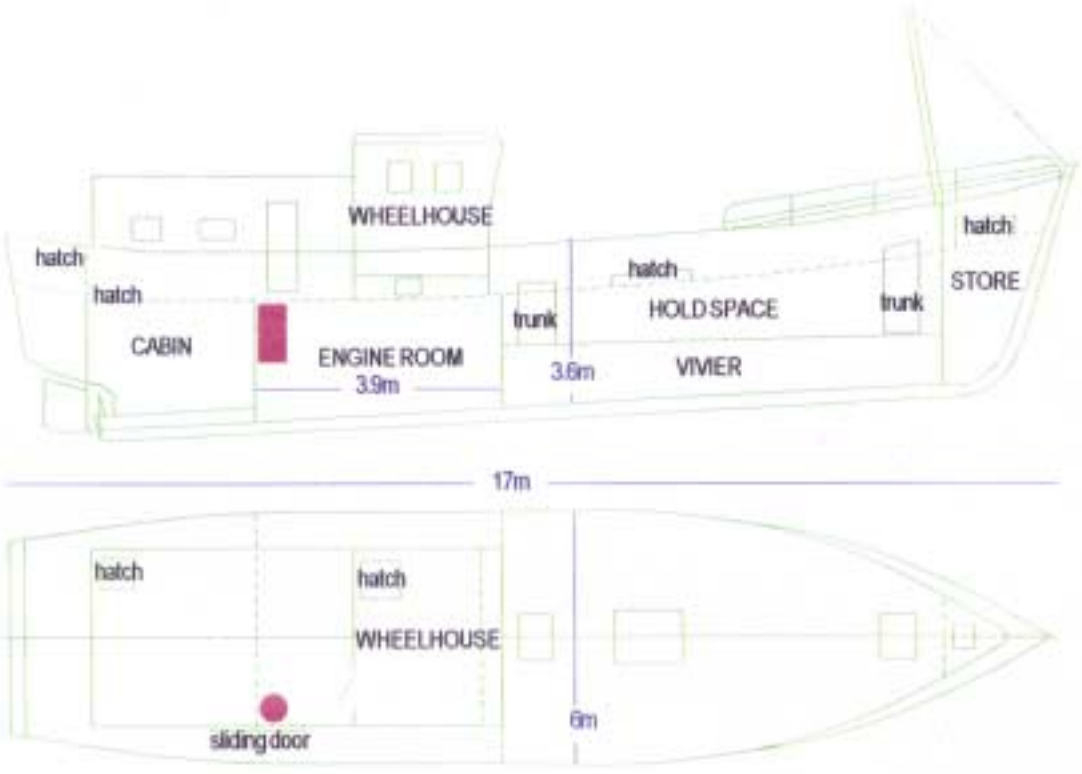
3 THE FISHING VESSEL

3.1 OVERVIEW

Two sketches of the vessel have been provided one showing the profile and plan of the vessel identifying the location of the wheelhouse, the engine room and the cabin etc and the other providing details of the wheelhouse in plan and two elevations. This second drawing also provides details of the 6mm thick steel plating floor of the wheelhouse and how it is fixed to the vessel's deck.

The first of these drawings is redrawn below with the location of the hot water cylinder indicated in red. The location has been identified from the description, "High against the aft bulkhead of the engine room, starboard side, was the hot water storage cylinder".

The drawing is not to scale but some principal dimensions are included (in blue). Using the drawing, the engine room would have the approximate dimensions of 3.9m fore to aft 4.2m width with a height of 2.5m.



3.2 CONSTRUCTION

The explosive forces resulting from the failure of the cylinder will load the structures surrounding the engine room. The relevant structures are the hull timbers, the decking lying between the engine room and the accommodation above it and the bulkhead between the engine room and the cabin.

A portion of the hull timbers are protected by the inertia of the water outside the vessel below the sea-line so that the vulnerable timbers will lie above the water line and where the connection with the deck occurs. The connections associated with the attachment of the decking between engine room and wheelhouse will also be vulnerable.

Hull timbers are 200mm in width and 55mm thickness. Frame spacing is 400mm. All timber is oak.

The decking structure is attached to the vessels hull/deck by attachment to a coaming which was added when the ship was modified. The details are shown the second of the drawings (Ref.2) and it would appear that the fixings are not substantial. Insufficient information is available to determine the precise nature of the fixing and their spacing.

The decking between the engine room and the wheelhouse is made of 6mm steel plate supported by 65mm x 50mm x 6mm I beams on 457mm spacing. These beams are attached to a 6mm steel plate frame which is anchored to the coaming on the vessels deck (see above).

It is stated that the bulkhead between the engine room and the cabin may be considered to be substantial.

The weight of the superstructure above the engine room and the cabin is not known and cannot be established sufficiently accurately from the information available.

4 TECHNICAL ASSESSMENT

4.1 INTRODUCTION

Two cases have been evaluated and these are dealt with in detail separately in Sub-sections 4.2 and 4.3 below. Full details of the calculations are not included since standard methods are employed. Appropriate references to technical publications are provided. A general description of the approach employed in this study is provided first in this introduction.

4.1.1 WATER CYLINDER FAILURE

To begin with, the failure pressure for the cylinder is estimated. It is not realistic to perform very sophisticated strength analyses of the cylinder to determine the failure pressure and standard hazard assessment techniques will be used. These estimate a probable failure pressure from either the design pressure or the test pressure by employing a multiplier. However, such failure pressures are used in the context of 'worst case' predictions and in the present study a direct application of this approach is not appropriate. I have therefore looked at two figures as follows and then chosen the higher:

a) 4 times the working pressure
b) 1¼ times the design pressure.

Having obtained an estimate of the failure pressure the probability of such a pressure being achieved in the cylinders under consideration is determined on the basis of a simple heat balance involving the heat input from the heater which has been specified and heat loses from the cylinder which can be assessed on the basis of the specified insulation properties. The heat loss specified in the standard is modified in proportion to the difference in temperature between that of its contents and the air outside raised to the 1¼ power.

The difference between the heat input and the heat loss is evaluated at the temperature at which the failure pressure would be reached in a closed system containing water (calculated on the basis of the thermodynamic properties of steam) and if this is significantly greater than zero then it is assumed that the hot water system would eventually explode.

4.1.2 EXPLOSIVE FORCES

In the two cases being studied in this report the cylinder contains a liquid under pressure heated above its atmospheric boiling point. The failure pressure alone does not determine the explosive forces generated when the cylinder fails. Account has to be taken of the energy released upon the expansion of the liquid into vapour. Hence, the full calculations set out in Ref.1 for the evaluation of explosive forces resulting from BLEVE (Boiling Liquid Expanding Vapour Explosions) have been used.

An energy of explosion E_{ex} is calculated using the conditions in the cylinder at failure and the thermodynamic properties of steam. The failure pressure and this explosion energy defines the scaling distance r_{scale} which is then used to scale distances from the centre of the explosion where blast peak overpressure and impulse are to be evaluated.

Both the peak overpressure, Δp_s, and the impulse, I_s, of the blast wave are obtained graphically as described in Ref.2. The former requires an assessment of the maximum peak overpressure, p_{s0}, to select the appropriate curve. This maximum is determined using standard shock wave formulae (quoted in Ref.2) from the ambient air conditions and the conditions inside the cylinder at the time of failure. The impulse is obtained from the appropriate graph in Ref.2 using the same scaling distance and a scaling impulse which is determined by the explosion energy.

In addition to the explosive forces associated with the blast wave generated by the rupture of the cylinder, it is necessary to consider the quasi-static pressure developed by the release of energy into the confined space of the engine room. The quasi-static overpressure is estimated to be the pressure which would occur if the contents of the cylinder were to expand under isenthalpic conditions to fill the confinement (the engine room). The presence of air originally in the confinement is included in the calculations. The duration of the quasi-static pressure is estimated using the approach suggested in Ref.2.

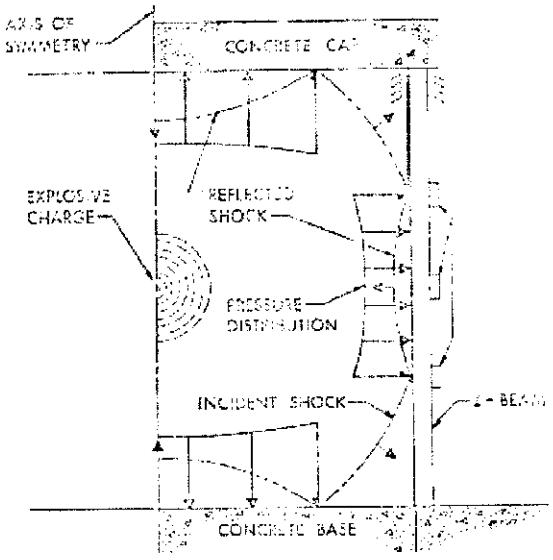
Finally, the impact forces which the ruptured water cylinder body acting

as a missile can exert on the surrounding structures needs to be considered. The initial velocity of the broken missile casing cannot be evaluated satisfactorily by any well established methods. Methods based on the pressure at failure are inadequate since they do not include any of the energy of the expanding water/steam system and velocities are substantially underestimated. On the other hand, methods employing the explosion energy E_{cx} yield values that are unrealistically high since they do not take account of the maximum limitation imposed by the finite nature of the explosion source. In view of this difficulty an approach has been developed based on a suggestion found in Ref.1. The maximum peak pressure p_{s0} is related to the velocity, v_{s0}, of the air directly behind the blast wave at the instant when the cylinder ruptures. Hence, the velocity can be established employing standard equations for shock waves (Ref.3). It is assumed that the cylinder casing achieves this velocity which is an upper limit to the velocity of any expanding region behind the blast wave

4.1.3 STRUCTURAL LOADING

The loads exerted on the structures by the overpressures from the explosion or the impact of the cylinder casing have to be determined in relation to the location of the explosion and the interaction between the blast or missile and the structure.

The blast wave from the explosion reflects in a very complex way within the engine room space. An illustration from Ref.2 is reproduced on the right and shows an example of the way the blast from a conventional explosive reflects inside a symmetrical containing room. In the present instance with the explosion epicentre in one corner and a finite source size the reflection patterns would be more complex.



Reflections amplify the peak overpressure of the blast wave and some account must be taken of these increases. To make a detailed assessment of these effects would not be cost effective and the simple approach of including a multiplier of 2 on the magnitude of the peak overpressure and the impulse has been used in this study. It is expected that this simple method will provide a conservative assessment of whether or not the explosion could lead to the breaching of the hull. This multiplier is used to modify the blast wave overpressure and impulse but is not relevant to quasi-static pressures.

There is no simple way to determine the effect of the impact of the cylinder casing with the vessel's hull. A qualitative approach has been employed which compares the velocity of the cylinder casing with the hammer velocity in impact tests on timber samples.

No account is taken of the flight of any missile or any loss in velocity.

4.1.4 STRUCTURAL DAMAGE

The damage from impulsive loads on a structure is difficult to assess without resource to finite element methods which are costly and involve considerable specialist expertise and time. Alternative methods have been used.

Graphical techniques set out in Ref.2 are based on energy methods for evaluating structural response to dynamic loads. Diagrams called PI charts are available for different structural elements which provide assessment of elastic/plastic damage from a knowledge of the peak overpressure and the impulse of the dynamic load.

The diagrams are implemented for a particular problem by the use of dimensionless overpressure and impulse values obtained by combining actual values with the properties of the structure such as strength properties and structural dimensions.

The two dimensionless values are plotted on the PI chart and the location of the point relative to a series of curves provides the measure of the

level of damage.

In the present instance, the structural members under consideration have been selected as the hull planking so that the specific diagram employed in this case is for beams with various end conditions.

The physical properties for these beams has been taken from Ref.4 for european oak (strength class SE9) and they are as follows:

Density	720 kg m^{-3}.
Elastic Modulus	20 x 10^9 N m^{-2}.
Yield strength	20 x 10^6 N m^{-2}.

Impact damage from the cylinder body acting as a missile can only be assessed qualitatively. Standard tests of resistance to bending from impact employ a hammer of mass 1.5 kg falling a distance of 0.86m on a beam of european oak with a cross section 20 x 20mm over a span of 240mm. At this height the impact produces a central deflection of over 60mm which is taken to indicate failure of the material. The mass of the test beam is negligible in comparison with that of the hammer so the beam achieves the full velocity of impact of about 4 m s^{-1} in these tests.

In the failure of the hot water cylinder the mass of a possible missile would be over 50 kg and, in comparison, the structure subjected to impact would have a negligible mass. It may be assumed that in this case the structure would achieve the full velocity of impact.

4.2 CASE 1 - GRADE 4 WATER CYLINDER

4.2.1 WATER CYLINDER FAILURE

Maximum working pressure	=	0.6 bar gauge
4 times working pressure	=	2.4 bar gauge (3.4 bar abs)
Test pressure	=	1 bar gauge
1¼ times test pressure	=	1.25 bar gauge (2.25 bar abs)
Failure pressure	=	3.4 bar abs

Saturated steam temperature at 3.4 bar is 138°C giving a temperature difference from ambient of 15°C of 123.

The heat loss rate is 120 x (123 / 50)$^{1.25}$ = 369W.

This is significantly below the heat input of 6 kW.

It may be concluded that the cylinder would eventually fail in the circumstances under consideration.

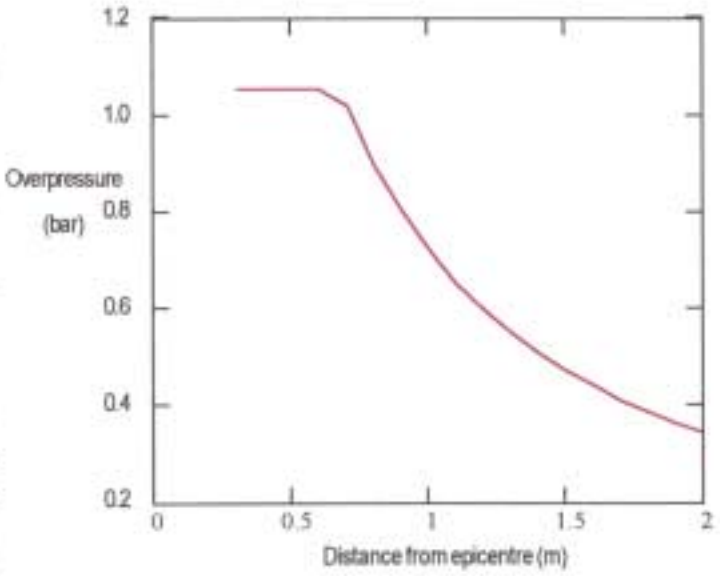
4.2.2 Explosive Forces

With a value of pressure of failure of 3.4 bar, calculations for steam inside the cylinder of capacity 120 litre yield an 'energy of explosion' of 2.1MJ which produces a scaling distance of 2.75m when combined with the atmospheric pressure of 1 bar.

The calculation of the initial peak blast pressure is 2.06 bar abs (which is equivalent to an overpressure of 1.06 bar).

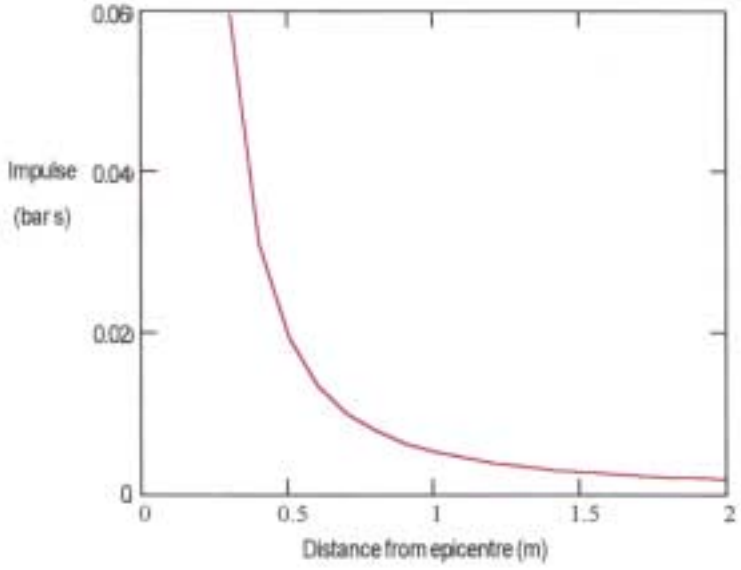
The appropriate graphical result relating peak blast overpressure as a function of distance from the explosion epicentre for this explosive energy is shown on the right.

The same explosive energy and scaling length is employed to calculate the blast wave impulse. The appropriate scaling impulse has a value of 0.008 bar s.



The appropriate graphical result relating blast impulse as a function of distance from

the explosion epicentre for this explosive energy is shown below. The maximum value close to the water cylinder perimeter is 0.06 bar s.

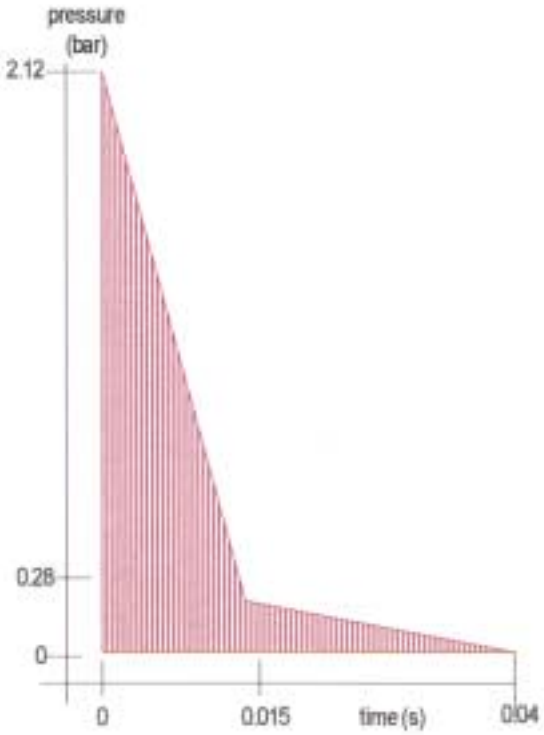


4.2.3 STRUCTURAL LOADING

Loading closest to the water cylinder will be considered.

The load applied to the structure consists of a peak blast wave overpressure of 2.12 bar (multiplier of 2) with a duration of 0.015 s (obtained from the blast impulse of 0.06) and a quasi-static over pressure of 0.28 bar applied for 0.04 s. The load transient is shown on the right.

The effective load therefore possesses a peak value of 2.12 bar and an impulse (the shaded area under the transient curve) of 0.0215 bar s.

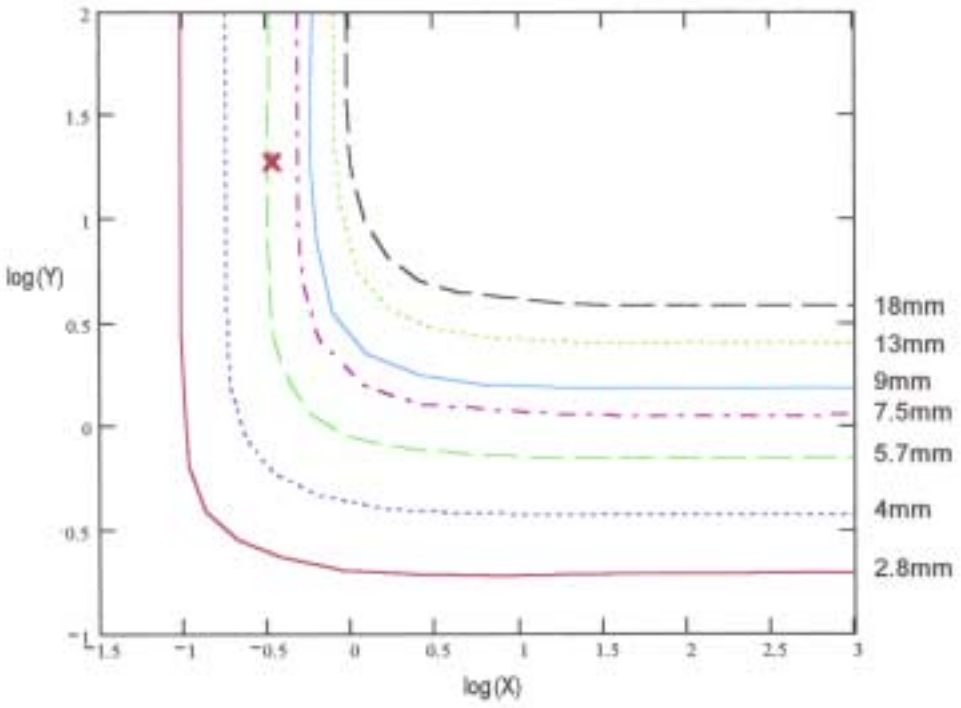


The velocity of the water cylinder body acting as a missile from the explosive forces is calculated to be 105 m/s.

4.2.4 STRUCTURAL DAMAGE

The PI chart for beams has been reproduced from the figure in Ref.2 and is shown below. The X-axis represents the resistance to peak overpressure and the Y-axis represents the resistance to impulse. The X and Y values for the peak overpressure of 2.12 bar and the impulse of 0.0215 bar s and for the hull plank defined earlier are 0.336 and 19.5 respectively and these figures are represented by the point X on the chart.

The individual curves represent the performance of the beam for a series of deflections which are shown on the right of the diagram.



This result shows that the blast load would expect to deflect a hull plank by up to 6mm between the frames. This would apply to all the planks in similar locations.

Impact from the missile formed by the water cylinder body would be

expected to be considerable since its velocity could be above 100 metres per second and the impact could be spread over an section of the hull extending the length of a frame space.

4.3 CASE 2 - MARINE GRADE WATER CYLINDER

4.3.1 WATER CYLINDER FAILURE

Maximum working pressure	=	0.6 bar gauge
4 times working pressure	=	2.4 bar gauge (3.4 bar abs)
Test pressure	=	5.17 bar gauge
1¼ times test pressure	=	6.46 bar gauge (7.46 bar abs)
Failure pressure	=	7.46 bar abs

Saturated steam temperature at 7.46 bar is 168°C giving a temperature difference from ambient of 15°C of 153.

The heat loss rate is $106 \times (153 / 45)^{1.25} = 490W$.

This is significantly below the heat input of 6 kW.

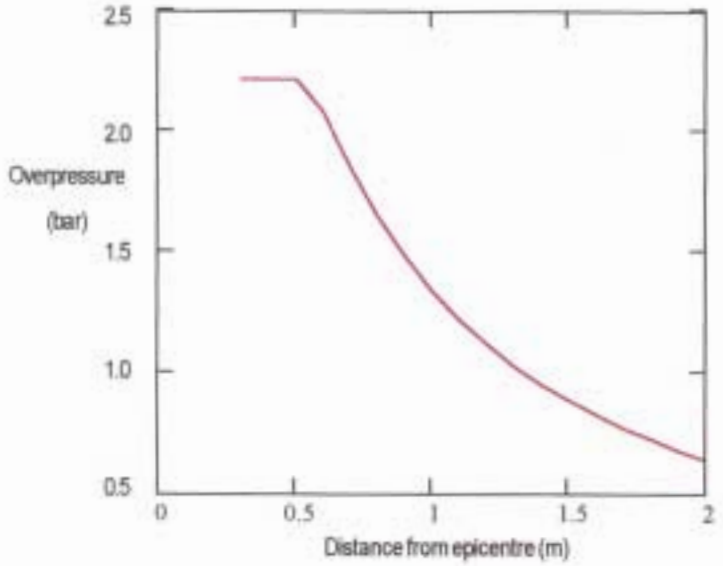
It may be concluded that the cylinder would eventually fail in the circumstances under consideration.

4.3.2 EXPLOSIVE FORCES

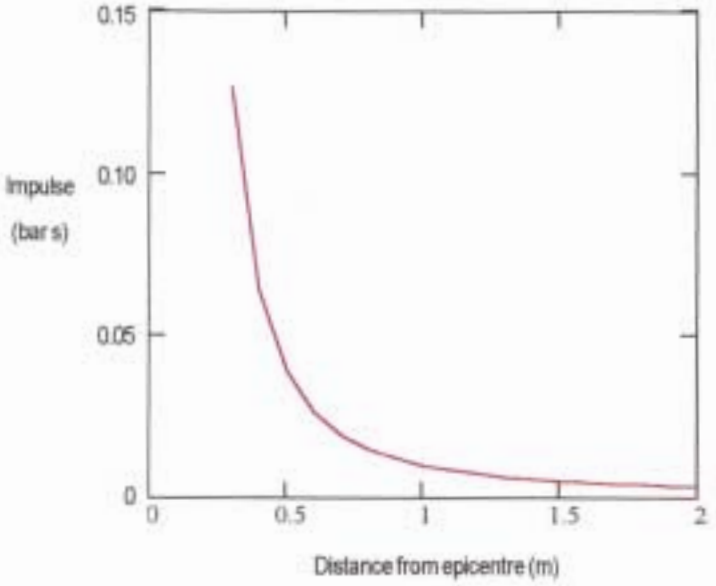
With a value of pressure of failure of 7.46 bar calculations for steam inside the cylinder of capacity 106 litre yield an 'energy of explosion' of 4.1MJ which produces a scaling distance of 3.44m when combined with the atmospheric pressure of 1 bar. The calculation of the initial peak blast pressure is 3.22 bar abs (an overpressure of 2.22 bar).

The appropriate graphical result for this explosive energy is shown on the next page.

The same explosive energy and scaling length is employed to calculate the blast wave impulse. The appropriate scaling impulse has a value of 0.01 bar s.



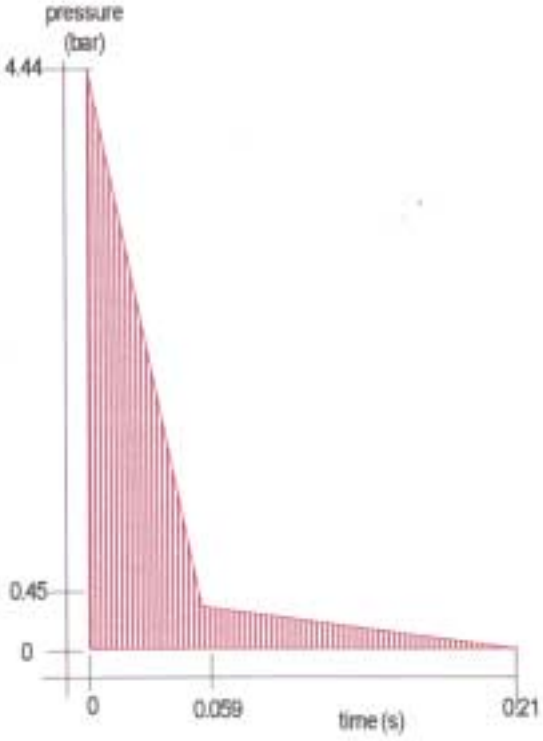
The appropriate graphical result relating blast impulse as a function of distance from the explosion epicentre for this explosive energy is shown below. The maximum value close to the water cylinder perimeter is 0.13 bar s.



4.3.3 STRUCTURAL LOADING

Loading closest to the water cylinder will be considered.

The load applied to the structure consists of a peak blast wave overpressure of 4.44 bar (multiplier of 2) with a duration of 0.059 s (obtained from the blast impulse of 0.13) and a quasi-static over pressure of 0.45 bar applied for 0.21 s. The load transient is shown on the right.



The effective load therefore possesses a peak value of 4.44 bar and an impulse (the area under the transient curve) of 0.155 bar s.

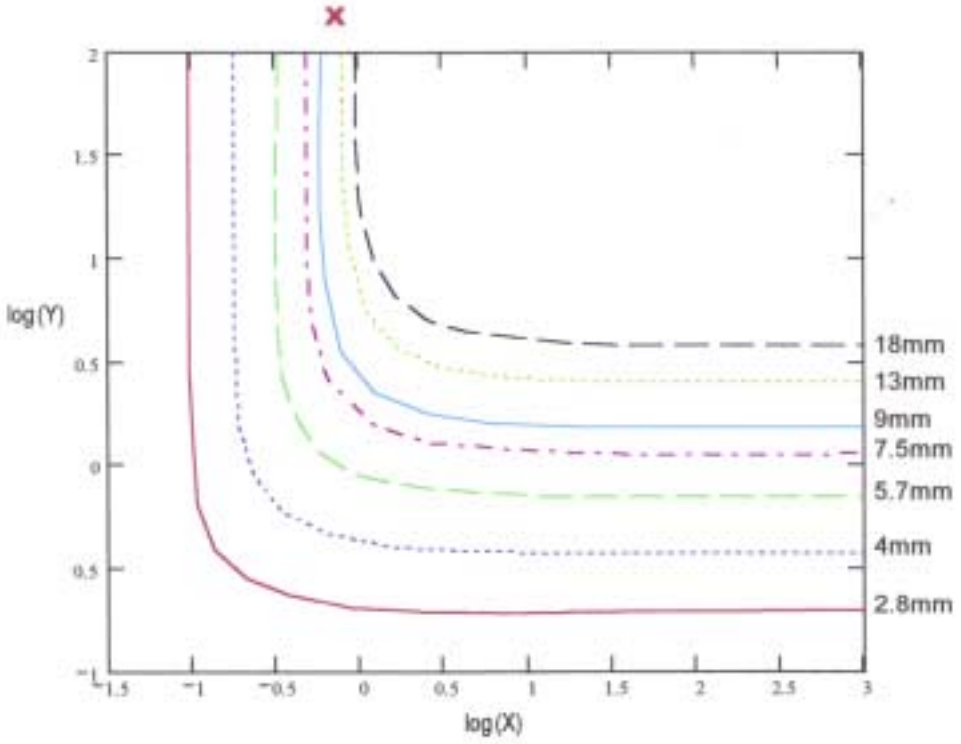
The velocity of the water cylinder body acting as a missile from the explosive forces is calculated to be 254 m/s.

4.3.4 STRUCTURAL DAMAGE

The PI chart for beams has been reproduced from the figure in Ref.2 and is shown below. The Y-axis represents the resistance to peak overpressure and the X-axis represents the resistance to impulse. The X and Y values for the peak overpressure of 4.44 bar and the impulse of 0.155 bar s and for the hull plank defined earlier are 0.705 and 141 respectively and these figures fall outside the chart as shown in the figure on the next page.

The individual curves represent the performance of the beam for a series of deflections which are shown on the right of the diagram.

This result shows that the blast load would expect to deflect a hull plank by up to 11mm between the frames. This would apply to all the planks in similar locations.



Impact from the missile formed by the water cylinder body would be expected to be considerable since its velocity could be above 200 metres per second and the impact could be spread over an section of the hull extending the length of a frame space.

5 CONCLUSIONS

5.1 It can be concluded that the water cylinder, in both cases, would have burst under the growing internal pressure if the immersion heater had been left on for an extended period and with no venting of pressure.

5.2 Calculations employing standard procedures specifically developed for the circumstances under consideration show that explosion overpressures close to the water cylinder are of the order of bars. Blast wave pressure durations are of the order of a hundredth of a second. However, the explosion of the water cylinder does set up a significant quasi-static overpressure which have considerably longer durations. Load transients have been produced for both cases.

5.3 Expected damage from the explosion has been assessed by appropriate methods and in both cases it is expected that significant damage could have occurred as a result of the blast wave produced by the explosion.

5.4 The water cylinder body would form a missile as a result of the explosion. Missile velocities have been calculated and these are significant. It is expected that the missile could breach the hull planking in both cases.

5.5 The effect of an explosion involving the Grade 4 water cylinder may have produced sufficient damage to breach the hull and flood the vessel.

5.6 The effect of an explosion involving the Marine Grade water cylinder would probably have produced sufficient damage to breach the hull and flood the vessel.