ACCIDENT REPORT

Report on the investigation of

the engine failure and fire on board

the ro-ro cargo vessel

Finlandia Seaways

resulting in injury to one crewman

11 miles east of Lowestoft

16 April 2018

SERIOUS MARINE CASUALTY REPORT NO 2/2021 FEBRUARY 2021

MAIB MARINE ACCIDENT INVESTIGATION BRANCH

The United Kingdom Merchant Shipping

(Accident Reporting and Investigation)

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

APT	-	Annual Performance Test
bar	-	metric unit of pressure: 1bar is equal to 100,000 pascals
BSU	-	Bundesstelle für Seeunfalluntersuchung
CCR	-	Cargo control room
C/E	-	Chief engineer
C/O	-	Chief officer
CO_2	-	Carbon dioxide
CPP	-	Controllable pitch propeller
CSM	-	Continuous Survey Machinery
DFDS	-	DFDS Seaways AB-Lithuania
DSG	-	Diesel Service Group UAB
ECR	-	Engine control room
EEBD	-	Emergency escape breathing device
Hz	-	Hertz
IMO	-	International Maritime Organization
kg	-	kilogramme
kW	-	kilowatt
LMSA	-	Lithuanian Maritime Safety Administration
LR	-	Lloyd's Register
LTSA	-	Lithuanian Transport Safety Administration
MAN	-	MAN Diesel and Turbo SE [renamed MAN Energy SE on 26/6/2018] (engine manufacturer)
MAN PrimeServ	-	Brand name for MAN's aftersales and maintenance service division
mbar	-	millibar
MCA	-	Maritime and Coastguard Agency
MGN	-	Marine Guidance Note
mm	-	millimetre
nm	-	nautical miles
OMD	-	Oil mist detector
OOW	-	Officer of the watch
Piston pin bush	-	Connecting rod small end piston pin bearing bush

PMS	-	Planned Maintenance System
RINA	-	Registro Italiano Navale
RMRS	-	Russian Maritime Register of Shipping
rpm	-	revolutions per minute
SOLAS	-	International Convention for the Safety of Life at Sea 1974, as amended
TAIID	-	Lithuanian Transport Accident and Incident Investigation Division
TTH	-	The Test House (Cambridge) Ltd
UPS	-	Uninterruptible power supply
UTC	-	Universal Co-ordinated Time
V	-	volt
VDR	-	Voyage data recorder
VHF	-	Very high frequency
2/E	-	Second engineer
3/E	-	Third engineer

TIMES: all times used in this report are UTC unless otherwise stated

SYNOPSIS

At 2003 on 16 April 2018, the Lithuanian registered ro-ro cargo vessel *Finlandia Seaways* suffered a catastrophic main engine failure that caused serious structural damage to the engine and a fire in the engine room. The vessel's third engineer, who was on duty in the engine room at the time, suffered serious smoke-related lung, kidney and eye injuries during his escape.

Finlandia Seaways was 11nm east of Lowestoft on a regular voyage from Zeebrugge to Rosyth when one of the main engine's connecting rods broke. Several of the engine's major internal rotating components were thrown through the side of the crankcase into the engine room, and a short but intense fire occurred. Within 20 minutes the crew had conducted a muster, sealed the engine room, activated its carbon dioxide fixed fire-fighting system and extinguished the fire. The third engineer was recovered by coastguard helicopter to Norfolk and Norwich hospital for medical care, and made a successful recovery.

The MAIB's technical investigation was carried out with support of the Lithuanian Transport Accident and Incident Investigation Division and the engine manufacturer, MAN Diesel and Turbo SE. The investigation identified that a fracture of the connecting rod small end had led to the sudden failure of the main engine. The investigation also found that the method used to replace the connecting rod small end piston pin bearing bushes by the vessel manager's maintenance support contractor had introduced stress raisers that signficantly increased the likelihood of crack initiation and fatigue failure.

Other factors that contributed to the engine failure included: standards of maintenance management; lack of appreciation of the importance of following the engine manufacturer's instructions for the removal and refitting of the piston pin bearing bushes; and external oversight of the engine maintenance process.

With regard to the emergency response, although the carbon dioxide fire-fighting system was activated successfully, the third engineer was fortunate to have survived given that there were no emergency escape breathing devices on his escape route. In common with other accidents in which carbon dioxide has been released following a fire, the inability to confirm which gas bottles had discharged hampered re-entry to the engine room. In addition to this, the voyage data recorder did not record the incident due to the uninterruptible power supply failing.

On 27 July 2018, the MAIB and the Lithuanian Transport Accident and Incident Investigation Division wrote to MAN Diesel and Turbo SE and the vessel's classification society recommending that they provide technical advice to *Finlandia Seaways*' operator to reduce the likelihood of a similar accident occurring in the future. In response, *Finlandia Seaways*' sister vessel was withdrawn from service and its engine connecting rods removed and replaced. In addition to many actions taken by stakeholders as a result of this accident, further recommendations aimed at addressing the safety issues raised in this report have been made to the vessel operators, DFDS Seaways AB-Lithuania and its engine maintenance support contractor, Diesel Service Group.

SECTION 1 - FACTUAL INFORMATION

1.1 PARTICULARS OF *FINLANDIA SEAWAYS* AND ACCIDENT

SHIP PARTICULARS	
Vessel's name	*Finlandia Seaways*
Flag	Lithuania
Classification society	Lloyd's Register
IMO number/fishing numbers	9198721
Type	Ro-ro cargo vessel
Registered owner	DFDS Seaways AB-Lithuania
Manager(s)	DFDS Seaways AB-Lithuania
Construction	Steel
Year of build	2000
Length overall	162.58m
Gross tonnage	11530
Minimum safe manning	13
Authorised cargo	Freight vehicles

VOYAGE PARTICULARS	
Port of departure	Zeebrugge
Port of arrival	Rosyth
Type of voyage	International
Cargo information	A mixture of heavy goods vehicles, containers, cars, campervans and caravans
Manning	19
Passengers	4

MARINE CASUALTY INFORMATION	
Date and time	16 April 2018 at 2003 (2203 ship's time)
Type of marine casualty or incident	Serious Marine Casualty
Location of incident	11 miles east of Lowestoft
Place on board	Engine room
Injuries/fatalities	One injury
Damage/environmental impact	Main engine structural damage; fire damage in engine room
Ship operation	On passage
Voyage segment	Mid-water
External & internal environment	South-westerly wind, slight sea
Persons on board	23

1.2 NARRATIVE

1.2.1 Passage from Zeebrugge

At 1445 on 16 April 2018, *Finlandia Seaways*' **(Figure 1)** main engine was started in preparation for leaving port. On duty in the engine room were the chief engineer (C/E), second engineer (2/E) and an electrician. The vessel's relief C/E was also in the engine room. At 1510, engine control was passed to the bridge and, at 1545, the vessel departed Zeebrugge on passage to Rosyth, Scotland. At 1600, the on watch 2/E was relieved by the third engineer (3/E) and the former left the engine room.

At 1610, the vessel cleared Belgium's 12nm coastal limit and the engineers began to change over the engine fuel supply from low sulphur marine diesel oil to heavy fuel oil. This was completed at 1642 and, by 1800, the C/E, relief C/E and electrician had all left the engine room. The on watch 3/E monitored machinery operating parameters from the engine control room (ECR) and undertook hourly inspection rounds of the engine room.

Image courtesy of www.shipspotting.com

Figure 1: *Finlandia Seaways*

1.2.2 The engine failure and subsequent fire

At about 2000, the 3/E left the ECR and commenced his hourly rounds of the engine room and machinery spaces. Shortly after entering the purifier room **(Figure 2)**, he heard loud metallic knocking sounds coming from the engine room. At the same time, powerful vibrations were being felt on the bridge by the officer of the watch (OOW), who immediately checked the propeller pitch angle and main engine speed gauges. The OOW saw that both gauges were fluctuating and immediately reduced the propeller pitch from 60% to 25%. He then saw that the fuel consumption meter was also fluctuating and giving abnormal readings, while various engine warning lights were illuminated.

Figure 2: Engine room purifier room

The 3/E opened the purifier room door, looked out into the engine room and saw smoke rising from the port forward end of the main engine. The noise and vibration levels rapidly increased and, sensing danger, the 3/E ran back into the purifier room and crouched behind one of the purifiers. Almost immediately, at 2003, there was a loud bang and flames flashed past the open purifier room door **(Figure 3)** and the space filled with thick black smoke. The ship blacked out[1], but within seconds the emergency generator cut-in and the emergency lighting came on. Despite this, the smoke in the engine room had reduced the 3/E's visibility to almost nothing.

1.2.3 Emergency response

The master, who had been alerted by the strong ship vibrations, arrived on the bridge as the blackout occurred. The fire alarm system had been activated and the bridge alarm panel indicated that all zones within the engine room were affected. The master immediately took command and put the vessel's controllable pitch propeller (CPP) to zero pitch. He then instructed the OOW to sound the general alarm and make an intercom broadcast stating that it was a genuine emergency and that the crew should go to their muster stations. At about the same time, the chief officer (C/O) arrived on the bridge and reported that he had seen smoke emitting from the funnel.

[1] The sudden and total failure of the ship's main electrical power supply.

Figure 3: Purifier room door

Like the master, many of the crew members had been alerted by the ship vibrations and had already begun to react. The C/E had noticed that the main engine's No.A5 cylinder exhaust gas temperature deviation alarm had activated on his cabin alarm panel. He initially thought it could be related to a fuel system problem. As he left his cabin for the engine room, the blackout occurred.

The C/E continued aft to the port side of the main vehicle deck and opened the engine room access door. He was met by significant smoke and some heat. He shouted out for the 3/E but heard no reply and was forced back onto the vehicle deck. He then tried to enter the ECR via the cargo control room (CCR) **(Figure 4)** and was again faced with smoke and heat. There was no sign of the 3/E. The C/E called the bridge from the steering gear space and informed the master of the fire in the engine room. He then operated the engine room fuel systems' quick-closing valves **(Figure 5)** and fuel pump emergency stops from the control box adjacent to the ECR.

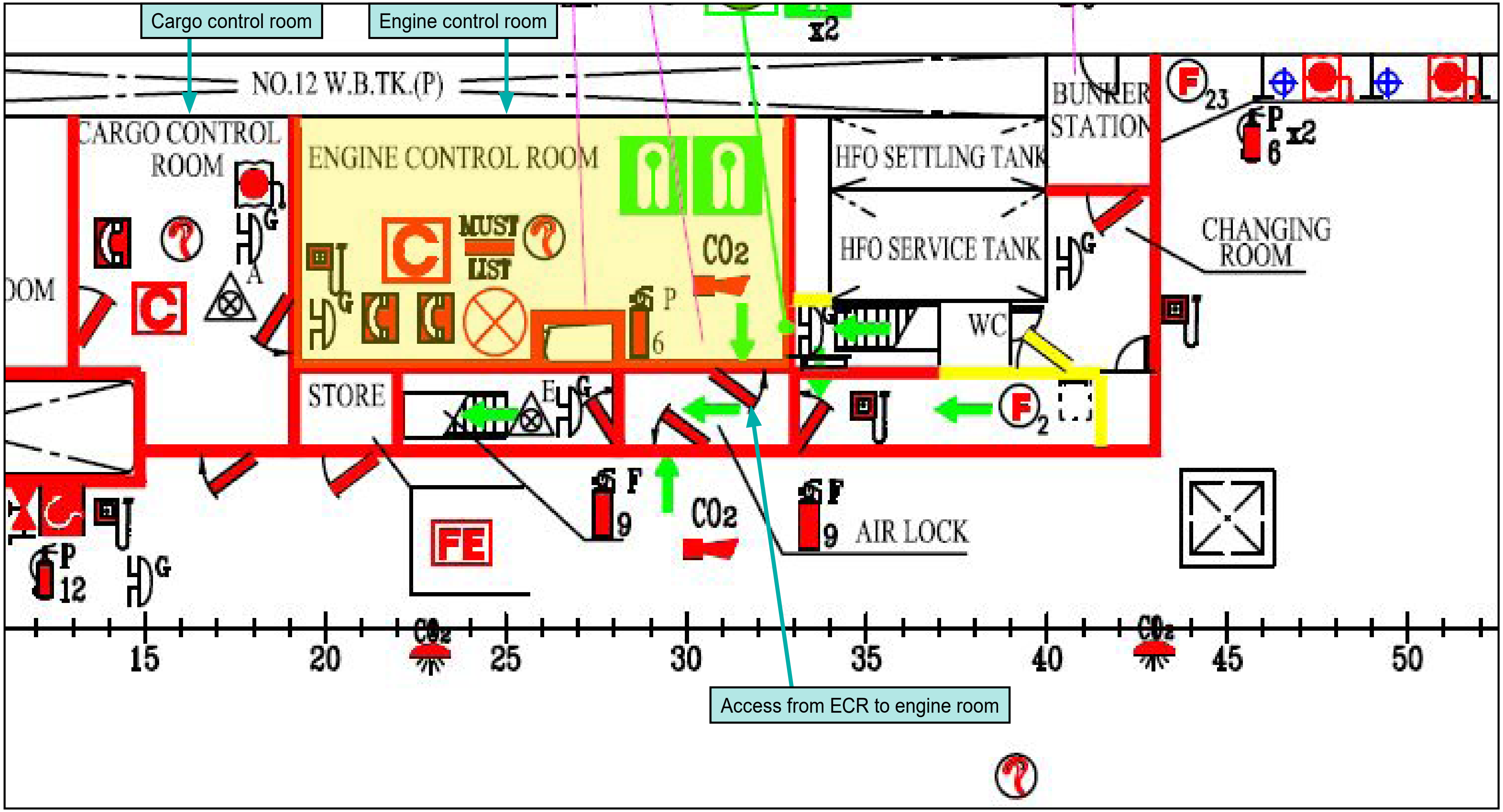

Figure 4: Access to ECR, CCR from vehicle deck

Figure 5: Control station for the engine room fuel systems' quick-closing valves

In the purifier room, the 3/E realised that his nearest escape route would take him past the main engine at cylinder head level and decided to use the secondary escape route at the aft end of the engine room **(Figure 6)**. He took a deep breath and then left the purifier room. On entering the dense black smoke, the 3/E ducked underneath the main engine exhaust gas trunking and ran aft past the two auxiliary generators. The escape route **(Figure 7)** led him to the first of three vertical ladders **(Figure 8)**. When he climbed the first ladder, he struggled to get past the ladder platform guard rail safety chains and fell back down the ladder three times, losing his torch in the process, before making good his escape.

The vessel's four passengers were taken to their assembly point on the upper vehicle deck and an initial crew muster was attempted at the port lifeboat. Some of the crew involved in the fire-fighting effort reported in via hand-held radios. The engine room fire party, which had arrived on the upper vehicle deck and was running out fire hoses, reported the 3/E missing. A second muster took place on the upper vehicle deck, where the 2/E and motorman had already begun to shut the engine room fire flaps.

At 2013, the 3/E escaped from the engine room through the funnel casing weathertight door onto the upper vehicle deck **(Figure 9)**. He then collapsed onto the deck, gasping for breath and struggling to see. The 2/E saw the 3/E collapse and went to help him. The 2/E radioed the bridge and informed the master that the 3/E required medical assistance. At 2015, on instruction from the master, the OOW contacted Humber Coastguard and requested a helicopter.

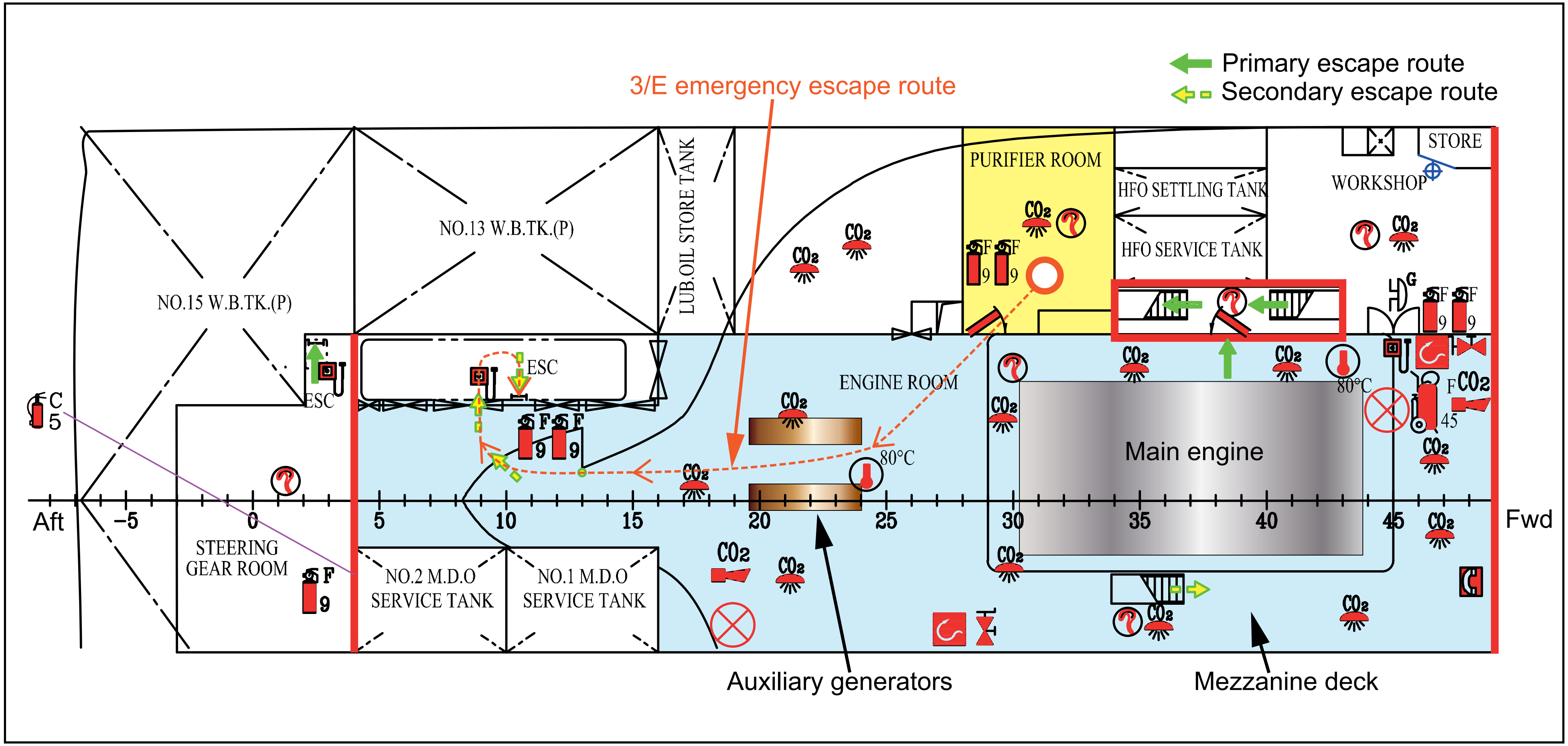

Figure 6: Purifier room and engine room tween deck (shaded blue) with 3/E's escape route

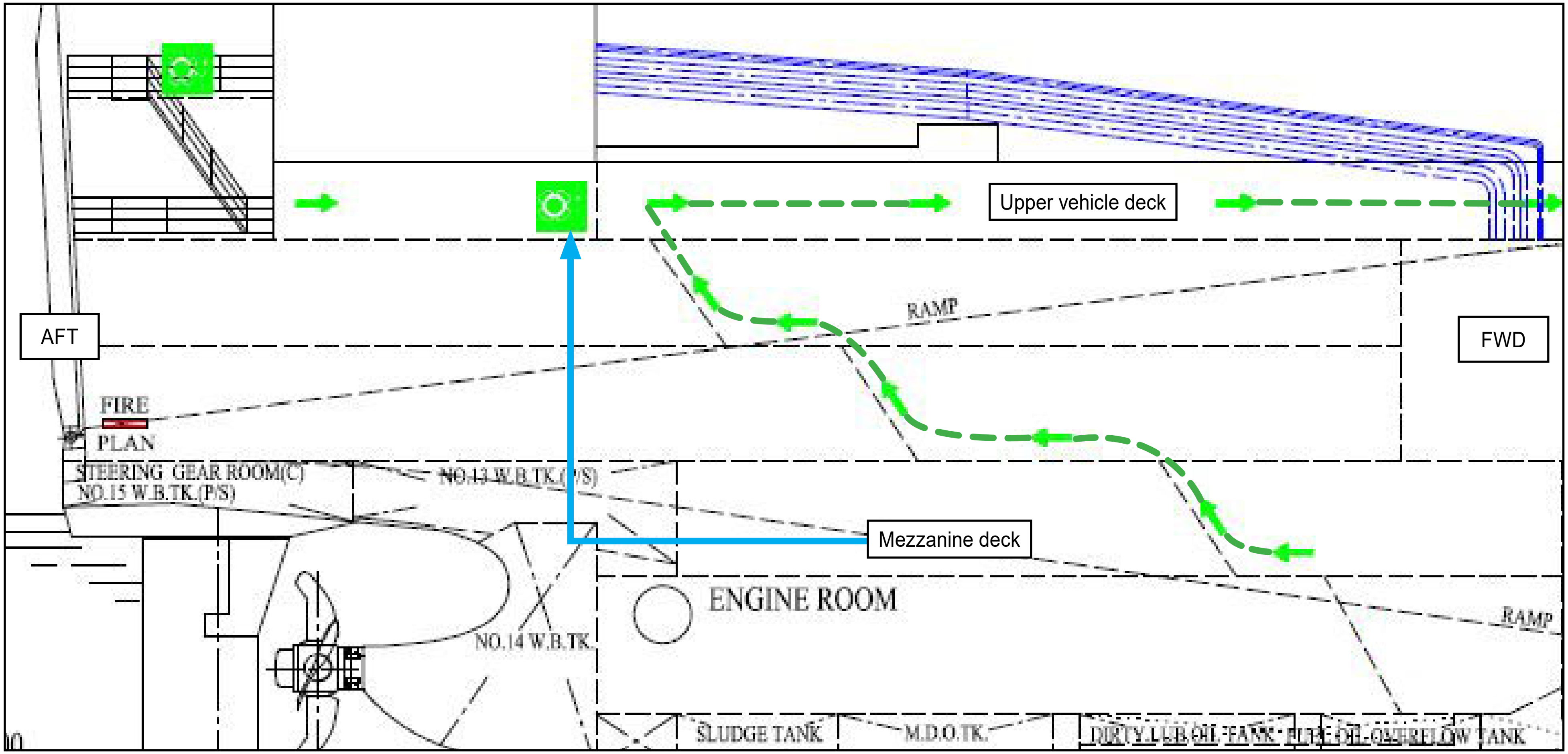

Figure 7: Elevation showing the primary escape route from the purifier room to the main vehicle deck and the secondary escape route taken by the third engineer
(Green: primary escape route | Blue: secondary escape route)

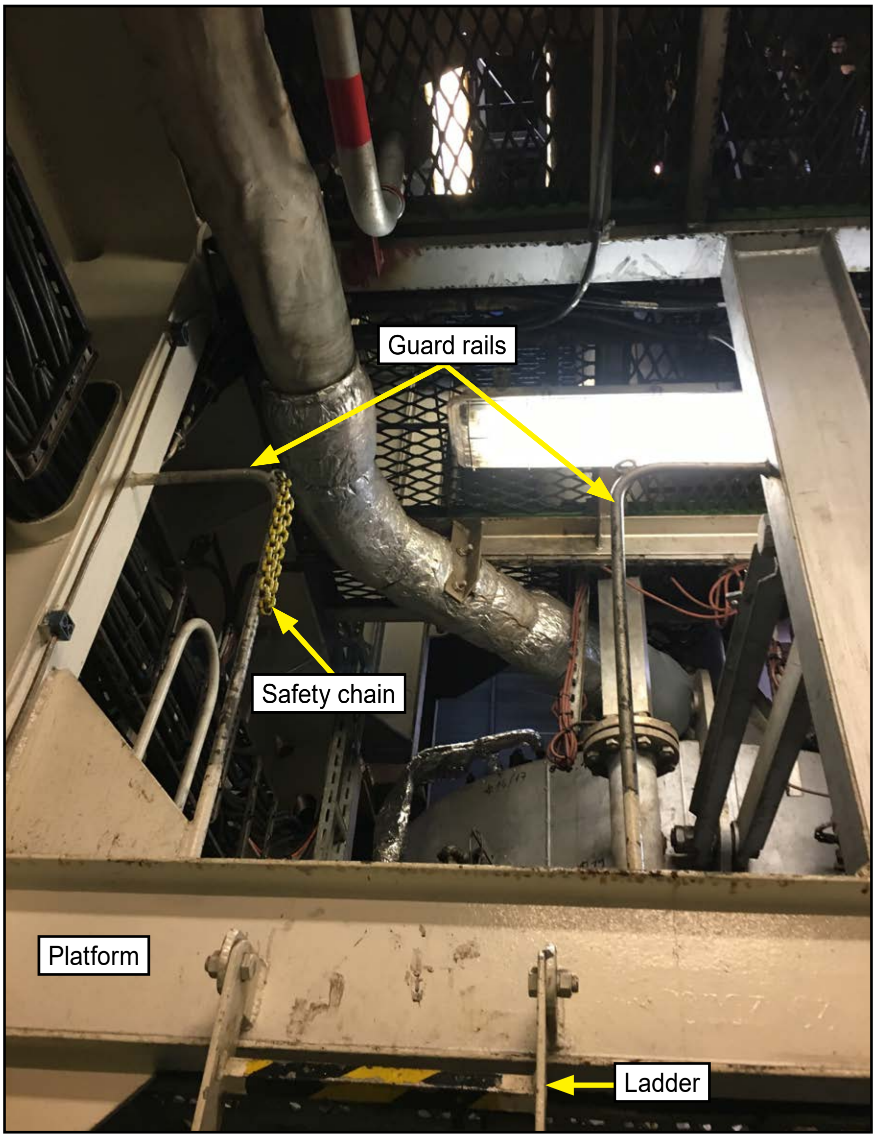

Figure 8: Escape route vertical ladder and safety chains

Figure 9: Upper vehicle deck

With confirmation that the 3/E had been found, all crew and passengers accounted for, the fire flaps closed and the engine room fuel supply isolated, the C/E advised the master to release the engine room's carbon dioxide (CO_2) fixed fire-extinguishing system. The master then called the 2/E and ordered him to operate the CO_2 system for the engine room.

The 2/E and the second officer went to the CO_2 remote release station **(Figure 10)** on the forecastle deck and, at about 2020, released the CO_2 into the engine room. The 2/E then went down to the main deck and entered the CO_2 bottle room **(Figure 11)**. He found that the control lever for the engine room had operated correctly and that the CO_2 pipework had frosted. He also noted that the main CO_2 supply line pressure gauge was indicating about 20bar pressure, and a short time later he saw it reduce to zero.

Figure 10: CO_2 remote release station

Figure 11: CO_2 bottle room

At 2027, Humber Coastguard tasked rescue helicopter R912 based at Humberside to evacuate the injured 3/E. Two warships were also in the vicinity and were tasked to close on *Finlandia Seaways* and stand-by if required.

While the medical team continued to provide medical support to the 3/E, other crew members were tasked to monitor engine room boundary temperatures. This was initially carried out by using their hands and, latterly, with fridge thermometers. Temperatures were measured and logged regularly and appeared to reduce over time.

The master instructed the bosun to drop the port anchor; one shackle ran out before it jammed. The starboard anchor was then released and it, too, initially jammed. However, with assistance from the bosun it ran out and held the ship with four shackles.

At 2203, after diverting to refuel, R912 arrived at *Finlandia Seaways*. At 2247, the 3/E was recovered into the helicopter and taken to Norfolk & Norwich hospital, where he received medical care for smoke-related lung, kidney and eye injuries. At 2337, *Finlandia Seaways*' master advised Humber Coastguard that the fire situation had been stabilised.

Finlandia Seaways was initially towed to the Hawke anchorage on the River Humber. A further tow was arranged, with the vessel arriving in Immingham on 20 April 2018, where it was boarded by the Humberside Fire & Rescue Service to confirm that the engine room fire had been extinguished.

1.2.4 Engine room fire damage

Fire damage was sustained primarily at the tween deck level in the engine room, with severe heat damage to the upper part of the main engine and engine room deckhead **(Figure 12)**. Most of the heat damage was sustained around the main engine cylinder heads, and to auxiliary equipment on the periphery at the forward end of the engine room. Further aft, towards the two auxiliary generators, smoke damage was the major contributor.

On the bottom plates, the main area of heat damage was at the port forward engine room access door and the adjoining stairwell. Impact damage to the access door caused by the components ejected from the main engine had enabled heat and smoke to enter the stairwell, which had then funnelled up the next two decks to the ECR.

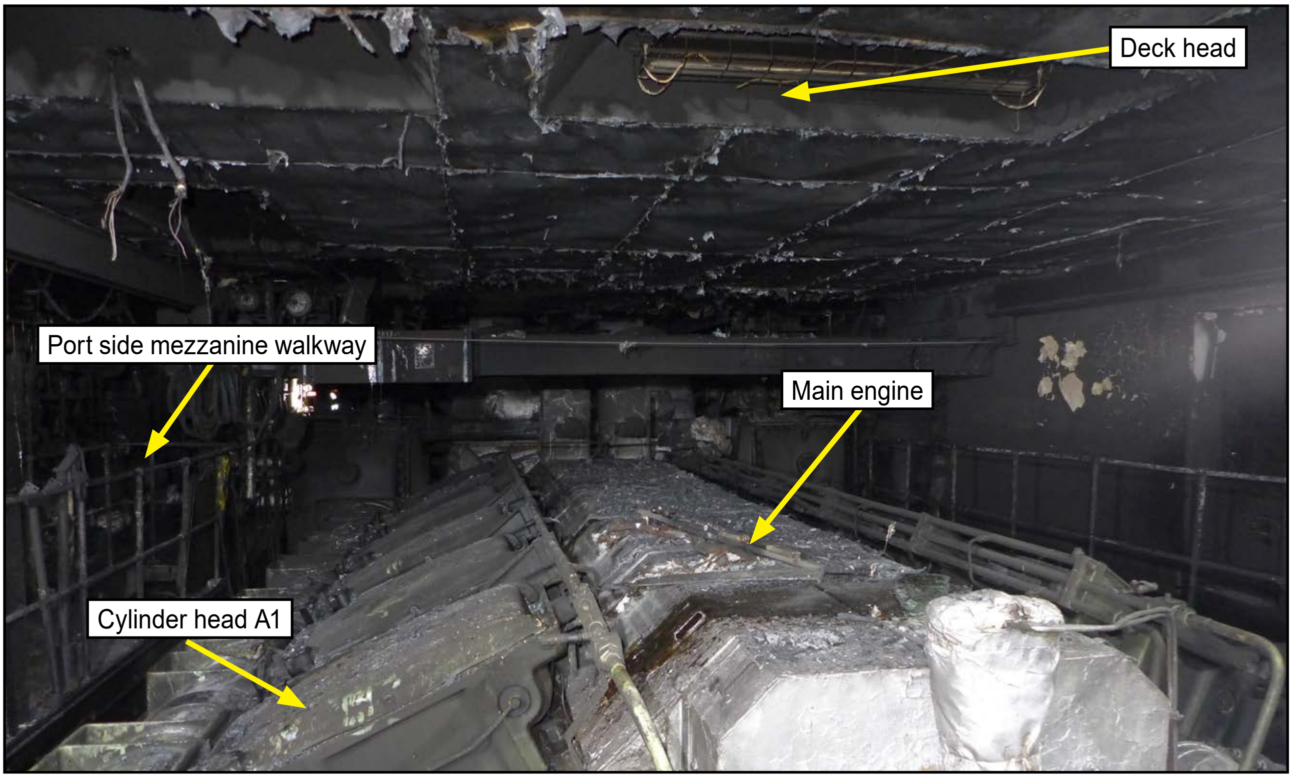

Figure 12: Fire damage to upper engine room (looking forward)

1.3 CREW

Finlandia Seaways was crewed by 19 Lithuanian nationals, one of whom had just joined the vessel in Zeebrugge as the relief C/E. Crew members normally worked 4 weeks on, 4 weeks off; or 6 weeks on, 6 weeks off.

Although *Finlandia Seaways* had an unattended machinery space[2] notation, the vessel's engine room was normally manned at all times with the 2/E and 3/E undertaking 4 and 6-hour watches in rotation[3]. The C/E, electrical engineer and motorman were day workers and typically worked from 0800 to 1800.

1.4 ENVIRONMENTAL CONDITIONS

At the time of the accident the wind was southerly, force 4-5, the sea was slight with fair weather and the visibility was good.

1.5 *FINLANDIA SEAWAYS*

Finlandia Seaways was a Lithuanian registered roll-on roll-off cargo vessel. It was owned by DFDS Seaways AB-Lithuania (DFDS) and operated by DFDS A/S. It was built in 2000 and purchased, along with its sister vessel *Botnia Seaways*, by DFDS in 2009. When first acquired, *Finlandia Seaways* and *Botnia Seaways* were named *Tor Finlandia* and *Tor Botnia*. The vessels were renamed in 2012.

Finlandia Seaways had provided a regular service on the Zeebrugge to Rosyth route since 2009. It had been classed by Lloyd's Register (LR) since new and, at the time of the accident, its certificate of class was valid until 9 August 2020.

DFDS A/S is a Danish shipping and logistics company. At the time of the accident it operated 28 vessels on passenger and freight services on 24 routes across northern Europe and within the Mediterranean Sea. DFDS Lithuania's management and technical teams were based in Klaipeda, Lithuania.

1.6 MAIN ENGINE

1.6.1 Overview

The vessel's main engine was a 12,600kW MAN Diesel and Turbo SE (MAN) 12V 48/60 single-acting medium speed four-stroke diesel engine **(Figure 13)**. It had two banks of six cylinders arranged in a "V" configuration with two turbochargers, one per bank. The '48/60' referred to the bore of the cylinders and the stroke of the pistons in centimetres.

The engine operated at a fixed speed of 500rpm, with load changes controlled by fuel input. It was connected via a flexible coupling to a single reduction gearbox, which drove a single CPP at an operating speed of 155rpm. The engine also drove a 400V, 1,500kW, 50Hz electrical alternator. At the time of the accident, the engine had a total of 110,662 running hours.

The MAN 12V 48/60 engine was commonly used in both ship propulsion and shoreside power generation systems.

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[2] Unattended machinery spaces are required to have levels of automation that allow them to be periodically unattended. Typically, outside normal daily working hours. If there is a malfunction in any machinery, or any operating parameters are exceeded, an alarm will be sounded in the duty engineer's cabin and other communal accommodation areas. It is then the duty engineer's responsibility to investigate.

[3] Engine room watch routine – 2/E: 0000-0400 and 1200-1800; 3/E: 0400-0800 and 1800-0000.

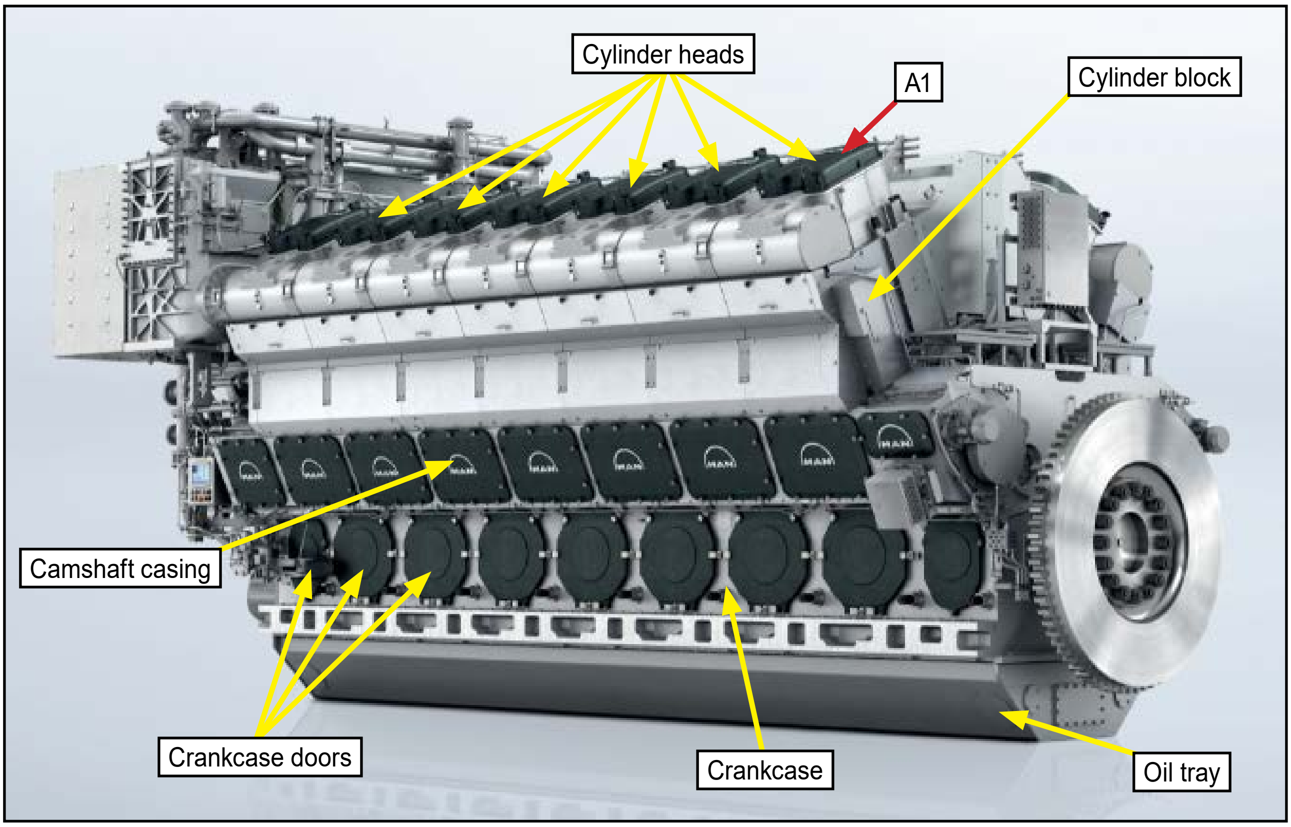


Figure 13: MAN 48/60 engine (engine shown 14V48/60B)

1.6.2 Engine design and key components

The engine design comprised a single-piece cast iron crankcase. The cylinder liners were separated from each other and were mounted in the engine frame, and the crankshaft was underslung. The crankcase was fitted with crankcase explosion relief valve doors, two per crank throw, i.e. one on each side. The crankcase relief valve operating pressure was 50mbar.

The forged crankshaft had two counterweights per crankpin journal to compensate for the oscillating masses. The counterweights were held in place by anti-fatigue bolts. All the major bolting arrangements within the crankcase were hydraulically tensioned.

The cylinders were numbered 1 to 6 from aft to forward and labelled “A” for the port side bank and “B” for the starboard side bank. Each cylinder bank had a camshaft, which operated four valves per cylinder head and the fuel injection pumps. A cylinder and its associated valves, piston and con rod was referred to as a ‘unit’, i.e unit A1, unit B1 etc.

The piston connecting rods were cast in one piece. During manufacture, the connecting rod shank was cut below the small end eye, flanged and bolted together. This was to facilitate piston removal without the need to remove the connecting rod big end bearing. The shank’s flanged connection was the weakest part of the connecting rod assembly **(Figure 14)**.

The connecting rod small ends were stamped with the manufacturer’s unique identification code numbers (e.g. COC 1234) and LR identification numbers for survey purposes. A one-piece piston pin bearing bush (piston pin bush[4]) was

[4] Connecting rod piston pin bearing bushes are also often referred to as small end bushes.

installed into the eye of the small end **(Figure 15)**. The surface finish of the inner face of the small end eye was prepared during manufacture by shot-peening[5] to reduce the potential for fatigue fractures developing under high operational loads.

The masses of key rotating and oscillating components within the engine were: piston – 337kg; piston pin – 102kg; connecting rod – 655kg; and crankshaft counterweight – 525kg.

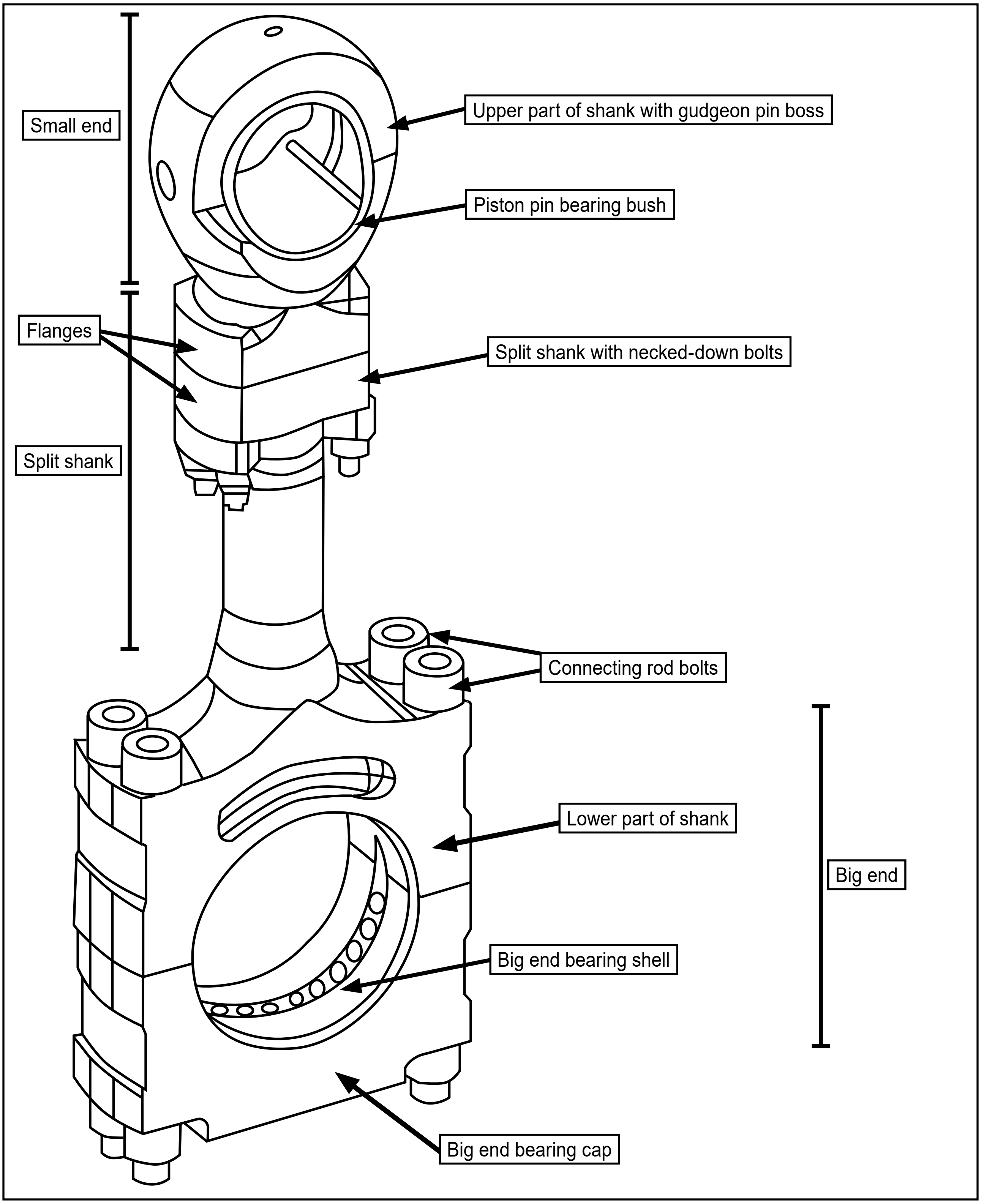


Figure 14: Connecting rod assembly

5 Shot peening is a surface cold worked process of bombarding the material with small high velocity spherical metal particles (shot), which introduces residual compressive stress.

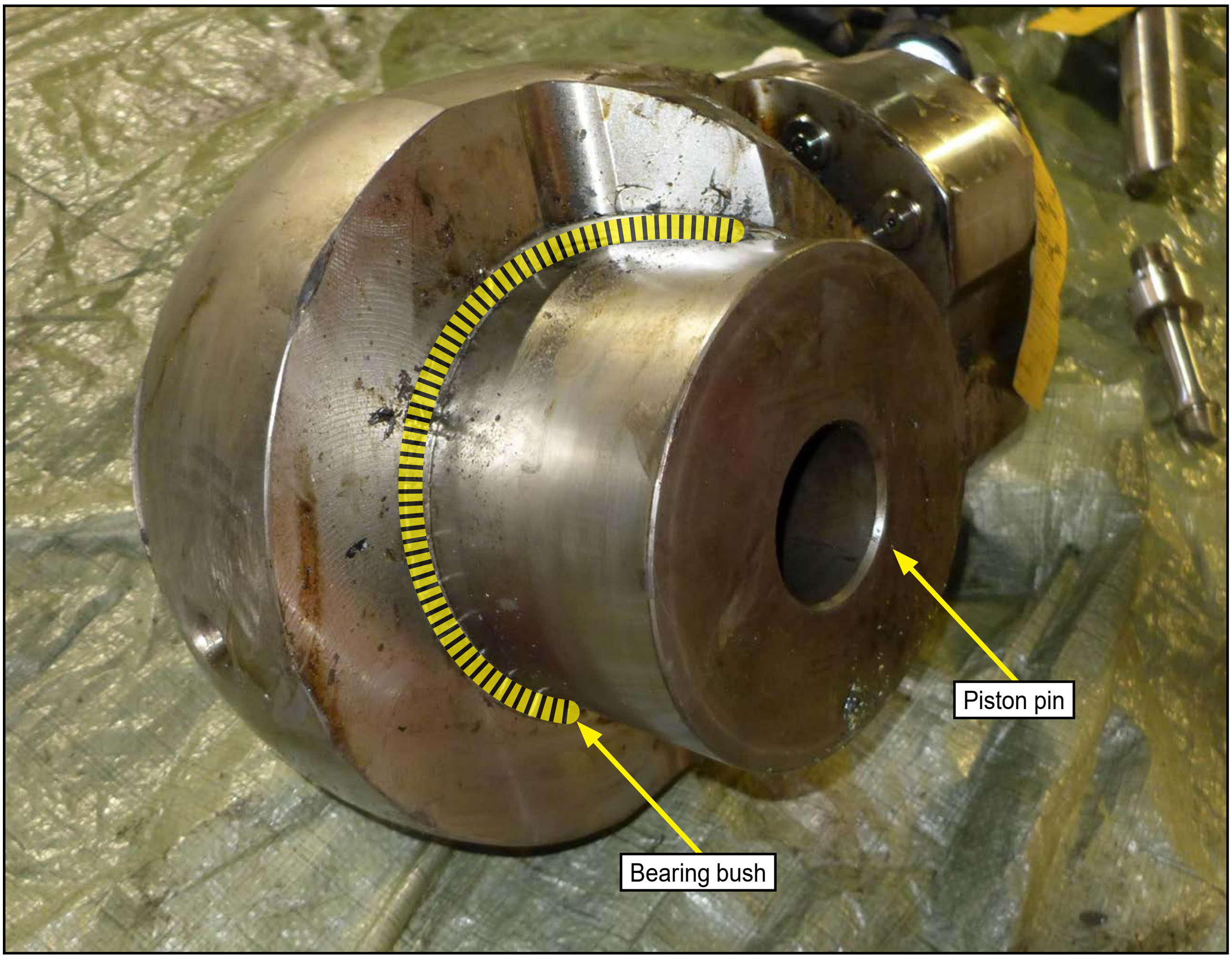


Figure 15: B5 small end with piston pin

1.6.3 Engine condition monitoring and protection systems

The engine was equipped with the following crankcase monitoring systems:

- main bearing temperature monitoring system,
- splash oil monitoring system, and
- oil mist detector (OMD).

The crankshaft bearing temperature monitoring system used temperature sensors that were fitted in the underslung crankshaft main bearings. The sensors transmitted electronic signals to the engine safety system. The splash oil monitoring system measured and compared the oil temperature dripping from the connecting rod bearings. Both temperature monitoring systems could trigger an alarm and automatically shut down the engine.

The OMD was manufactured by Schaller Automation and was fitted on the starboard side of the engine crankcase **(Figure 16)**. The OMD measured and compared the oil vapour concentrations present in each crankcase compartment and provided an audible and visual alarm when anomalies were identified. The OMD could also trigger an engine shutdown if high levels of mist developed in one or more compartments.

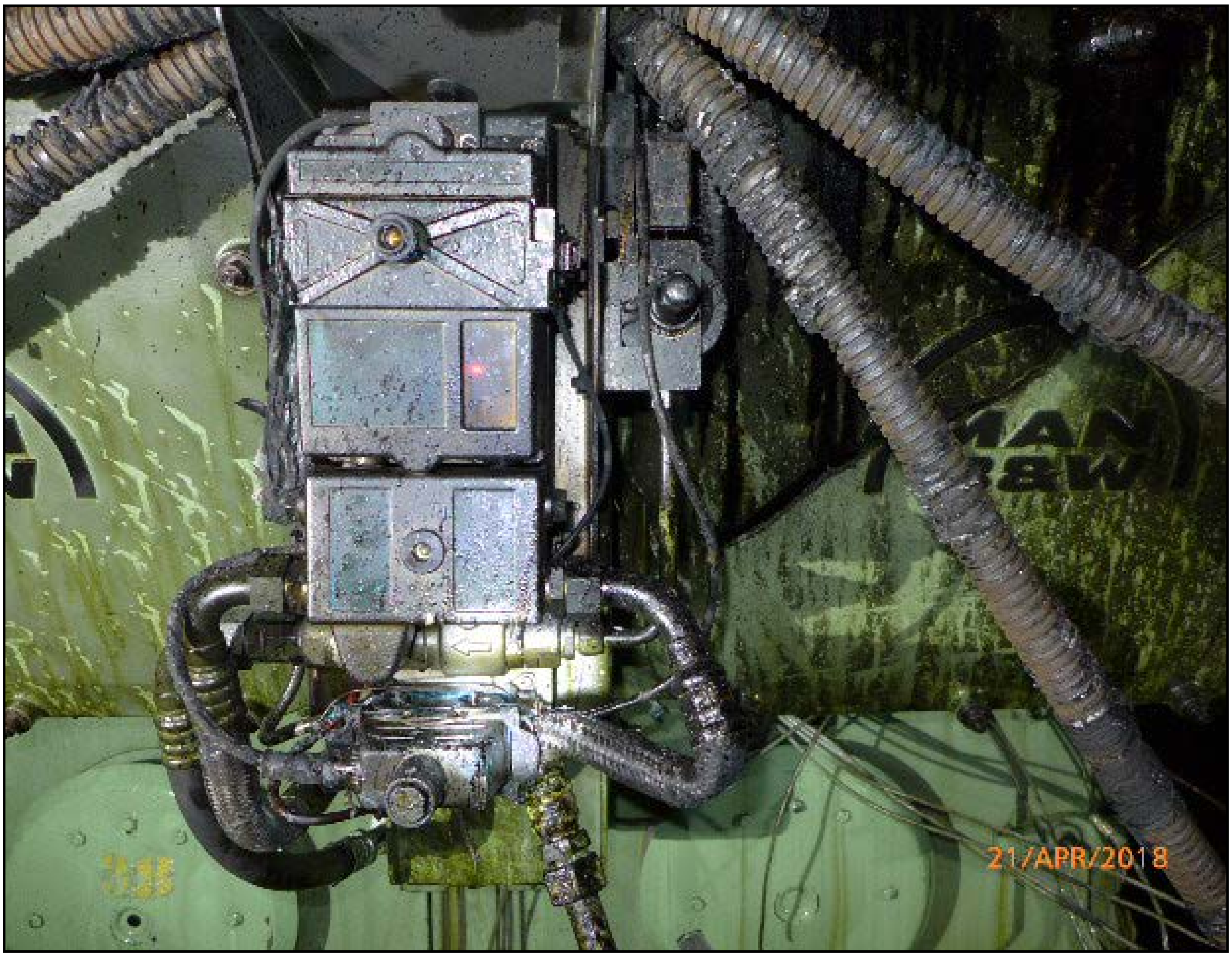


Figure 16: Crankcase oil mist detector

High oil mist concentrations are created in a crankcase by the presence of hot spots, which cause oil to evaporate and then form a mist when they start to condense. The ignition of the oil mist can lead to violent crankcase explosions, the consequence of which can be severe, including death and serious injury to crew, and extensive engine damage.

1.6.4 Post-fire inspection

Finlandia Seaways' main engine suffered substantial structural and component damage during its failure. The engine crankcase structure was ruptured on the port and starboard sides of units five and six, with crankcase explosion relief valve doors and large sections of the crankcase casting being propelled several metres across the floorplates **(Figures 17** and **18)**.

A5's connecting rod **(Figure 19)**, the lower half of its piston and its crankshaft counterweight had been ejected through the starboard side of the crankcase. The connecting rod had separated at its small end eye, shank flange and big end bolted connections. The big end bearing cap was found at the forward end of the engine room deck plates on the port side. B5's connecting rod and its piston had also been ejected from the crankcase and were found on the starboard deck plates **(Figure 20)**, the connecting rod assembly having separated at its bolted shank flange. The broken upper half of A5's small end, and B5's big end lower half, were found in the engine room starboard bilge.

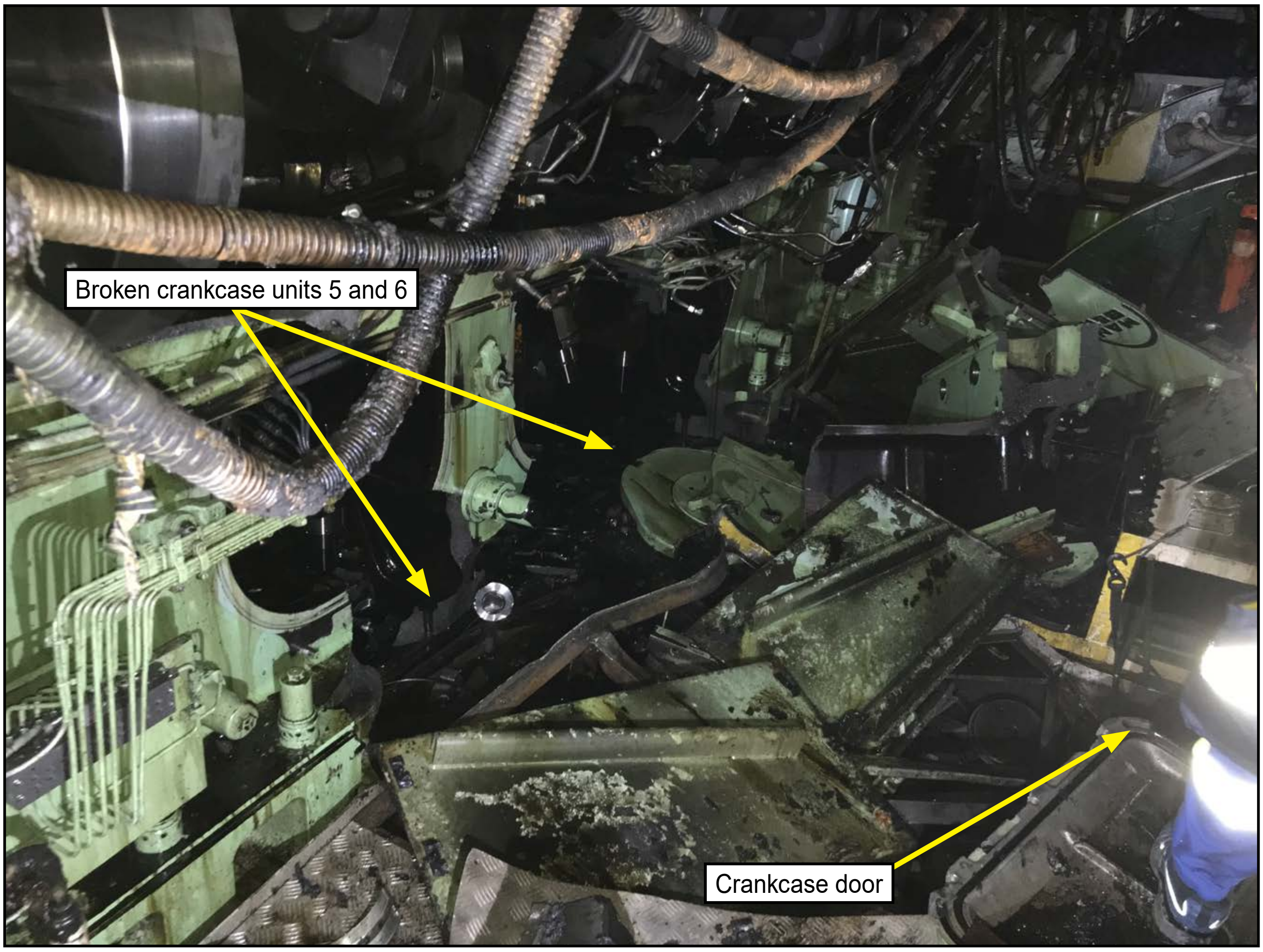


Figure 17: Port side main engine

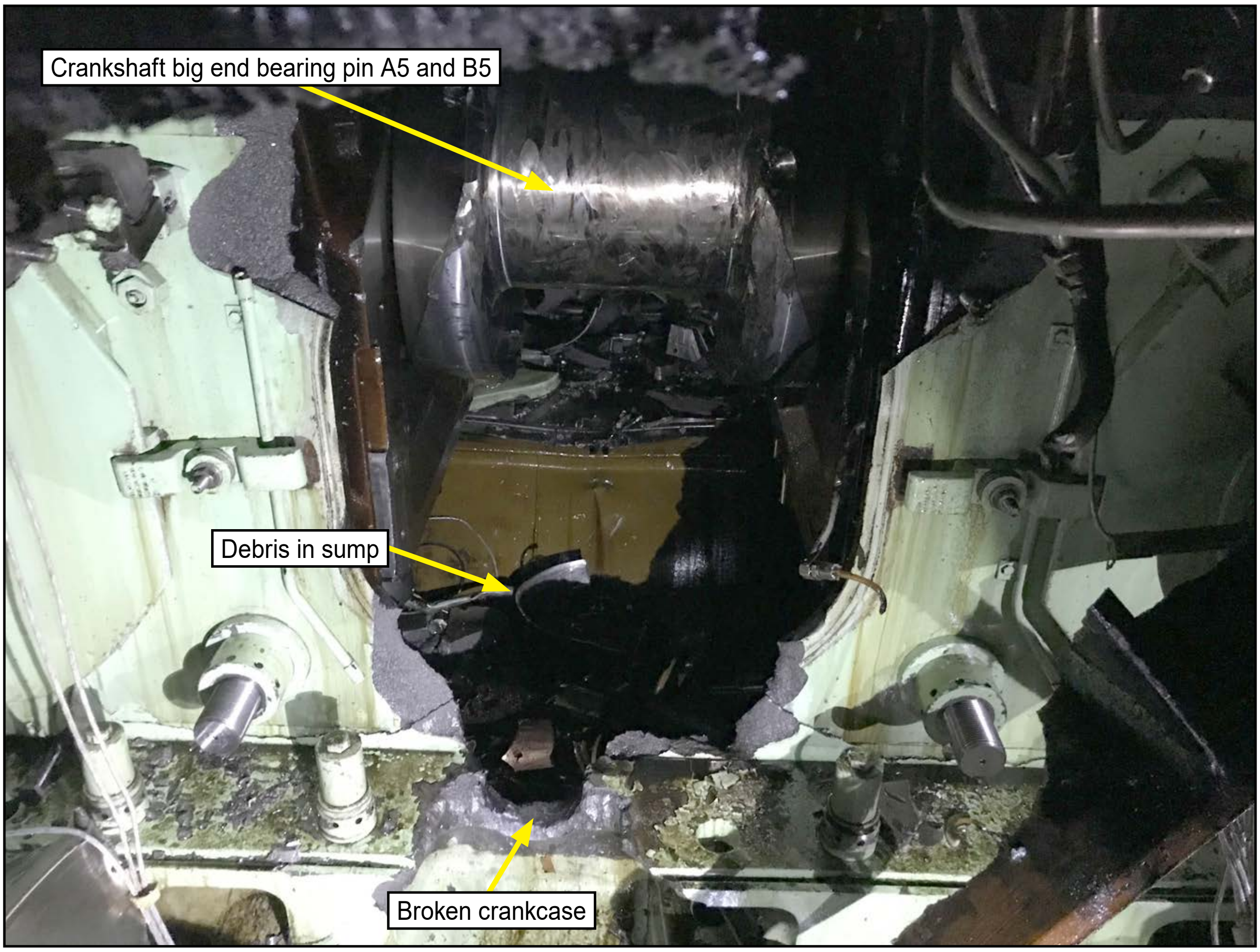


Figure 18: Starboard crankcase damage at B5

Figure 19: Section of A5 connecting rod (after removal from engine room)

Figure 20: B5 components on starboard side deck plates

The upper part of A5's piston and its piston pin[6] remained in the upper section of the cylinder liner **(Figure 21)**; the lower section of the cylinder liner had shattered and dropped into the sump. Although badly damaged at its lower end, B5 cylinder liner did not suffer the same level of damage as A5 **(Figure 22)**. Impact damage had occurred to the crankshaft at number five crankpin journal and the crankpin webs. The camshaft covers for both banks had become detached and the A-bank camshaft had also been partially displaced.

[6] Piston pins are also widely referred to as gudgeon pins.

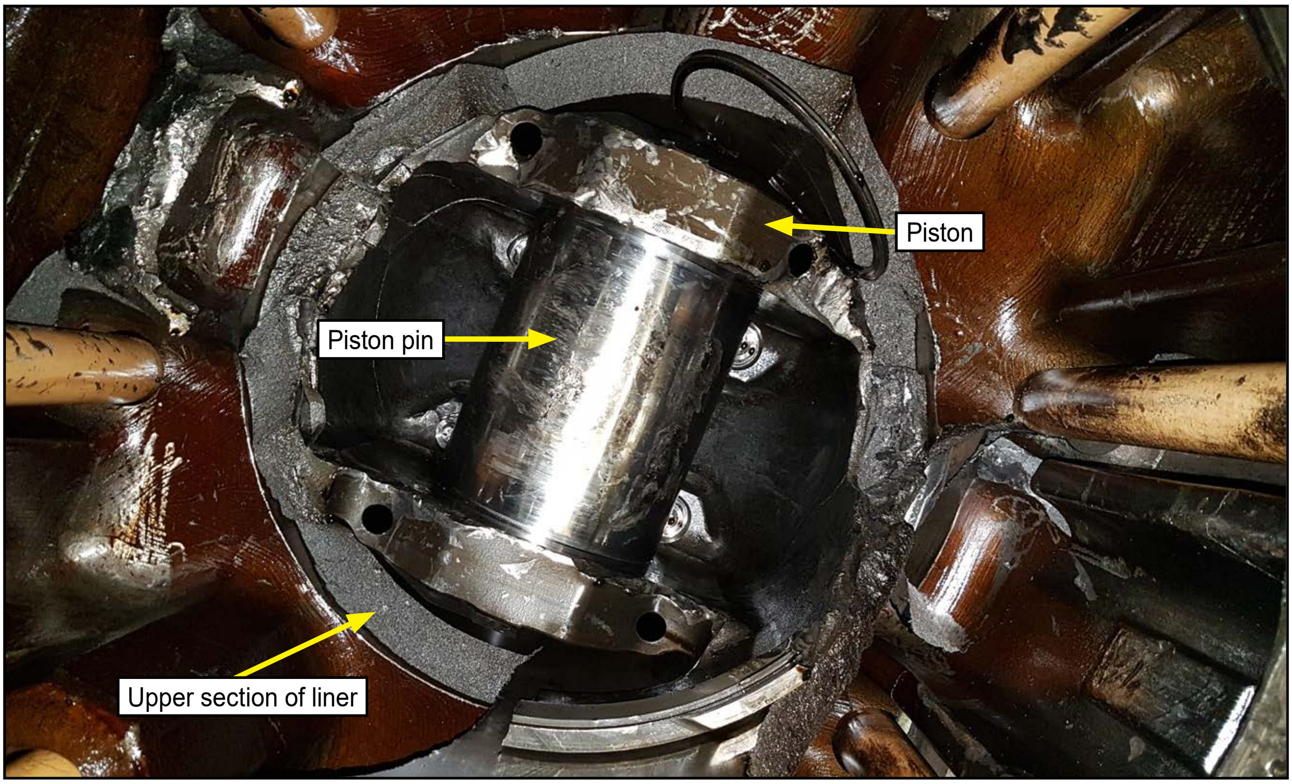


Figure 21: A5 cylinder viewed from engine sump

Figure 22: B5 liner (looking up to inlet/exhaust valves from engine sump)

1.6.5 Engine room alarms

During the engine failure and ship blackout many alarms activated in the engine control room and on the bridge. A summary of key alarms is listed in **Table 1** below.

Ship's time (UTC+2)	Alarm	Alarm State
2203:21	Main engine crankcase oil mist	High
2203:22	Main bearing 6 high temperature	Sensor (Fault)
2203:22	Main engine splash oil monitor	Fail
2203:24	Lube oil pump stand-by	Start
2203:25	Main engine slowdown	
2203:28	Main bearing 5 high temperature	Sensor (Fault)
2203:28	Main bearing 7 high temperature	Sensor (Fault)
2203:32	Main bearing 1 high temperature	Sensor (Fault)
2203:32	Main bearing 2 high temperature	Sensor (Fault)
2203:32	Main bearing 3 high temperature	Sensor (Fault)
2203:32	Main bearing 4 high temperature	Sensor (Fault)
2203:35	Fire alarm	
2203:43	Cylinder A5 exhaust gas out temp	Low

Table 1: Key alarms relating to the engine failure and engine room fire

1.6.6 Planned maintenance

The main engine planned maintenance work on board *Finlandia Seaways* was conducted in accordance with the schedules contained in the vessel's electronic planned maintenance system (PMS). The PMS schedules were based on MAN's engine running hours maintenance schedule **(Table 2)**.

Description	Hours
Check one big end bearing	6,000
Remove, clean/check one piston	6,000
Check all pistons	12,000
Remove one piston pin	12,000
Disassemble one piston	12,000
Replace all big bearing shells and small end bearing bushes	36,000

Table 2: MAN's planned maintenance schedule

Day to day defect maintenance and minor planned maintenance work on the main engine were carried out by the vessel's engineers. This included the replacement of fuel injectors and fuel pump servicing. In addition, the engineers conducted routine inspections of the engine's crankcase, camshafts, bearings, liners, bolt security and lubricating oil supply lines. They also took regular fuel and lubricating oil samples and sent them ashore for analysis. Major maintenance work, such as piston removal, inspection and overhaul was usually carried out by shore contractors during maintenance layover periods at Rosyth. The attendance of the shore contractors was facilitated by the vessel's technical superintendents.

The maintenance requirements for the main engine connecting rods and pistons were set out in the same PMS schedules, under the headings *No.1 Unit A*; *No.1 Unit B*, etc. To assist with piston overhauls and enable swifter maintenance period turnarounds for *Finlandia Seaways* and *Botnia Seaways*, DFDS held six spare small ends. To help monitor small end running hours, the vessels' C/Es recorded their running hours, based on their COC number, on a separate spreadsheet.

1.6.7 Outsourcing of main engine work

Since taking operational control of *Finlandia Seaways* and *Botnia Seaways* in 2009, DFDS had outsourced most of the vessels' main engine repair work to the ship repair company Diesel Service Group UAB (DSG). Initially, DSG was tasked to work alongside MAN service engineers but, over time it was contracted to carry out increasing amounts of the routine main engine work alone. MAN was used only to do complex tasks that required specialist tools and specific expertise. Recent work items undertaken on board *Finlandia Seaways* by MAN included replacing a camshaft in 2016, replacing the Vulcan shaft coupling and overhauling the engines' oil and freshwater pumps.

DFDS had held discussions with DSG to ascertain its capability to undertake specific tasks. In this respect, DFDS considered that DSG had the necessary tools and skills to undertake replacement of the connecting rods' piston pin bushes. No written agreement for this was recorded.

The last visit by DSG (concurrent with an engine inspection by ship's engineers) had taken place on 3 April 2018, with engine running hours at 110,365. During the visit, DSG replaced the engine thrust bearing and carried out crankshaft deflection measurements.

1.7 DIESEL SERVICE GROUP UAB

1.7.1 Overview

DSG was established in 1995 and was based in Klaipeda, Lithuania. It specialised in the repair of marine diesel engines and other engine room and deck equipment. The company had provided a service for a wide range of ships. Many of its technical staff had previously worked in the Western Ship repair yard, Klaipeda.

1.7.2 Certification

DSG was certified by the Lithuanian Maritime Safety Administration (LMSA)[7] to perform repairs, checks and testing of ships' main and auxiliary mechanisms, devices and related systems. DSG's certification was renewed on 22 January 2016, and it was audited by LMSA on 28 February 2017; no non-conformities were raised.

[7] The LMSA was renamed the Lithuanian Transport Safety Administration (LTSA) on 1 December 2017.

DSG was also registered with the Russian Maritime Register of Shipping (RMRS), which had issued a 'Certificate of Firm Conformity' in November 2015. The certificate was valid for 5 years subject to annual confirmation and stated that DSG was certified for, among other things:

> *Code 22014000 'Construction, conversion, modernization and repair of items of technical supervision products', include:*
>
> 1. *Repair of ship's engines up to 8500kW.* [sic]

DSG was also accredited by the Italian classification society Registro Italiano Navale (RINA) with a 'Workshop Approval Statement', covering the design, diagnostics, maintenance and repair of ships' systems and equipment. The certificate was valid until 18 March 2019. The approved workshop status was based on evidence provided, including qualification levels and experience, and a review of the workshop procedures and instructions. The statement did not specify any engine size or power limitation.

DSG was not required to have a quality management system but was in the process of applying for ISO 9001:2000[8] and gaining third party certification. In this respect, a quality management system was under development, including a quality policy, project planning, division of responsibilities and quality objectives. To perform the maintenance on various engines, it had a range of marine engine manufacturers' instructions, including MAN and S.E.M.T. Pielstick engines. DSG was not an accredited service provider for MAN.

1.8 CONNECTING ROD PISTON PIN BUSH RENEWAL

1.8.1 MAN guidance and procedure

The wear limit between the piston pin and its bearing bush was 0.46mm. From experience, MAN expected the bearing pin bush to be replaced after 36,000 running hours.

MAN's piston pin bush removal procedure required the use of a milling machine to accurately cut a groove along the internal face of the bush. The cut needed to be a sufficient depth to leave less than 0.5mm of material on its outer edge without cutting into the surface of the connecting rod small end. The compression force acting on the bush due to its interference fit[9] in the eye of the small end, caused the remaining thin layer of material to collapse inward, allowing the bush to be removed. New bushes were required to be cooled and shrunk using liquid nitrogen before they could be inserted in the small ends. The MAN 48/60 engine maintenance manual stated:

> *Important! If required, the piston pin bush should be replaced in a Service Workshop, as the bush is to be cooled down before being installed.*

[8] ISO 9001:2000 specifies requirements for a quality management system where an organisation needs to demonstrate its ability to consistently provide a product that meets the customer and applicable regulatory requirements.

[9] An interference fit (press fit and shrink fit) is a frictional connection for rotating components. Joint pressure in the friction surface between the two components is necessary for the torque to be effectively transmitted; this pressure is generated by the deformation of the two components, e.g. a shaft and its bearing.

MAN PrimeServ, the brand name for MAN's service division, offered aftersales and through-life maintenance support for all MAN engines and systems. It provided a worldwide, round-the-clock service and had a global network of service workshops and test facilities. It also offered a variety of training courses for its customers' marine engineers and other technical staff. MAN PrimeServ had two service stations worldwide that it considered equipped and able to conduct the bush renewal process; one of them was based at MAN's headquarters in Hamburg, Germany.

1.8.2 Diesel Service Group guidance and procedure

DSG carried out work on a range of vessels and engine types, including five operated by DFDS. On average, DSG had replaced two to three piston pin bushes per year for DFDS, of which about 24 were fitted to the MAN 12V 48/60 engines on board *Finlandia Seaways* and *Botnia Seaways*.

The removal and installation of the MAN connecting rod piston pin bushes was carried out by DSG at its workshops in Klaipeda **(Figure 23)**. DSG's documented *piston pin bush removing and installing* procedure for the MAN 12V 48/60 engine **(Figure 24)** was similar to that followed by MAN. To remove the piston pin bush in accordance with the procedure, one side of the bush had to be bored away using a milling machine before pressing it out. The new bush needed to be cooled using liquid nitrogen to – 195°C and measured before being inserted into the small end eye; a specialist tool was required to be used when aligning the bush.

DSG employed one person to oversee the work and produce the technical repair document, and only one technician was permitted to use the milling machine. DSG was unable to confirm whether anyone else, including possible subcontractors, had undertaken this work.

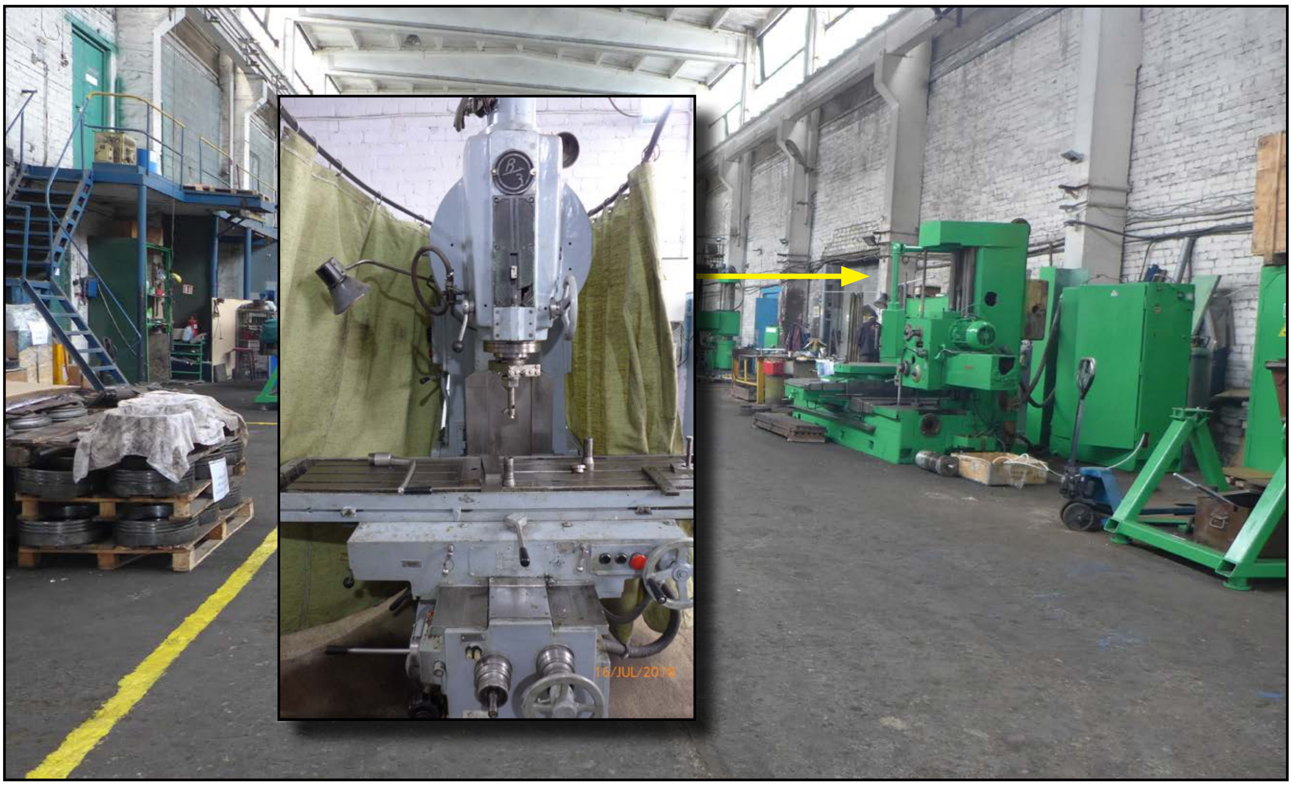


Figure 23: Diesel Service Group workshop and milling machine **(inset)**

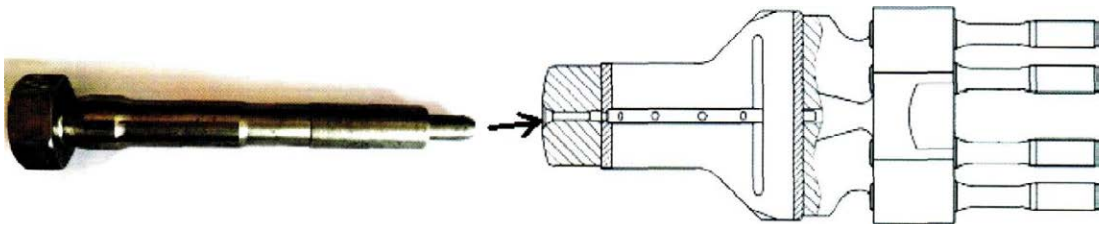
UAB“Diesel Service Group"	Nr. S0115-PTECH/DSG
Piston pin bush removing and installing PROCEDURE	
M.E. MAN B&W 12V 48/60	

The piston pin bush should be replaced in a service workshop, because it needs to be supercooled for assembly.

1.Piston pin bush removing. Piston pin bush to be removed by machining of one side with boring machine. Bush to be pressed out.

2. Piston pin bush installing. The new bush shall be liquid nitrogen refitted (-195 C temperature). The bush shrinking to be measured prior to installation to provide the easy pass into small end hole.

For the levelling and matching of center hole special tool should be used, as shown in a picture below:



Projection of bush has to be equal from both connecting rod small end sides.

After bush is mounted special tool to be taken out.

The inner bush diameter to be measured when the small end temperature becomes the same as the ambient temperature.

Engineer technologist

[redacted]

2015.01.15 [redacted]

Figure 24: Diesel Service Group: small end piston pin bearing bush renewal procedure

DSG carried out similar piston pin bush replacements on S.E.M.T Pielstick engines. The S.E.M.T Pielstick manufacturer's instructions specified that the connecting rod small end bearing bush could be removed by making two diametrically opposed saw cuts in the bush.

In February 2017, DSG carried out a 12,000-hour overhaul of *Finlandia Seaways* unit A5. The total engine running hours was 103,007 and the remarks recorded in the vessel's PMS included:

- *Piston with connecting rod small end:*
    - *Dismantling, disassembling, cleaning, measurements, disassembling of piston, replacement of piston head (used), assembly of piston with new studs,*
    - *Replacement of conrod small end, assembling of piston and conrod small end with new small end bush, installing with new piston rings in accordance with engine manual.*
    - *Installing with new piston rings.*

The work was carried out in Rosyth, and the small end was replaced with one of DFDS's spare small ends (COC 61584), which had been overhauled in November 2016. A summary of A5 small end overhauls based on engine running hours only is set out in **Table 3**.

Date	Engine operating hours	Remarks
20/12/2002	15,885	*Piston pin checked ok*
03/03/2005	30,631	*Pin and bush inspected*
25/06/2007	46,279	*Piston pin checked*
02/02/2010	60,009	*Piston pin bush checked, measured the clearance*
03/10/2012	75,058	*Fitted connecting rod with new piston pin bush*
07/10/2014	87,637	*Piston pin bush replaced*
21/02/2017	103,007	*Replacement of con rod small end with new small end bush* [COC 61584]

Table 3: A5 small end overhauls and inspections

The MAIB and Lithuanian Transport Accident and Incident Investigation Division (TAIID) inspectors visited DSG on 16 July 2018. DSG was unable to identify when, or by whom, the A5 piston pin bush had been replaced.

A subsequent inspection by LTSA on 4 September found that DSG was unable to provide evidence to confirm that liquid nitrogen had been used to shrink the piston pin bush during the overhaul of the small ends.

As DSG was not accredited by MAN, it did not have access to MAN's piston pin bush removal and installation tools and procedures.

1.9 ENGINE MANUFACTURER'S POST-FAILURE ENGINE INSPECTION AND GUIDANCE

1.9.1 Engine inspection and failure mode analysis

MAN attended *Finlandia Seaways* after the accident while it was berthed alongside in Immingham. The engine debris had been left untouched to allow their site examination. Independently, but like the MAIB's initial examination, the focus of interest became the A5 connecting rod. The upper half of the broken small end was found in the debris field on the starboard side of the engine, and the severely damaged piston pin bush was found nearby. Inspection of the failed surfaces of the small end identified a potential fracture face on one side of the small end eye **(Figures 25a**, **25b** and **25c)**.

The remnants of the failed A5 small end, the B5 small end and various other components, including the OMD, were taken ashore by MAN for further analysis.

MAN examined the failed A5 connecting rod small end on 22 June 2018 at its laboratory in Augsburg, Germany. MAIB inspectors and a DFDS representative were in attendance during the examination process. Work carried out included:

- microscopic examination of the small end fracture faces,
- metallurgical composition testing, and
- notch toughness testing[10].

The MAN investigation of A5 connecting rod small end (COC 61584), identified that:

- The small end was originally fitted to *Botnia Seaways* at build in 1999 and was the latest design version.
- It had never been serviced by MAN.
- The fracture might have occurred over a period of weeks or months.
- Due to the damage on the fracture surface, it was not possible to identify the locus of the fracture.
- The chemical composition did not fully correspond with the material specification. The ductile properties of the material were slightly below the required specification.
- A microsection showed a quenched and tempered microstructure but with an aggregation of non-metallic inclusions.

The examination of B5 (COC 113544) found no abnormalities and MAN's investigation established that it was delivered in 2007.

In addition, the investigation report **(Annex A)** concluded that:

- The OMD alarm was the first indicator of a problem, quickly followed by physical destruction of internal engine components.

[10] A standardized high strain-rate test, which determines the amount of energy absorbed by a material during fracture.

- The OMD did not have the ability to record alarms or faults to assist the investigation.

- The A5 small end was probably the first major component to exit the crankcase.

For engines of the type 48/60, MAN also identified that over half of its engines in service had accumulated over 100,000 running hours, with two operating at 180,000 running hours without similar small end failures.

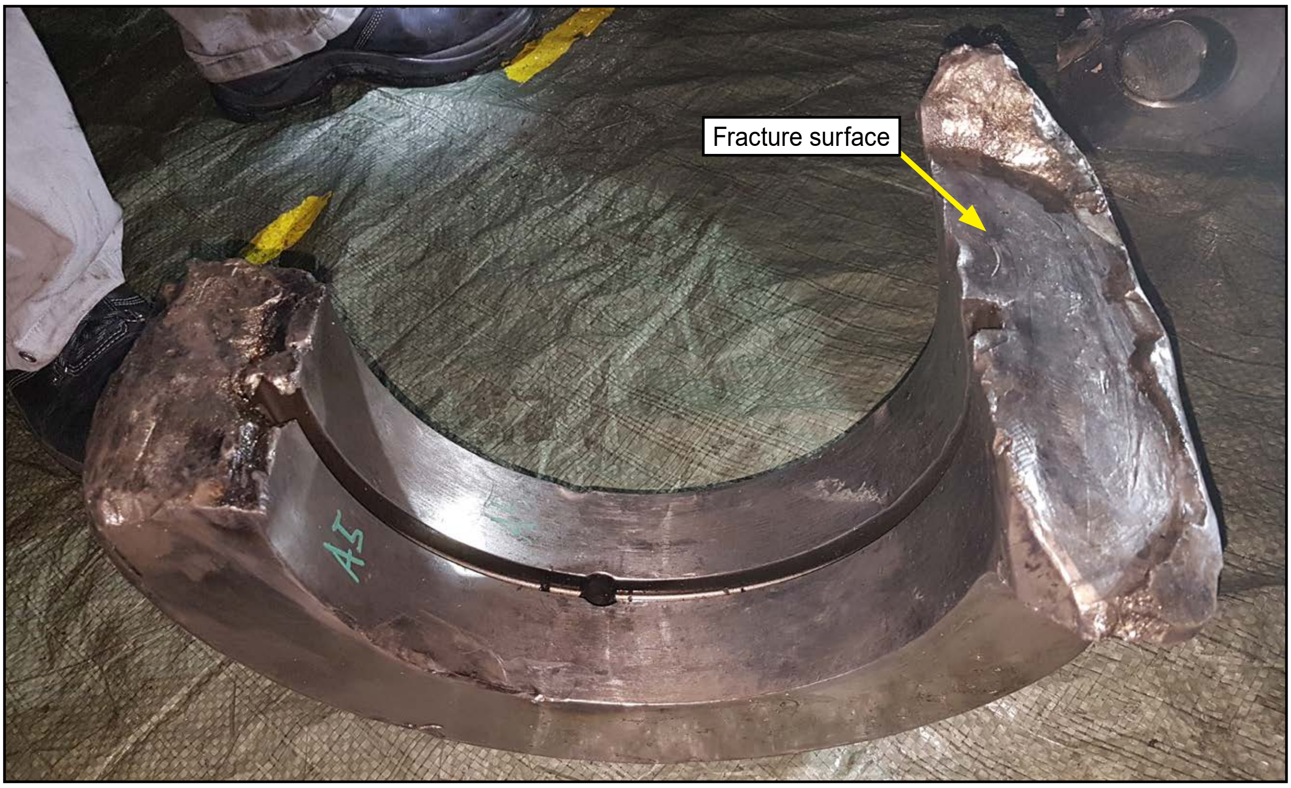


Figure 25a: A5 small end upper half

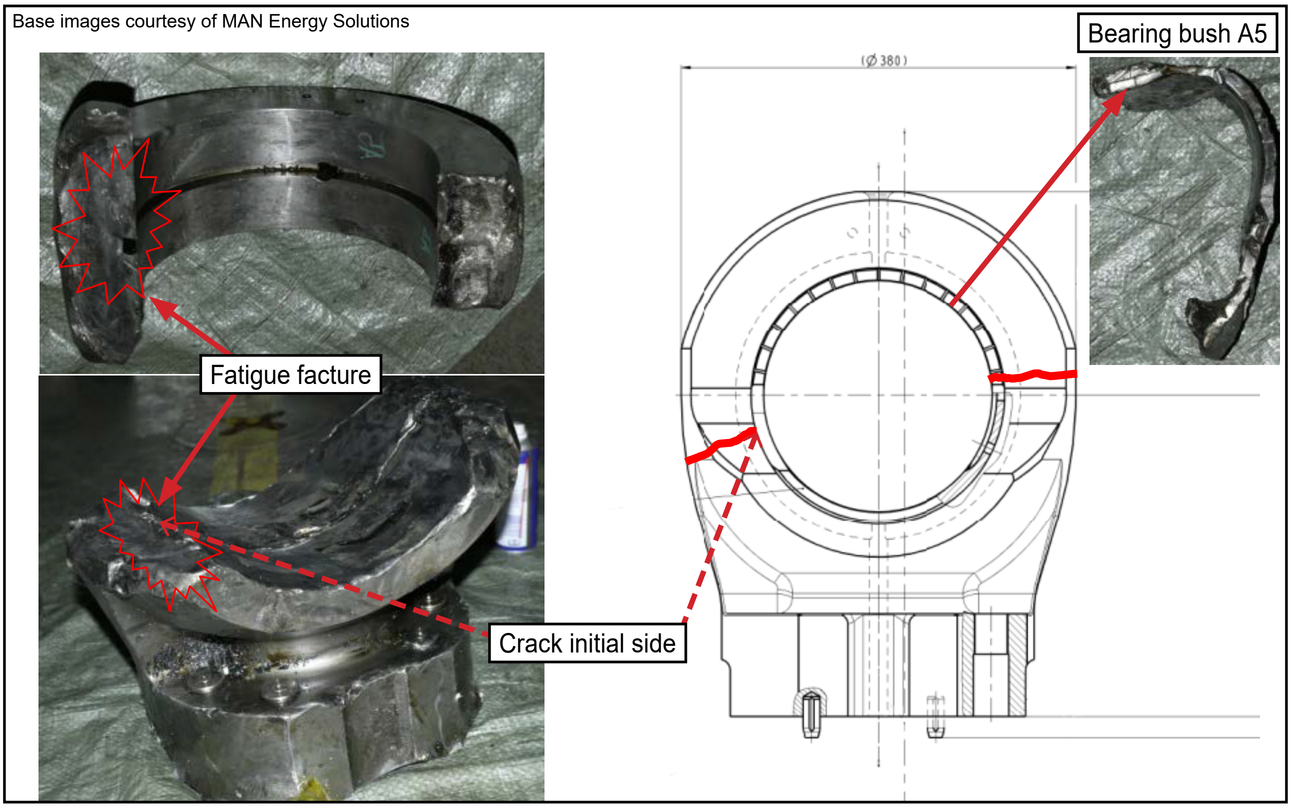


Figure 25b: A5 small end fatigue fracture

Base image courtesy of MAN Energy Solutions

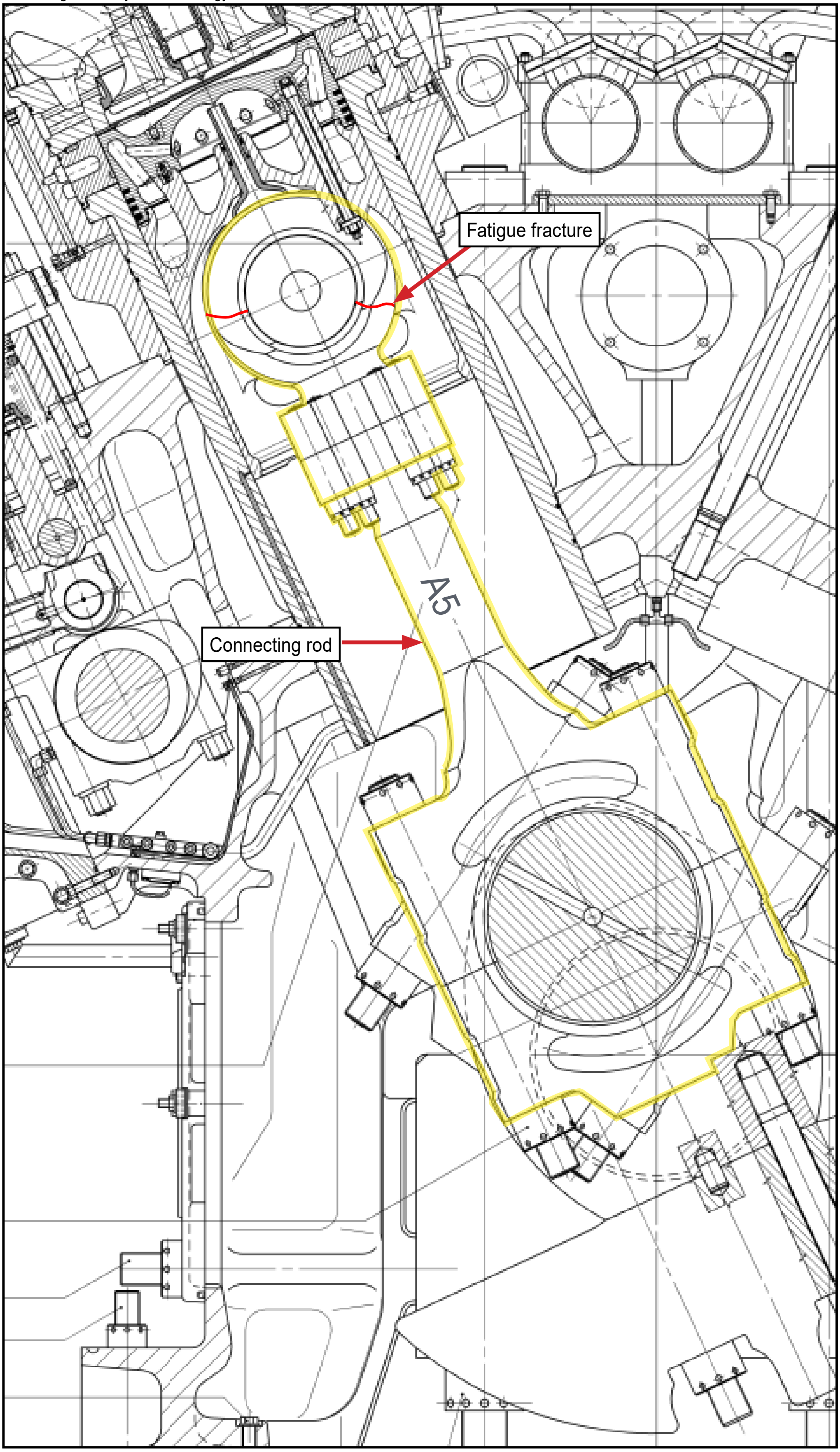


Figure 25c: A5 looking forward and fatigue fracture

At MAN's request, the remaining 10 connecting rod small ends from *Finlandia Seaways* were sent to MAN for inspection. After the piston pin bushes were removed, seven were found to have cuts, or notches, at the edges and on the internal faces of the small end eyes **(Figure 26** and **Table 4)**. The cuts were symptomatic of the use of a disc cutter or angle grinder.

Small ends: A3; B1; B2 and B4 were subsequently identified as having the same respective overhaul and installation dates. It is probable that the overhauls were carried out at the DSG workshop in Klaipeda before installation while the vessel was alongside in Rosyth.

Small end (COC No)	**Date installed in engine**	**Date overhauled by DSG**	**New piston pin bush fitted**	**Cuts or notches found in small end eye**	**Engine running hours at installation**	**Small end running hours at time of engine failure**[11]
A1 (62085)	29/12/2016	unknown	Yes	Yes	102,091	88,765
A2 (61868)	06/06/2017	unknown	Yes	Yes	105,058	89,233
A3 (62009)	15/08/2017	15/08/2017	No	Yes	106,399	91,344
A4 (62110)	06/06/2017	unknown	Yes	Yes	105,058	88,946
A5 (61584)	**21/02/2017**	**11/2016**	**Yes**	**Unknown**	**103,007**	**90,467**
A6 (113538)	18/04/2017	unknown	Yes	No	104,096	88,677
B1 (61993)	02/01/2017	02/01/2017	No	Yes	102,140	89,455
B2 (61944)	18/04/2017	18/04/2017	No	No	104,096	88,466
B3 (61948)	07/11/2016	07/11/2016	No	No	101,146	91,237
B4 (61857)	21/12/2016	21/12/2016	No	Yes	102,091	90,389
B5 (113544)	29/12/2016	unknown	Yes	No	102,091	87,455
B6 (61996)	21/02/2017	unknown	Yes	Yes	103,007	89,048

Table 4: *Finlandia Seaways*' main engine connecting rods, including small end damage

[11] Engine running hours: 110,662

Figure 26: MAN – *Finlandia Seaways*' small ends investigation

1.9.2 *Botnia Seaways*

Following the initial damage assessments and MAN findings, on 27 July 2018 MAIB and TAIID wrote jointly to MAN and LR raising concerns about the risk of similar catastrophic engine failures on board *Botnia Seaways* and other vessels operating MAN engines overhauled by DSG. In the letters, the engine manufacturer and classification society were recommended to provide technical advice on actions to be taken by vessel operators at risk. DFDS subsequently withdrew *Botnia Seaways* from service.

Between 6 and 25 August 2018, while out of service in Marseille, France, all of *Botnia Seaways*' main engine connecting rods were replaced. During the initial inspection of the small ends, the attending LR surveyor identified heat marks on the inner edge of one of the small ends **(Figure 27)**. MAN specialists examined the marks and concluded that they were not caused during engine operation. MAN's assessment was that the localised heat marks had been caused by the application of intensive heat from something like a gas welding torch. MAN suggested that

Figure 27: *Botnia Seaways* small end heat damage (circled)

this had been to assist with the piston pin bush removal/installation process. MAN further concluded that the intense local heating would have produced an annealing[12] effect of the metal, resulting in structural changes affecting the material strength.

MAN's subsequent investigation of the 12 small ends returned for inspection identified:

- Notches/cuts on three small ends.
- Localised heat marks on three small ends.
- Damaged shank bolts on three connecting rods.
- Various levels of other spurious damage and wear.

1.9.3 Engine design modifications and updates

MAN regularly provided targeted customer service information to advise customers on maintenance updates for specific engine types. Since February 2000, MAN had distributed 94 customer information documents for the 48/60 engine, including all the variants.

In 2015, MAN circulated customer information notice No.344/2015 (PCI 344/2015) **(Annex B)**, which advised that the connecting rod be renewed after 100,000 running hours. This was primarily based on increased ovality identified in the big end bearing housings. On receipt of the notice, DFDS checked the ovality of a selection of its connecting rod big ends during routine maintenance and, finding no ovality, kept them in service.

Although DFDS had received them, the MAN customer information notices issued after *Finlandia Seaways*' build were not available on board.

1.10 METALLURGICAL ANALYSIS

As the initiation point of the A5 small end fracture was not identified during the examinations conducted by MAN, the MAIB commissioned The Test House (Cambridge) Ltd (TTH) to undertake further metallurgical analysis work. The remains of *Finlandia Seaways*' A5 small end, and B5 and B6 small ends were delivered to TTH in October 2018.

TTH's initial inspection of A5 identified that:

The fracture surface showed a flat/featureless surface, clear evidence of beach marks, post fracture mechanical damage on the fracture surface and bearing contact surface and a secondary crack in the oilway groove perpendicular to the fatigue fracture.

The conclusions contained in TTH's report **(Annex C)** included:

The engine had failed in a catastrophic manner as a result of the A5 connecting rod small end failing due to fatigue. The fracture had initiated at the bearing contact surface and propagated through the body.

[12] Annealing is a heat treatment that alters the physical and sometimes chemical properties of a material to increase its ductility and reduce its hardness, making it more workable.

Due to post fracture mechanical damage it was difficult to identify the point of initiation.

The intact A6 small end had gouge marks on the edges of the bearing bush contact surface. The TTH report stated that:

Although the intact small end [A6] *showed no evidence of consequential features due to the gouge marks, such practises should be avoided at all costs as they can conclude to points of stress raisers.*

1.11 EXTERNAL OVERSIGHT

Classification societies conduct periodic reviews of critical machinery components to ensure they are in an appropriate condition; normally 20% of Class items are inspected per year over the mandated 5-year survey cycle.

In accordance with LR rules and regulations, *Finlandia Seaways* was operated on a Continuous Survey Machinery (CSM) cycle. Consequently, its C/Es were authorised to carry out examinations of selected machinery while the ship was at sea or in port when LR was not represented. The process was explained by LR in its document *Examination of Surveyable Machinery Items by Chief Engineers*, effective 1 March 2015 **(Annex D)**.

The C/Es' records of examination were audited annually by an LR surveyor and confirmatory surveys carried out. LR provided a template statement **(Annex D)** for completion by the C/E with a requirement that a copy be provided to the surveyor and a second copy remain on board.

Applicable machinery items that could be examined by a C/E included:

- main engine connecting rods,
- piston pins, and
- piston pin bushes.

The connecting rod was a certified item and had an LR stamp on it, but its piston pin bush was considered a consumable item. The replacement of a small end piston pin bush was considered routine maintenance on the part of the ship owner, and LR did not expect to be called in by an owner to witness routine maintenance between its mandated surveys. LR did expect to be notified if a certified component, such as the connecting rod, had been deemed beyond economical repair and was replaced, had a defect that was repaired, or if the component was modified.

Cylinder A5 had previously been overhauled on 7 October 2014; the C/E's statement of examination was dated 29 December 2014. The examination was then credited under the CSM cycle by an LR surveyor on 31 January 2015 **(Table 5)**.

Conrod	Description	Date last credited by LR	Type of credit[13]
A1	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
A2	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
A3	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
A4	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
A5	**Cylinder, cover, bearings, piston, con-rod, valves and gears**	**January 2015**	**Complete**
A6	Cylinder, cover, bearings, piston, conrod, valves and gears	September 2017	Confirmatory
B1	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
B2	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
B3	Cylinder, cover, bearings, piston, conrod, valves and gears	January 2015	Complete
B4	Cylinder, cover, bearings, piston, conrod, valves and gears	September 2017	Confirmatory
B5	Cylinder, cover, bearings, piston, conrod, valves and gears	September 2017	Confirmatory
B6	Cylinder, cover, bearings, piston, conrod, valves and gears	September 2017	Confirmatory

Table 5: Lloyd's Register Component Survey List

A subsequent C/E's statement was completed on 4 September 2017 and included various engine parts examined since February 2017. These included cylinder B6 on 21 February 2017:

> *No.6 STBD bank cylinder, cover, piston, cylinder liner, connecting rod & bearings, valves & gears were inspected during overhaul of cyl No6B. All parts cleaned, measured and found in good sound condition. Replaced piston rings, all o-rings and gaskets. No6B cyl was tested in work after assembling. No remarks.* [sic]

There was no reference to the replacement of the small end bush that had also occurred.

[13] Items credited with 'Complete' indicate that the surveyor conducted a full survey of the item. 'Confirmatory' indicates that the surveyor was provided documentary evidence from the chief engineer regarding the condition of the equipment.

DFDS only had the C/E's statement of examinations for cylinders A1, A2 and A5 that were overhauled during 2014, and LR interim certificates for July 2012 and December 2017. The local Klaipeda LR surveyor did not routinely retain his copies of the survey results as there was no obligation to do so.

During their examinations, LR surveyors were advised to take pictures of the general condition of compartments and also of defects/observations. For specific engine components, photographs would be deemed necessary only if defect observations were made. As no defect observations had been made, no photographic evidence of surveys was available.

1.12 EMERGENCY RESPONSE

1.12.1 Carbon dioxide fixed fire-extinguishing system

Finlandia Seaways' CO_2 fixed fire-extinguishing system comprised 221 x 53kg gas bottles, with the capacity to protect the engine room, upper cargo hold, lower cargo hold and paint store. Each protected space required a specified number of bottles to ensure that the correct percentage of CO_2 was injected to smother a fire. Thirty-one bottles were required for the engine room, and they were released via the remote release station on the forecastle deck. The system could also be operated from the CO_2 bottle room.

Confirmation that CO_2 had been released into the protected space was achieved by entering the CO_2 bottle room and checking the appropriate control valve had activated and the manifold gas pressure gauge had dropped to zero. Frosting of the bottles and manifold pipes provided a further visual indication that gas had been released. Information to enable the crew to easily identify which spaces individual CO_2 bottles protected was not provided in the bottle room, and the gas bottle operating valves did not provide a visible means of identifying whether they were open or closed **(Figure 28)**.

Following the activation of the CO_2 system, it was unclear how many bottles had been released. Consequently, a specialist service engineer was required to attend the vessel and confirm that all 31 CO_2 bottles had been released into the engine room.

Marine Guidance Note (MGN) 389 (M+F) *Operating Instructions and Signage for Fixed Gas Fire-Extinguishing Systems* was published in 2009 by the Maritime and Coastguard Agency (MCA) following a series of fire investigations conducted by the MAIB, which identified issues relating to the quality and effectiveness of operating instructions and signage. The MGN quotes Chapter 5, Section 2.1.3.3 of the International Maritime Organization's (IMO) Fire Safety Systems Code, which states:

> *The means of control of any fixed gas fire-extinguishing system shall be readily accessible, simple to operate and shall be grouped together in as few locations as possible at positions not likely to be cut off by a fire in a protected space. At each location there shall be clear instructions relating to the operation of the system having regard to the safety of personnel.*

MGN 389 (M+F) recommends the use of colour coded controls for different discharge zones, and emphasises the importance of ensuring gas has been correctly released for a protected zone immediately after activation. For systems such as that fitted on board *Finlandia Seaways*, the MCA advised crew to look for frosting around the bottom of the discharged gas bottles.

Figure 28: Carbon dioxide bottle operating valve

1.12.2 Means of escape

Under the International Convention for the Safety of Life at Sea (SOLAS) Amendments (Chapter II-2, Part D, Regulation 13 – Means of escape), ships of more than 1000gt shall have two means of escape from each machinery space of category A[14].

Each escape shall be widely separated from each other and lead to the open deck. One of the escapes shall have a continuous fire shelter from the lower part of the space to a safe position outside.

Finlandia Seaways met the means of escape requirements, with the continuous fire protection route being the primary escape route via the steel self-closing door at the port-forward bottom engine deck, up the enclosed stairwell via the control room and to the main deck **(Figure 29)**.

[14] Spaces which contain internal combustion machinery used for main propulsion.

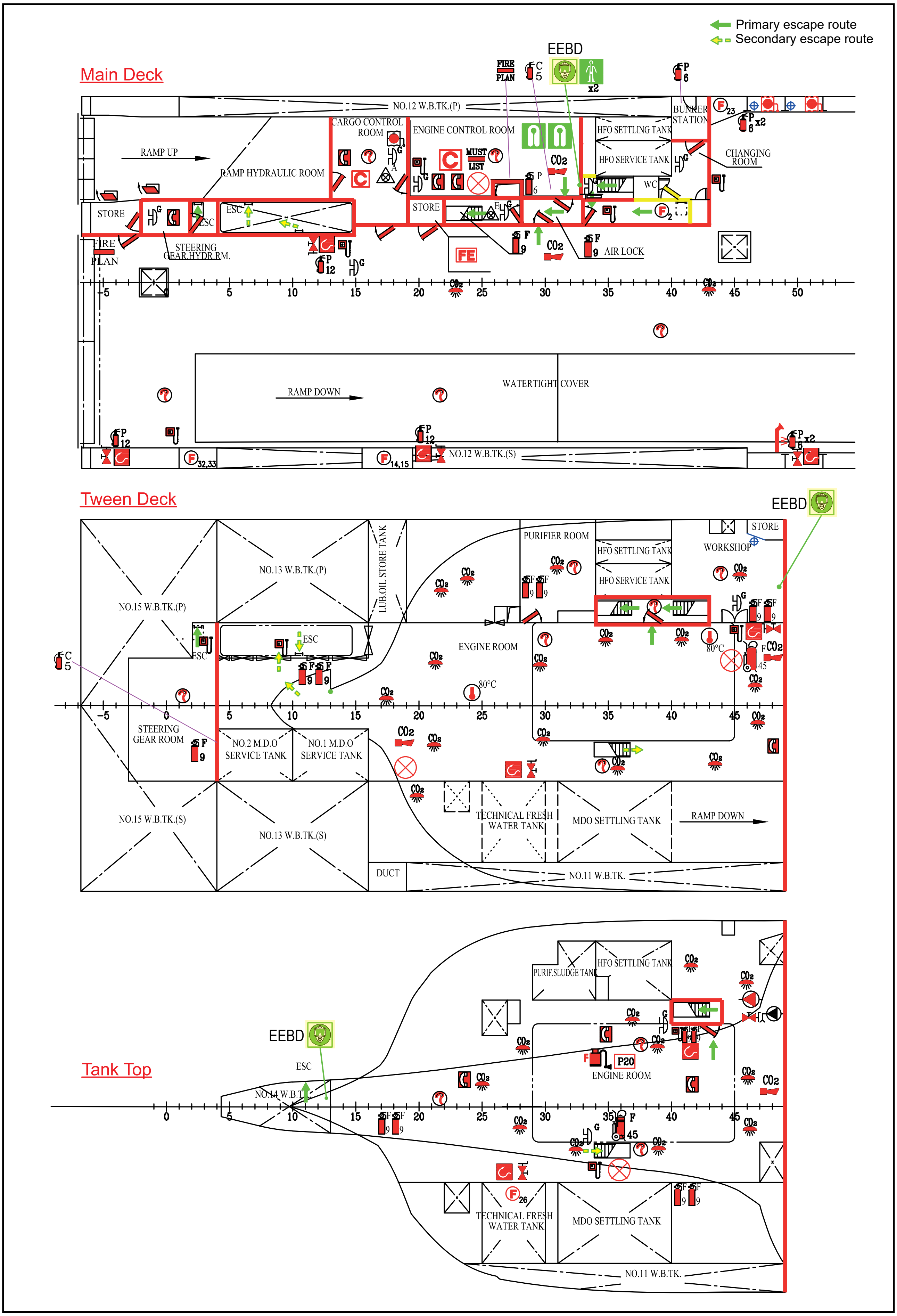


Figure 29: Distribution of EEBDs in or near to the engine room and escape routes

The secondary means of escape, as used by the 3/E, via the funnel casing aft of the generators, was not enclosed. This route could be accessed from the bottom engine room deck, via a steel ladder near the propeller shaft on the port side, and up through a hinged steel hatch grating at generator deck level.

1.12.3 Emergency escape breathing devices

Emergency escape breathing devices (EEBDs) are part of ships' safety equipment, and their primary purpose is to enable crew to escape from a smoke-filled compartment. They should provide a minimum air supply of 10 minutes and are mandatory under SOLAS for ships where a safety equipment certificate applies.

SOLAS 2000 Amendments (Chapter II-2, Part D, Regulation 13) introduced the requirement for emergency escape breathing devices (EEBDs). Section 4.3 Emergency escape breathing devices states:

> *4.3.1 On all ships, within the machinery spaces, emergency escape breathing devices shall be situated ready for use at easily visible places, which can be reached quickly and easily at any time in the event of fire. The location of emergency escape breathing devices shall take into account the layout of the machinery space and the number of persons normally working in the spaces.*

IMO MSC/Circ.849 (8 June 1998) – Guidelines for the performance, location, use and care of emergency escape breathing devices in section 4.6 states:

> *Unless personnel are individually carrying EEBDs, consideration should be given for placing such devices along the escape routes within the machinery spaces or at the foot of each escape ladder within the space.*

IMO MSC/Circ.1081, *Unified Interpretation of the Revised SOLAS Chapter II-2*, 13 June 2003, relating to EEBDs, includes:

> *Regulation 13.4.3 Emergency escape breathing devices (EEBD)*
>
> > *1. This interpretation applies to machinery spaces where crew are normally employed or may be present on a routine basis.*
> >
> > *2. In machinery spaces for category A containing internal combustion machinery used for main propulsion, EEBDs should be positioned as follows:*
> >
> > > *.1 one (1) EEBD in the engine control room, if located within the machinery space;*
> > >
> > > *.2 one (1) EEBD in workshop areas. If there is, however, a direct access to an escape way from the workshop, an EEBD is not required; and*
> > >
> > > *.3 one (1) EEBD on each deck or platform level near the escape ladder constituting the second means of escape from the machinery space (the other means being an enclosed escape trunk or watertight door at the lower level of the space).*
>
> *Alternatively, a different number or location may be determined by the Administration taking into consideration the layout and dimensions or the normal manning of the space.*

The unified interpretation applies to all ships constructed on or after 1 July 2003.

Finlandia Seaways had three EEBDs located in the engine room machinery spaces: one in the ECR, one in the workshop, and one on the engine room bottom deck at the aft end adjacent to the propeller shaft **(Figure 29)**. A further six EEBDs were provided in the forward accommodation block (one on each deck) and one on the main deck forward equipment room. The LR Record of Approved Cargo Ship Safety Equipment (dated 31/12/12) identified 10 EEBDs, with two located in the engine room and eight in the accommodation.

The engine room escape routes and locations of the EEBDs were clearly marked on *Finlandia Seaways*' fire control and safety plan, which had been approved by LR on behalf of the vessel's Administration. The nearest EEBD to the 3/E when he began his escape from the engine room tween deck, was one deck below, at the aft end adjacent to the propeller shaft.

1.12.4 Voyage data recorder recovery

Finlandia Seaways was equipped with a Kelvin Hughes MDP-A5 voyage data recorder (VDR). It was fitted in 2010 and was supported by an uninterruptible power supply (UPS) battery to enable it to maintain recording capability when ship's power was lost. The UPS batteries were last replaced in January 2015.

Shortly after the fire, the company and master were requested to save the data recorded on the VDR. The MAIB recovered the VDR data as part of its investigation and discovered nothing had been recorded after the blackout.

On 11 September 2017 a Kelvin Hughes representative had conducted an annual performance test (APT). The APT report identified that the UPS battery had an expiry date of 1 March 2019 and, during testing, sustained power to the VDR for more than 1 hour 55 minutes after the main power supply was removed. The report was returned to Kelvin Hughes, vetted and approved.

1.13 PREVIOUS/SIMILAR ACCIDENTS

1.13.1 *Thetis D*

On 26 October 2015, the container ship *Thetis D* suffered a major main engine failure and subsequent engine room fire while on passage. Its MAN 58/64 CD engine suffered serious damage to its number 7 piston and connecting rod big end bearing. It also suffered structural damage to the crankcase adjacent to the bottom end bearing.

The investigation report[15] published by the German government's marine transport accident investigation body, Bundesstelle für Seeunfalluntersuchung (BSU), identified that the bottom end bearing had been inspected by the vessel's C/E 7 months earlier. The findings of the examination of the failed components by MAN and an independent engineer identified that after the inspection of the bottom end bearing, the conrod bolts had not been tightened correctly. The loss of bolt tension eventually resulted in bottom end bearing damage, piston seizure and ejection of engine components through the crankcase.

[15] BSU report 431/15 – Serious engine damage followed by fire on board the cargo vessel *THETIS D* on 26 October 2015 in the Kiel Bight.

BSU recommended that *Thetis D*'s owners take the necessary steps to ensure qualified engine room personnel prepare, carry out and record maintenance and servicing works on key components properly. They also recommended that the classification society, at its next International Safety Management audit, focus on the procedure for maintaining and servicing key components to ensure it exists and is implemented.

1.13.2 Power station, Spain

A Spanish power station using MAN 48/60 engines suffered a catastrophic engine failure during operation. MAN's investigation identified the failure of a connecting rod small end to be the cause. Its investigation found that the technicians operating the engine had carried out a small end overhaul on the failed connecting rod. During the overhaul the technicians used a disc cutter to remove the piston pin bushes from the small ends. The disc cutter had also cut into the eye of the small end. MAN concluded that the disc cutter damage had introduced stress raisers, which eventually led to fatigue fracture and small end failure.

SECTION 2 - ANALYSIS

2.1 AIM

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

2.2 ACCIDENT OVERVIEW

Finlandia Seaways' main engine suffered a catastrophic failure that resulted in the violent ejection of heavy internal components from the crankcase into the engine room. The subsequent release of hot oil vapours caused a fire to break out and the engine room to become engulfed in thick black smoke. The 3/E was in the engine room at the time and he was extremely fortunate to have escaped and survived.

In this section of the report, the engine failure mode will be identified and the factors that contributed to it will be analysed. The emergency response by the vessel's crew, and the levels of emergency preparedness for the casualty event, will also be discussed.

2.3 ENGINE FAILURE

2.3.1 Sequence of events

The initial indications that there was a problem with *Finlandia Seaways*' main engine were loud metallic knocking noises heard by the on watch 3/E in the purifier room, and powerful vibrations felt throughout the ship by the OOW, master, C/E and the rest of the crew. The first engine alarm to activate was the *main engine crankcase oil mist – high* alarm, which was immediately followed by number six main bearing high temperature and splash oil monitor failure alarms. Within 2 seconds of the first alarm the engine's standby lubricating oil pump started, and the automatic engine slow down sequence began. Ten seconds later, the engine room fire alarm was activated.

OMDs are designed to identify and alert engineers to small changes in crankcase oil mist levels and therefore protect an engine against the potential consequences of hot spots created over a period of time due to events such as bearing wear or piston ring blow past. In cases where oil mist is ignited, the sudden increase in crankcase pressure should be released via the crankcase explosion relief valve doors. Although the initial alarm indicated that an oil mist had been generated in the crankcase, there was no evidence to suggest that a crankcase explosion had occurred prior to the catastrophic engine failure.

The witness accounts and machinery alarm sequence clearly indicate that the accident was the consequence of a sudden major engine component failure rather than as a result of gradual wear and/or lubrication starvation. The loud mechanical knocking noises, automatic starting of the standby lubricating oil pump, the sequential failure of internal alarm sensors and the fact that the crankcase explosion relief valve doors did not open prior to the ejection of rotating components into the engine room, support this conclusion.

2.3.2 Identification of the component failure

The structural damage to the engine crankcase was restricted to units five and six, with internal components from A5 and B5 cylinders being released into the engine room. It was therefore apparent that the initial component failure must have occurred in either A5 or B5 cylinder. The accident site damage inspection conducted by MAIB and MAN engineers was focused on identifying the likely locus of the failure and eliminating the components that had suffered secondary damage due to contact with other moving parts or sudden loss of lubrication.

Both A5 and B5 connecting rods had failed and been thrown into the engine room. B5's piston had also been thrown out of the crankcase, but the upper half of A5 piston was found to be seized in its damaged cylinder liner, with its piston pin still in place. It was therefore evident that the A5 connecting rod had failed at its small end eye. Either the piston had seized within the liner to such an extent that the connecting rod small end eye had sheered under tension, or the small end itself had suffered a metallurgical failure.

The types of friction marks and liner damage typically associated with piston seizures due to misalignment, lack of liner lubrication or ring failure were not found when the recovered pieces of the broken A5 cylinder liner and A5 piston skirt were inspected. Furthermore, had a piston seizure caused the catastrophic failure, the connecting rod's flanged shank connection should have failed first as it was the weakest part of the connecting rod assembly. Because of this, the failure of the A5 connecting rod small end was identified as the most likely cause of the catastrophic engine failure.

When the small end failed, the A5 connecting rod would have begun flailing around inside the crankcase. At 500rpm, damage within A5 cylinder unit developed rapidly, tearing away alarm cabling and causing B5 cylinder components to also fail. Within seconds, the heavy rotating components were released and, with great energy, thrown through the crankcase into the engine room.

2.3.3 Failure mode

The A5 connecting rod's small end had completed just over 90,000 running hours. This was 10,000 hours fewer than the recommended limit set by MAN for the connecting rod, 20,000 less than the engine operating hours and up to 80,000 fewer than some of those accumulated on some similar MAN engines. This suggests that the failure had most likely been the result of either damage caused during the overhaul of the small end, an assembly error during the overhaul process or during its installation, or a metallurgical defect introduced during the initial manufacturing process.

MAN's metallurgical analysis of A5's small end identified the presence of non-metallic inclusions within the material's microstructure, and that the ductility of the metal was marginally below that required in its material specification. Although both factors would have an adverse effect on the material strength and durability of the small ends, MAN determined that the deviations were minor and within the acceptable safety margin limits set out in published guidelines. Both the MAN and TTH examination reports dismissed a manufacturing defect as being a likely cause of the failure.

When the upper half of the A5 connecting rod small end was found, a brief inspection of its failure faces was sufficient to identify the development of a fatigue fracture on one side of the small end eye **(Figure 25a** and **25b)**. Following closer examination of the failure faces, both MAN and TTH concluded that the mode of failure was a fatigue fracture.

2.4 FRACTURE MECHANISM

2.4.1 General

Fatigue fracture is one of the primary failure modes in structural metal components and is often referred to as metal fatigue. Fatigue fracture results from cyclic stresses that are below the ultimate tensile strength, or even the yield strength of the material **(Figure 30)**. As the original design strengths are not exceeded and the only warning sign of an impending fracture is a crack, which is often hard to see, fatigue damage is particularly dangerous.

2.4.2 Fatigue fracture

Fatigue failure occurs in three stages: crack initiation, crack growth (slow propagation through the metal) and fracture (rapid failure of the remaining intact metal) **(Figure 31)**. Fatigue cracks almost always start at the surface of a material. This is because:

- The most highly stressed fibres are usually located at the surface (bending fatigue). And

- The intergranular flaws, which precipitate tension failure are more frequently found at the surface.

Crack initiation points, crack growth and propagation rates can be established by analysing the macroscopic beach marks that are usually created on a failure face prior to final fracture. TTH analysed the beach marks found on the small end's failure face, and determined that the fracture had initiated at the bearing bush contact surface and had propagated outward. It also identified a secondary crack in the oilway groove perpendicular to the fatigue fracture.

Since fatigue cracks generally initiate at a surface, the surface condition of the component being loaded will influence its fatigue life. Surface roughness is important because it is directly related to the level and number of stress concentrations on the surface. The higher the stress concentration the more likely a crack is to develop. Smooth surfaces increase the time before crack development. Notches, scratches and indentations can act as stress raisers and therefore decrease the time before crack development.

The bush mating surface of the internal face of the small end eyes had been shot-peened to increase crack resistance. However, the introduction of notches, caused during the bush removal process, introduced stress raisers into the small end, increased the likelihood of fatigue crack initiation and therefore fatigue failure.

2.4.3 Notch effect and toughness

Toughness is the ability of a metal to deform plastically and to absorb energy before fracture. There are several variables that have a major influence on the toughness of a material. These variables include: strain rate, temperature and notch effect.

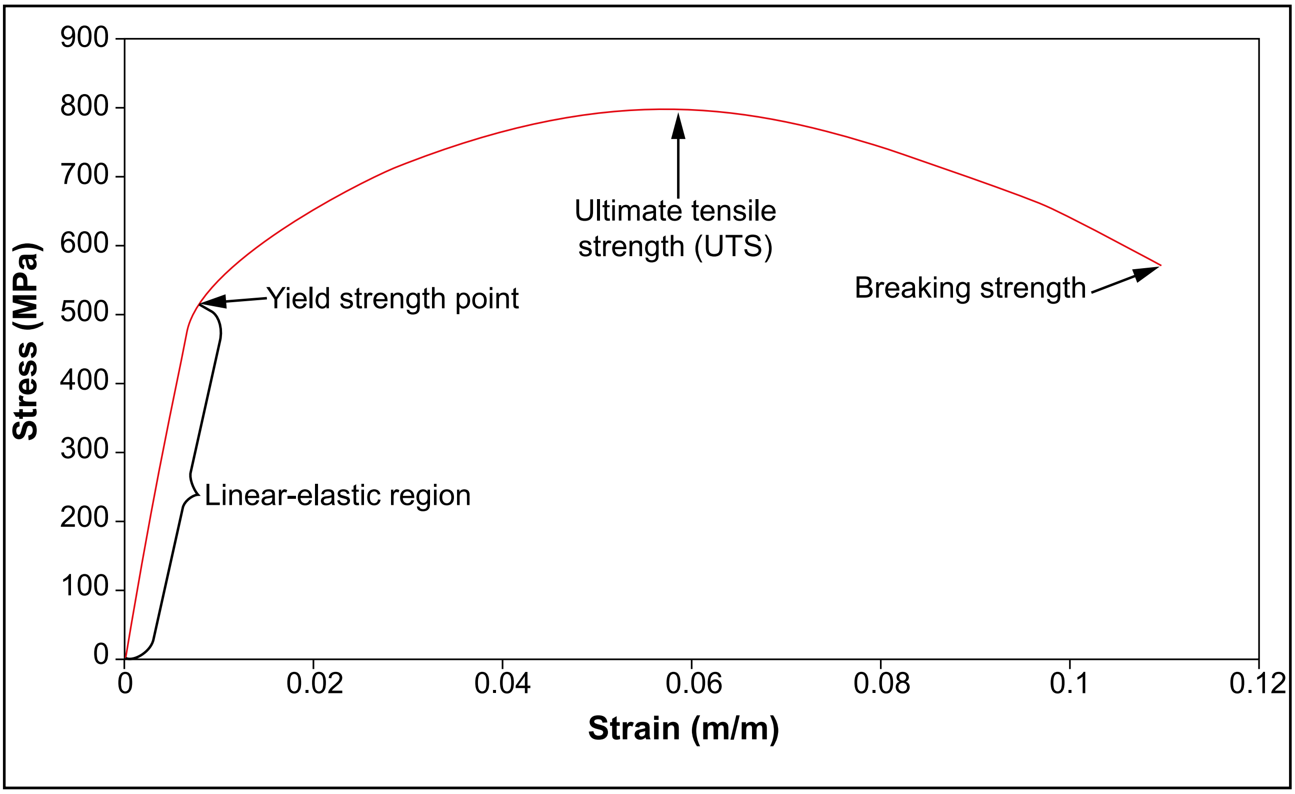


Figure 30: Stress/strain curve

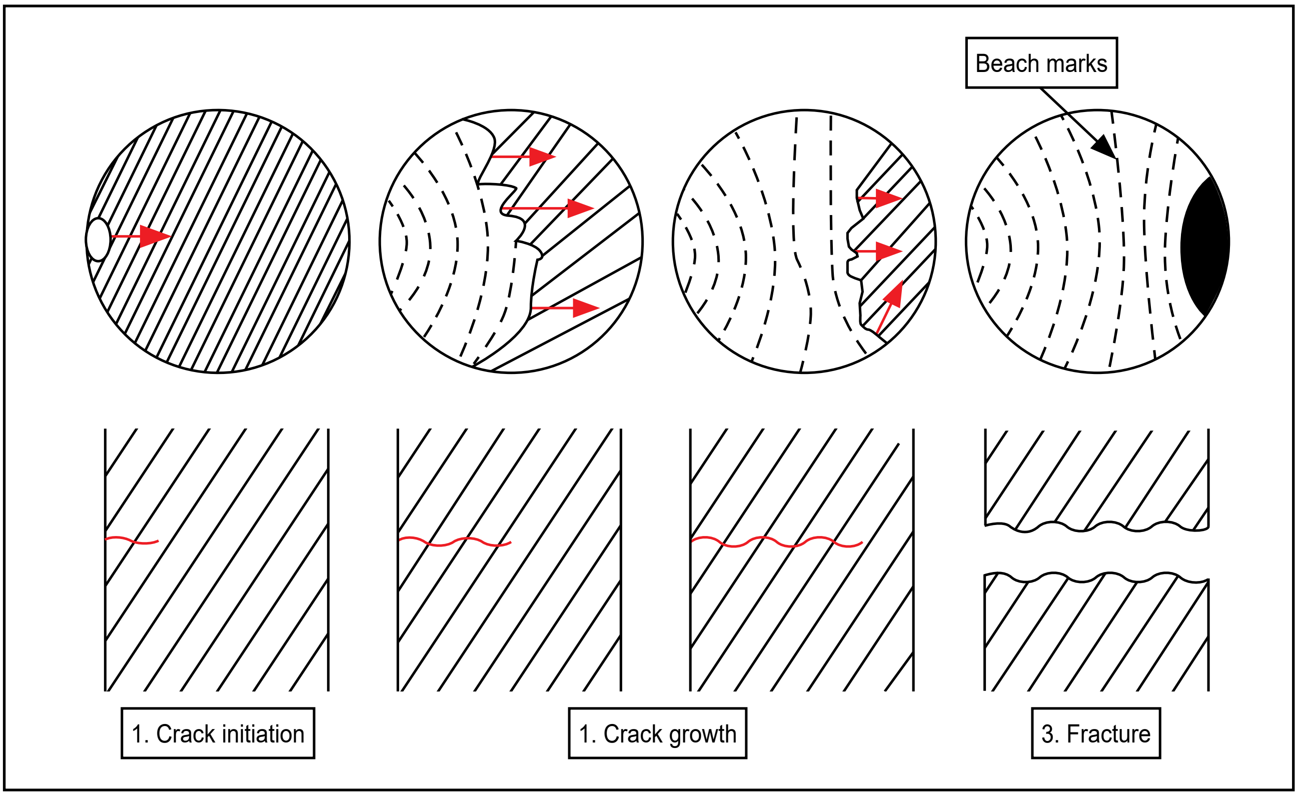


Figure 31: Crack propagation

The third variable, notch effect, involves the distribution of stress. A material might display good toughness when the applied stress is uniaxial. However, when a multiaxial stress state is produced due to the presence of a notch, the material might not withstand the simultaneous elastic and plastic deformation in the various directions.

A notch causes a disruption to the stress flow and introduces localised stress concentrations. The change of section concentrates stress most strongly where the transition is sharp **(Figure 32)**. The introduction of a notch, or cut, in a material will affect the fracture development. The shape of the notch will also have an effect on how the stress propagates through the material. Fatigue loading is cumulative, and the fatigue strength decreases more rapidly over the cycling lifetime for notched samples.

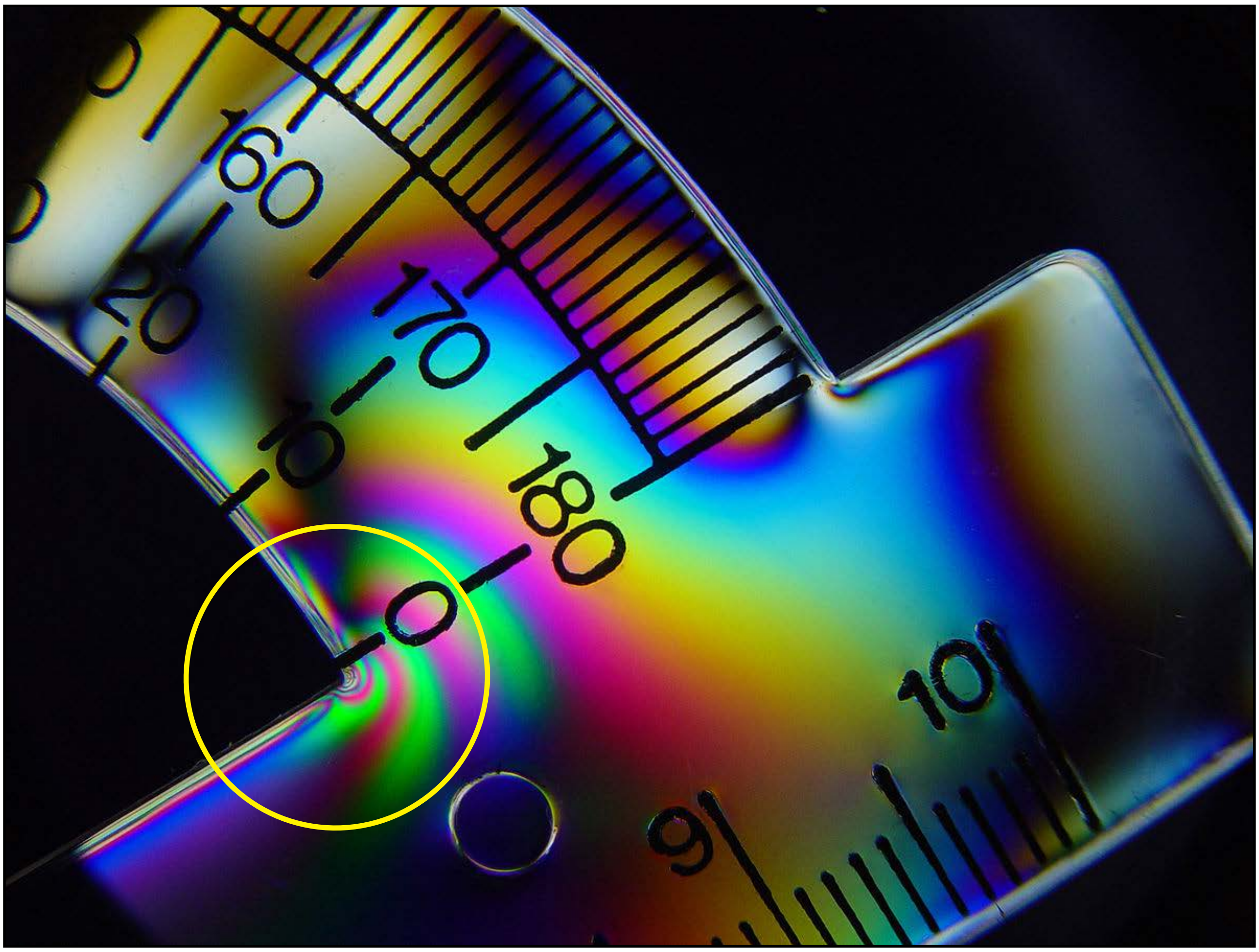


Figure 32: Plastic protractor under polarising light showing stress concentration

2.4.4 Localised heating

Heat marks were found on several of the small ends removed from *Botnia Seaways*, all of which were condemned and had to be replaced. It was apparent that the heat marks were the result of localised heating applied by a gas welding torch or similar device.

Temperature can also influence the fatigue life of materials. As the material's temperature increases, so the fatigue life often decreases. A cyclic temperature change encourages failure by thermal fatigue; when the material heats in a non-uniform way, some parts of the structure expand more than others. This non-uniform expansion introduces a stress within the material, and when the structure cools and contracts, stresses of the opposite nature are then imposed. As a consequence of the thermally-induced stresses and strains, fatigue fracture can eventually occur.

Large masses of steel of heavy section will cool more slowly than small components of thin section. If not uniformly heated and quenched to produce a harder material overall, the effect of gradual cooling will introduce stresses between the hard and brittle surface and the softer layers below. These stresses can eventually initiate crack development. Uneven heating and subsequent cooling can also exacerbate crack formation.

2.4.5 Inspection and analysis

MAN's inspection and testing of the upper half of *Finlandia Seaways*' failed A5 connecting rod small end was unable to identify the fatigue crack initiator due to heavy secondary damage of the part. However, MAN's initial hypothesis on the failure, based on the visual inspection of the crack surface and the age of the small end, was that the relative movement between the bearing bush and the small end during the small end's estimated 90,000 running hours exceeded the allowable value. This could have been caused by:

- plastic deformation of the small end (ovality), or
- heavily worn bearing bush, or
- maintenance irregularities during the bearing bush replacement.

TTH's examination assessed that the fatigue crack had started in the region of the oil groove, with a secondary crack within the groove itself, although post-failure damage prevented an accurate identification of the start point.

The later inspection of *Finlandia Seaways*' remaining small ends, and those of *Botnia Seaways*, confirmed that poor overhaul practices, in respect of notch and heat damage, were the most probable cause of the A5 small end failure.

2.5 MAINTENANCE MANAGEMENT

2.5.1 Overview

The routine maintenance and major component overhauls for *Finlandia Seaways*' and *Botnia Seaways*' MAN 12V 48/60 main engines was undertaken in accordance with the schedules contained in the vessels' electronic PMS. Most of the maintenance schedules were based on the accumulated running hours set by MAN. Minor routine maintenance was carried out by ship's crew, but major overhauls were contracted out by DFDS. This included the inspection and, where necessary, replacement of the connecting rod small end piston pin bushes. To facilitate quick maintenance turnaround times, DFDS held a stock of six spare overhauled small ends for use on either vessel.

Finlandia Seaways' main engine maintenance and overhauls had been carried out in accordance with the schedules set out in the PMS, and were recorded electronically by its engineers. However, the post-accident examinations and laboratory tests carried out during this investigation, clearly showed that MAN's guidance and recommended procedures for overhauling the connecting rod small ends had not been followed, and the small ends had been damaged during the piston pin bush removal and fitting process. The extent of the damage was clearly visible to the naked eye but was either not identified during the engine/component overhauls or was ignored.

2.5.2 Connecting rod small end overhaul process

MAN had a detailed set of procedures for the removal and installation of the 48/60 engine connecting rod piston pin bush, and its maintenance manual warned that they should be replaced in a *Service Workshop* because they had to be cooled before being installed. MAN's aftersales service division, PrimeServ, offered around-the-clock support from its global network of service centres, which included two workshops specifically equipped to remove and fit the piston pin bushes.

DFDS's technical management was aware of MAN's requirements and contracted DSG to carry out most of its engine overhauls. DSG was not a MAN-accredited service agent and did not have access to all of MAN's maintenance guides and overhaul procedures. However, DSG's documented piston pin bush removal and installation procedures were similar to MAN's and included the use of a milling machine to cut a groove in the bush during the removal process, as well as liquid nitrogen and use of a special alignment tool during the fitting process. DSG had also designated a competent fitter to undertake the specific task of removing the piston pin bushes at its workshops in Klaipeda. Despite this, seven of the intact 11 small ends removed from *Finlandia Seaways*' engine were found to have notch damage on the internal surfaces of their small end eyes. Three of *Botnia Seaways*' small ends had similar damage and three had evidence of localised heat damage. Although the technical investigations did not identify when the damage had been done, it was clearly apparent that it had been caused by using a disc cutter and a gas torch during the overhauls undertaken by DSG's service engineers.

DSG's failure to follow its own procedures might have been influenced by the fact that its engineers had experience of working on smaller engines where mechanical saws and presses were often used to remove and fit piston pin bushes. It is also possible that some of the overhauls were carried out on board the ships or in local workshops that did not have the specialist tooling required or a supply of liquid nitrogen. Regardless, the extent of the damage caused during the piston pin bush overhauls was visually apparent and, therefore, it was obvious that DSG's service engineers did not appreciate the potential consequences of the stress raisers they had introduced.

2.5.3 Rotation of connecting rod small ends

The two major components that comprised the split shank connecting rod – the big end and small end – each had their own COC identification numbers. As the two parts were not specifically matched to each other, it enabled DFDS to replace the small ends with spares, and therefore reduce the time taken to conduct connecting rod overhauls. Consequently, there was a disparity between engine running hours (110,662 hours at failure) and individual small end running hours, of roughly 20,000 hours, with the A5 small end having accumulated just over 90,000 hours in total. This was further complicated because the six spare small ends had been rotated between *Finlandia Seaways* and *Botnia Seaways*.

The rotation of the small ends could be considered efficient in terms of keeping vessel downtime to a minimum, but it required an operating hours' log for both the connecting rod big end and the small end. Although the onboard records were maintained, the DSG maintenance documents gave the COC numbers for only some of the small ends, having misunderstood which identification number to use. This introduced the possibility for errors to occur.

MAN's customer information notice PCI 344/2015 required the connecting rods to be replaced after 100,000 running hours. MAN viewed the connecting rod as a whole unit, however PCI 344/2015 referred only to the risk of bottom end ovality as the reason for replacement. Although DFDS understood that PCI 344/2015 related to the whole connecting rod, in referring to only the bottom end as the reason for replacement, MAN potentially introduced confusion over whether replacement included the small end. Regardless, DFDS did not replace the connecting rod big ends after they reached 100,000 hours; instead, it measured a selection of big ends for ovality. Finding no ovality, DFDS decided to continue operating the connecting rods. This decision was made without consulting either MAN or LR.

MAN had not considered the possibility of a vessel operator rotating small ends and keeping a supply of spares. It might make sense to occasionally replace a damaged small end with a new or overhauled spare. However, PCI 344/2015 referred to the connecting rod in its entirety, regardless of its separate components, and the manufacturer's instructions should have been followed. Nevertheless, the ability to separate the small end from the shank, which included the big end, introduced the possibility of them being seen as separate components and maintained independently of each other.

2.5.4 Diesel Service Group quality control

DSG was an established ship repair company and was certified and accredited to carry out repairs to ships' auxiliary systems and main propulsion engines by various state authorities and maritime organisations. It had worked on DFDS MAN engines for almost 10 years and had replaced at least 24 piston pin bushes on board *Finlandia Seaways* and *Botnia Seaways*. It had also worked alongside PrimeServ technicians and was in the process of gaining ISO9001-2000 accreditation for its quality management system.

DSG employed one person to oversee the work and produce its technical repair documents. However, documentation giving dates when each small end was overhauled, and by whom, was not available, and identification of every small end from DSG records was unclear as DSG had not always used the small end COC numbers for identification purposes.

The visits to DSG by the MAIB, TAIID and LMSA included requests for documentation to identify when and how small end bush replacement was carried out. DSG was unable to provide this documentation. It was also apparent from the MAIB's and TAIID's visit to DSG that the damage to the small ends was viewed as inconsequential when compared with the mass of metal that made up the small end. As such, no comments or other references to the damage were identified in the available documentation.

DSG's *Certificate of Firm Conformity* for the *construction, conversion, modernization and repair of items of technical supervision products*, issued by RMRS, included an engine power limitation of 8,500kW. This limitation implied that the Russian maritime administration did not consider DSG competent or equipped to undertake work on more powerful engines, such as MAN's 12,600kW 48/60 engine. DSG attributed the power rating discrepancy to an administrative error, but was unable to substantiate this. However, the RINA 'Working Approved Statement', which included the repair of ships' main engines, did not specify a power limit.

Given DSG's experience and the number of the ship repairer's other external accreditations, it is possible that the power rating limit set on its RMRS certificate was an administrative error. However, this should have been noticed and rectified by DSG's quality control manager. Similarly, the poor record keeping identified during the MAIB, TAIID and LMSA visits to DSG's workshops in Klaipeda, and the standards of work its service engineers were allowed to carry out over a prolonged period of time, were strong indicators of significant weaknesses in the company's quality management system.

2.5.5 DFDS quality control

DSG's work on board *Finlandia* and *Botnia Seaways* was overseen by the vessels' engineers and a DFDS technical superintendent. It was unclear what processes the vessels' engineers and the technical superintendent followed when the overhauled small ends were returned to the vessels. There were no written inspection or quality control procedures, and it is unknown if any of the vessels' engineers thoroughly examined the small ends before they were installed in the engine.

It was apparent from MAN's photographs **(Figure 26)** of the seven damaged small ends, that the cut marks at the periphery of the small end eyes were visible to the naked eye even with the bush installed. Consequently, either no pre-installation inspection took place, or there was no concern about the cut marks. The latter was probably the most likely as, when the damage was discussed with DFDS's technical management team, a similar view to DSG was expressed.

Any damage identified to major engine components, no matter how inconsequential it might appear, should be properly assessed, and any actions taken, or decisions made should be recorded in the planned maintenance system. The extent of the damage found to the connecting rods fitted to *Finlandia Seaways* and *Botnia Seaways* was significant and should have been highlighted to MAN and LR.

2.5.6 Classification Society oversight

Finlandia Seaways' main engine connecting rods were class survey items, but LR was unaware of the damage caused to the small ends during overhaul, or the fact that the connecting rod big ends had accumulated more running hours than recommended by the engine manufacturer. *Finlandia Seaways* was being managed on a CSM cycle, and its C/Es were authorised by LR to carry out examinations and report on the condition of selected machinery items. LR would then carry out a confirmatory survey with a review of the records of examination by the C/E and a general examination of items to be credited.

It was apparent from the C/Es' statements of examined machinery items that the replacement of piston pin bushes, or the use of the spare small ends, was not being reported. Furthermore, the small end damage had not been photographed or noted in the vessel's planned maintenance records. Consequently, once the small ends had been installed in the engine, the opportunity for an LR surveyor to identify a safety issue was lost.

During machinery examinations, it is the vessel operator's responsibility to present satisfactory maintenance and monitoring records and valid supporting information, such as original equipment manufacturers' maintenance recommendations and service updates, in order for the class surveyor to complete the survey. Otherwise, as in this case, machinery items could have been credited which, according to the manufacturer, might already exceed the recommended service life.

2.6 EMERGENCY RESPONSE

2.6.1 Overview

The vessel's machinery alarm log **(Table 1)** showed how rapidly events developed before the engine shut down and the fire started. It was apparent that the crew had little opportunity to conduct an emergency shutdown of the engine to prevent further damage.

After the catastrophic engine failure, the subsequent fire, caused by the ejection of hot oil, was intense but short-lived, and fire damage was localised. The fire was limited, in part, by the lack of readily available fuel sources, but also by the prompt actions of the crew, including closing the fire flaps on deck, shutting off the fuel quick-closing valves, stopping the fuel pumps and ultimately the injection of CO_2 into the engine room.

2.6.2 Carbon dioxide bottle identification

It was evident to the vessel's crew, when they entered the CO_2 bottle room, that the fixed fire extinguishing system had been activated and that CO_2 had been released into the engine room. This was because the engine room injection valve was open, the discharge pipe and some bottles had frosted, and the manifold pressure gauge was seen to drop to zero. However, it was unclear how many bottles had been released. This was because the 221 gas bottles in the bottle room had not been clearly marked to show which protected spaces they served.

It was several days after *Finlandia Seaways* arrived at Immingham that a specialist in fire protection systems confirmed that all 31 CO_2 bottles assigned to the engine room had been released. Although DFDS had operated *Finlandia Seaways* for many years, and some of its crew had served on board many times, information to identify the 31 bottles assigned to the engine room was not readily available on board.

It is apparent, both from this case, and from previous fire investigations as identified in MGN 389, that inadequate signage can potentially compound an already serious situation. If it is not possible to identify which, or how many bottles have been released, it leaves the crew in a predicament. On ships where several compartments are protected, each with a specified number of allocated bottles, crew need to be confident that a sufficient amount of gas has been released. MGN 389 states the measures that should be applied when checking the bottles that have been released, including frosting around the base of the bottles. However, in a large multiple bottle bank system it may not be feasible to inspect the base of bottles at the rear of a bank where only the bottle valves are visible. Having comprehensive guidance on board to enable identification of which bottles relate to a specific compartment will assist with checks after releasing CO_2, and reduce the likelihood of potentially fatal inadvertent releases of gas during post-accident activities.

2.6.3 Effective numbers and distribution of EEBDs

There were three EEBDs in *Finlandia Seaways*' engine room machinery spaces: one in the ECR, one in the workshop and one on the bottom plates close to the secondary escape route, meeting the requirements of MSC/Circ.849. As *Finlandia Seaways* was constructed before 1 July 2003, MSC/Circ.1081 was not applied, but, if it had been applicable, it would have required one EEBD to be positioned on each deck or platform level near the escape ladders, constituting the second means of escape. The escape route used by the 3/E to evacuate the engine room was the designated secondary means of escape, but only one EEBD was located at the lowest point of the secondary escape route, below the tween deck.

The 3/E was trapped by the fire at the aft end of the engine room tween deck and had no choice but to use the secondary escape route. Fortunately, he was able to locate the escape route ladder in dense black smoke, and despite falling off the first vertical ladder several times, he was able to climb out of the engine room onto the open deck without an EEBD.

EEBDs are designed to provide a minimum 10-minute air supply to allow personnel trapped by smoke or other toxic atmospheres to escape. To enable their use in an emergency, the number and distribution of EEBDs within a compartment needs to be considered carefully. If the 3/E had been able to don an EEBD during his escape, he would not have experienced the problems or suffered the injuries he did.

It is unfortunate that the unified interpretation in MSC/Circ.1081 was not retrospectively applied to all ships given that installing extra EEBDs would not be an overly onerous requirement for vessel operators. On *Finlandia Seaways*, anyone trapped by smoke on the tween deck and unable to reach the engine workshop would need to climb down to the bottom plates to get an EEBD before using one of the two escape routes. Climbing down to retrieve an EEBD before making an escape is not particularly intuitive in an emergency. It is apparent from this accident that more consideration could be given to the number and location of EEBDs in *Finlandia Seaways*' engine room. As a minimum, an additional EEBD at the secondary escape ladder on the tween deck level would be a sensible addition.

2.6.4 VDR

VDRs provide crucial evidence to aid safety investigations. The VDR on board *Finlandia Seaways* stopped recording as soon as the ship blacked out. This denied investigators information that could have supported various elements of the investigation, including propulsion and communications data.

Initial indications suggested that the UPS battery had failed. Although the VDR system had passed its yearly APT inspection in November 2017, the battery was incapable of providing power 5 months later.

Recognising that older or incorrect batteries may not provide the longevity required, in May 2018 Kelvin Hughes issued a technical advice sheet, reducing the battery replacement period to 3 years from the previously stipulated 4 years. The supply of a battery maintenance kit also became mandatory from 1 January 2019.

SECTION 3 - CONCLUSIONS

3.1 SAFETY ISSUES DIRECTLY CONTRIBUTING TO THE ACCIDENT THAT HAVE BEEN ADDRESSED OR RESULTED IN RECOMMENDATIONS

1. The fire on board *Finlandia Seaways* was the consequence of a sudden major engine component failure, which led to the ejection of heavy engine parts from the crankcase and release of hot oil vapours into the engine room. [2.3.1]

2. The catastrophic failure of *Finlandia Seaways*' main engine was caused by a fracture of the A5 connecting rod small end. The A5 small end was found to have suffered a fatigue fracture. [2.3.2, 2.3.3]

3. The introduction of notches, probably caused during the bush removal process, introduced stress raisers into the small end, increased the likelihood of fatigue crack initiation and therefore fatigue failure. Practical testing has shown that a notch in a loaded component will reduce its lifetime-to-failure. [2.4.2, 2.4.3]

4. MAN's inspection of *Finlandia Seaways*' remaining small ends, and those of *Botnia Seaways*, confirmed that poor overhaul practices were the most probable cause of the A5 small end failure. [2.4.4, 2.4.5]

5. This investigation found that MAN's guidance and recommended procedures for overhauling the connecting rod small ends had not been followed and the small ends had been damaged during the piston pin bush removal and fitting process. [2.5.1]

6. Seven of the eleven intact small ends removed from *Finlandia Seaways*' engine were found to have notch damage on the mating surface with the bush. These were clearly the result of the use of a disc cutter to remove the bushes. Additionally, heat marks identified on *Botnia Seaways*' small ends, and the lack of evidence provided by DSG on the use of liquid nitrogen, indicates that both heating and using a disc cutter on the bush insitu was common practice. [2.5.2]

7. The conrods were not overhauled in accordance with DSG's written procedures, and maintenance was not properly recorded. [2.5.4]

8. There was a lack of appreciation by DSG or DFDS of the potential consequences of the stress raisers introduced during overhaul of the connecting rod small ends, and the damage was viewed as inconsequential when compared with the mass of metal that made up the small end. [2.5.4, 2.5.5]

9. *Finlandia Seaways*' main engine connecting rods were class survey items, but LR was not informed of the damage caused to the small ends during overhaul, or that connecting rods had accumulated more running hours than recommended by the engine manufacturer. [2.5.6]

3.2 SAFETY ISSUES NOT DIRECTLY CONTRIBUTING TO THE ACCIDENT THAT HAVE BEEN ADDRESSED OR RESULTED IN RECOMMENDATIONS

1. Localised heating was found on several small ends from *Botnia Seaways*. If not uniformly heated, the large mass of steel of the small end could introduce stresses, which could eventually initiate crack development. [2.4.4, 2.5.2]

2. On receipt of the customer information notice PCI 344/2015, DFDS decided to continue operating the connecting rods without consulting either MAN or LR. Had a discussion taken place, it might have led to the replacement of the entire connecting rods, identified the differential in operating hours of the small ends and the fact that small ends were being rotated between the two vessels. [2.5.3]

3. Regarding the overhaul of small ends, DFDS had no written inspection or quality control procedures, but given the notch marks on the small ends were visible to the naked eye, it is evident any examination by the vessel's engineers was insufficiently thorough. [2.5.5]

4. It is apparent from the C/E's statements of examined machinery items that small end bearing bush renewal, or the replacement of the small end with a spare, was not being reported to LR. [2.5.6]

5. This case and previous fire investigations, as identified in MGN 389, have highlighted that having comprehensive on board guidance, to enable identification of which CO_2 bottles relate to a specific compartment, will assist with checks after releasing CO_2. [2.6.2]

6. The 3/E was very fortunate to have survived the fire given the lack of an EEBD placed along the secondary means of escape. If he had been able to don an EEBD, he would not have suffered the stress and injury that resulted from his escape from the engine room. [2.6.3]

7. It is unfortunate that the unified interpretation in MSC/Circ.1081 was not retrospectively applied to all ships given that installing a few extra EEBDs would not be an overly onerous requirement for vessel operators and it would improve the opportunity to successfully escape from machinery spaces in an emergency. [2.6.3]

8. The VDR UPS battery failure denied data that could have supported various elements of the investigation, including propulsion data and communications. [2.6.4]

3.3 OTHER SAFETY ISSUES NOT DIRECTLY CONTRIBUTING TO THE ACCIDENT[16]

1. The customer information notice PCI 344/2015, in referring to only the bottom end as the reason to replace the connecting rod and the ability to separate the 48/60 engine connecting rod shank from the small end, potentially introduced confusion over whether maintenance of each component could be carried out separately. [2.5.3]

[16] These safety issues identify lessons to be learned. They do not merit a safety recommendation based on this investigation alone. However, they may be used for analysing trends in marine accidents or in support of a future safety recommendation.

SECTION 4 - ACTION TAKEN

4.1 MAIB ACTIONS

The MAIB and **Lithuanian Transport Accident and Incident Investigation Division** have:

Issued a combined recommendation[17] on 27 July 2018 to MAN Energy Solutions and to Lloyd's Register to:

- Provide technical advice to DFDS on the actions the company should take to minimise the risk of a similar catastrophic engine failure on board *Botnia Seaways*, and any other vessel operators whose MAN engines might have been subjected to similar maintenance practices.

4.2 ACTIONS TAKEN BY OTHER ORGANISATIONS

DFDS Seaways AB-Lithuania has:

- Inspected and renewed all 12 connecting rods on board *Botnia Seaways*.
- Carried out main engine overhauls on board five of the company's vessels with reference to the MAIB/TAIID recommendation and manufacturers' service letters.
- Increased the number of staff in their preventative maintenance system support team.
- Issued a fleet safety bulletin that instructs crews on board their vessels:
  - to be familiar with CO_2 systems, that they have clear operating instructions and the number of cylinders for each compartment is understood;
  - to assess safe means of escape from the engine room and the location and number of EEBDs with respect to MSC/Circ.1081.
- Reviewed its database of contractors to ensure that those who carry out main engine repair and maintenance work on board its vessels are suitably qualified.
- Continued to review its company PMS on board vessels it operates to ensure that vessel equipment manufacturers' maintenance, repair and replacement guidance is followed.
- Complied with the Kelvin Hughes technical advice sheet regarding VDR battery replacement.

MAN Energy Solutions has:

- Investigated the cause of the A5 small end failure on board *Finlandia Seaways*.
- Analysed the remaining 11 small ends retrieved from *Finlandia Seaways*' main engine.

[17] Recommendation 2018/121

- Examined the small ends retrieved from *Botnia Seaways*' main engine.

- Liaised with LR to provide appropriate guidance to DFDS in respect of the MAIB/TAIID recommendation.

Diesel Service Group has:

- Provided assurances that only *Finlandia Seaways* and *Botnia Seaways*, using the MAN 12V 48/60 main engine, were at risk of small end damage during bearing overhaul.

Lloyd's Register has:

- Liaised with MAN Energy Solutions to provide appropriate guidance to DFDS in respect of the MAIB/TAIID recommendation.

- Attended *Botnia Seaways* to inspect the small ends bearings removed from the main engine.

- Assessed whether other vessels, classed by LR and maintained by DSG, were at risk.

- Updated "The Examination of Surveyable Machinery Items by Chief Engineers" to include:

    - the scope of service overhauls specified by the original equipment manufacturer;

    - that the chief engineer's maintenance and monitoring records should be made available;

    - if the surveyor is not satisfied with the chief engineer's statement, records or operating condition, they may request items be opened for inspection.

- Updated its instructions to surveyors relating to CSM surveys.

Lloyd's Register (Klaipeda) has:

- Undertaken to discuss the issue with technical superintendents of shipowners, operators and managers and/or ships' C/Es when diesel engines repair/maintenance works are undertaken by contractors, with respect to engine manufacturers' recommendations.

Kelvin Hughes has:

- On 14 May 2018, issued a VDR technical advice sheet for the supply of a battery maintenance kit to address regulatory requirement changes where old or incorrect type batteries had been used that failed to perform in the event of an incident. It advised that, on installation, the battery should be given a 3-year expiry date. The policy became mandatory from 1 January 2019.

SECTION 5 - RECOMMENDATIONS

DFDS Seaways AB-Lithuania is recommended to:

2021/102 Review and improve how its chief engineers conduct class-related equipment examinations as part of the Continuous Survey Machinery cycle to ensure that examinations are conducted thoroughly and reported accurately.

Diesel Service Group (Klaipeda) is recommended to:

2021/103 Fully apply equipment manufacturers' maintenance and repair guidance and procedures.

2021/104 Review and, as necessary, amend its record keeping in order to generate a full and auditable record of the maintenance carried out by its staff.

2021/105 Review and update staff training to ensure familiarity with engineering methods appropriate for the various repair and overhaul tasks, backed up with a suitable quality assurance process to ensure standards are maintained.

Safety recommendations shall in no case create a presumption of blame or liability

Marine Accident Report

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