ACCIDENT REPORT

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

Report on the investigation of the accidental discharge of a FirePro condensed aerosol fire-extinguishing system during its installation on board the fishing vessel ***Resurgam*** **(PZ1001)** resulting in one fatality in Newlyn Harbour, Cornwall, England on 15 November 2019

VERY SERIOUS MARINE CASUALTY REPORT NO 9/2023 DECEMBER 2023

The United Kingdom Merchant Shipping

(Accident Reporting and Investigation)

Regulations 2012 – Regulation 5:

"The sole objective of a safety investigation into an accident under these Regulations shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

NOTE

This report is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall be inadmissible in any judicial proceedings whose purpose, or one of whose purposes is to attribute or apportion liability or blame.

All MAIB publications can be found on our website: www.gov.uk/maib

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CONTENTS

FIGURES

TABLES

ANNEXES

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

°C	-	degrees Celsius
ABS	-	American Bureau of Shipping
ACOP	-	Approved Code of Practice
BAFE	-	British Approvals for Fire Equipment
cm	-	centimetres
CO	-	carbon monoxide
CO_2	-	carbon dioxide
DIP switch	-	dual in-line package switch
EPA	-	United States Environmental Protection Agency
FirePro UK	-	FirePro UK Limited
FirePro user manual	-	*Information, Instruction & User Manual Version 6, 24-06-16 Fire Extinguishing Aerosol Systems*
Firewatch	-	Firewatch South West Ltd
g	-	gram
HSE	-	Health and Safety Executive
HSW Act	-	Health and Safety at Work etc. Act 1974
IMO	-	International Maritime Organization
ISO	-	International Organization for Standardization
KEMA	-	Keuring van Elektrotechnische Materialen te Arnhem
kg	-	kilogram
LED	-	light-emitting diode
LPCB	-	Loss Prevention Certification Board
g/m^3	-	gram per cubic metre
GT	-	gross tonnage
m	-	metre
m^3	-	cubic metre
MCA	-	Maritime and Coastguard Agency
mg/m^3	-	milligrams per cubic metre
MGN	-	Marine Guidance Notice
MSDS	-	material safety data sheet
MSIS	-	Marine Survey Instructions for the Guidance of Surveyors

MSN	-	Merchant Shipping Notice
Ocean Engineering	-	Ocean Engineering (Fire) Limited
ppm	-	parts per million
PSU	-	power supply unit
SNAP	-	Significant New Alternatives Policy
SOLAS	-	International Convention for the Safety of Life at Sea, 1974, as amended
STEL	-	short-term exposure limit
Stevenson	-	W. Stevenson & Sons Limited
The Code	-	Merchant Shipping Notice 1872 Amendment 1 (F) *The Code of Safe Working Practice for the Construction and Use of Fishing Vessels of 15m Length Overall to less than 24m Registered Length*.
TLV	-	threshold limit values
UPS	-	uninterruptible power supply
USCG	-	United States Coast Guard
UTC	-	universal time coordinated
V	-	volt

TIMES: All times referred to in this report are UTC unless otherwise stated.

Image courtesy of Richard Kiessler (MarineTraffic.com)

*Resurgam (*PZ1001)

SYNOPSIS

On 15 November 2019, a FirePro condensed aerosol fixed fire-extinguishing system, which was undergoing installation, inadvertently activated in the engine room of the UK registered fishing vessel *Resurgam*, in Newlyn, Cornwall, England. Four shore workers were in the space but only three managed to escape. One of the four, an apprentice engineer, collapsed at the bottom of the engine room access ladder. He was recovered onto the open deck about 20 minutes later by the emergency services but could not be resuscitated. The postmortem report determined that he died from an inhalation injury and carbon monoxide poisoning.

Although the investigation of the accident fell under the remit of the Health and Safety Executive, the MAIB also conducted an independent marine safety investigation to ensure the lessons from this accident were brought to the attention of the marine industry.

Resurgam was undergoing maintenance and two Ocean Engineering (Fire) Limited technicians were on board installing the FirePro system. Also on board were a shore-based maintenance engineer and an apprentice engineer from W. Stevenson & Sons Limited, *Resurgam*'s owner and operator, who were repairing the main engine exhaust. In the final stages of the installation the aerosol generators were connected to a live electrical circuit, triggering the discharge process and rapidly filling the engine room with a dense cloud of fire-extinguishing aerosol particles.

The apprentice engineer collapsed and died while trying to escape the space because he inhaled large quantities of hot aerosol particles and combustion gases, including high levels of carbon monoxide. The aerosol generators had been mounted close to areas that people could occupy and one was sited close to the only escape route from the engine room, contrary to the manufacturer's guidance requirements. Post-accident testing provided evidence that, although the FirePro condensed aerosol system may be effective at fire-extinguishing, the risks associated with inhaling the aerosol particles and the carbon monoxide hazard were not appropriately featured in the manufacturer's safety-related documentation.

This investigation identified that the flag state requirement to approve the system before installation was not met. Additionally, and in contrast to land-based systems, there was no consistent and accredited training scheme for marine installers of this safety critical fire-extinguishing system.

FirePro has been recommended to undertake a specific risk assessment for the installation and operation of each of its fire-extinguishing systems; and, to review its safety-related documentation and incorporate all of the system's hazards, specifically carbon monoxide production. The Maritime and Coastguard Agency has been recommended to take steps to improve fire-extinguishing system installation standards. *Resurgam*'s owner has been recommended to revise its safety management system to ensure that personnel safety measures are in place.

SECTION 1 – FACTUAL INFORMATION

1.1 PARTICULARS OF *RESURGAM* AND THE ACCIDENT

VESSEL PARTICULARS	
Vessel's name	*Resurgam*
Flag	UK
Classification society	Not applicable
IMO number/Fishing numbers	8883551 / PZ1001
Type	Beam trawler
Registered owner	W. Stevenson & Sons Limited
Manager(s)	W. Stevenson & Sons Limited
Construction	Steel
Year of build	1969
Length overall	26.22m
Registered length	23.22m
Gross tonnage	134.0
Minimum safe manning	Not applicable
Authorised cargo	Not applicable

VOYAGE PARTICULARS	
Port of departure	Newlyn
Port of arrival	Not applicable
Type of voyage	Alongside
Cargo information	Not applicable
Manning	Not applicable

MARINE CASUALTY INFORMATION	
Date and time	15 November 2019 at 1540
Type of marine casualty or incident	Very Serious Marine Casualty
Location of incident	Newlyn Harbour, North Pier
Place on board	Engine room
Injuries/fatalities	1 fatality
Damage/environmental impact	None
Ship operation	Alongside, maintenance
Voyage segment	Alongside
External/internal environment	Moderate breeze and fine weather
Persons on board	4

1.2 BACKGROUND

The UK registered fishing vessel *Resurgam* was berthed alongside in Newlyn harbour for maintenance work at the time of the accident. The work was being carried out by shore workers and was not under the control of the fishing vessel's skipper or its crew. The main work to be completed in the vessel's engine room was a repair to the main engine exhaust and the installation of a FirePro condensed aerosol fixed fire-extinguishing system.

Resurgam's owners, W. Stevenson & Sons Limited (Stevenson) operated a fleet of fishing vessels and employed a team of shore-based mechanical and electrical engineers to help maintain them. The engine exhaust repair was to be carried out by shore-based Stevenson engineers, while the installation of the fixed fire-extinguishing system had been contracted to Firewatch South West Ltd (Firewatch), which then subcontracted to Ocean Engineering (Fire) Limited (Ocean Engineering).

As the work on board *Resurgam* was being undertaken by shore workers and was not under the control of the vessel's skipper or crew, the health and safety of those involved was subject to shoreside regulations, namely the *Health and Safety at Work etc. Act 1974*. In accordance with a memorandum of understanding[1] and an operational working agreement[2] between the Health and Safety Executive (HSE), the Maritime and Coastguard Agency (MCA) and the Marine Accident Investigation Branch (MAIB), the investigation of this accident fell under the remit of HSE. However, based on the initial findings of MAIB's preliminary assessment of the accident, the Chief Inspector of Marine Accidents assessed that there were significant safety lessons for the maritime industry and opened an independent marine safety investigation.

1.3 NARRATIVE

On the morning of 14 November 2019, *Resurgam* arrived in Newlyn and berthed at the fish quay to land its catch. When all the catch had been landed, *Resurgam* was moved from the fish quay to a maintenance berth on the harbour's North Pier **(Figure 1)**.

Once alongside North Pier, *Resurgam*'s engines and generators were shut down and electrical power for lighting and other systems was supplied via a shore connection. At about 0930, two Ocean Engineering installation technicians, a lead technician and a trainee, boarded *Resurgam* and spoke briefly to its skipper. The lead technician then carried out an initial inspection of the wheelhouse and engine room.

Following his inspection, the lead technician briefly discussed the installation process and the proposed positioning of the system's four aerosol generators with Stevenson's engineering project manager. Arrangements were then made for a Stevenson welder to secure the aerosol generator mounting brackets to the engine room bulkhead and deckhead structures.

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[1] Memorandum of Understanding between the Health and Safety Executive, The Maritime and Coastguard Agency and the Marine Accident Investigation Branch for health and safety enforcement and accident investigation at the water margin and offshore, dated May 2021.

[2] Operational Working Agreement between the Health and Safety Executive, The Maritime and Coastguard Agency and the Marine Accident Investigation Branch, dated 22 September 2021.

Figure 1: *Resurgam* berthed on the North Pier, Newlyn

During the afternoon, the Ocean Engineering technicians fitted the system's fire protection control panel **(Figure 2)** and power supply unit (PSU) in the wheelhouse. They also ran some cables between the wheelhouse and the engine room space. The technicians did not have sufficient cabling to complete the job and left the vessel at about 1500.

At about 0900 on 15 November, the Ocean Engineering technicians arrived back on site and boarded *Resurgam*. The lead technician entered the engine room and identified that two of the aerosol generator brackets needed to be moved and arranged for a welder to reposition them.

During the morning and into the afternoon the technicians completed the electrical cabling work, fitted coupling plugs and sockets to the aerosol generators and their electrical cables, and mounted the aerosol generators in their brackets **(Figure 3)**. The technicians did not have the test lamps and connectors to conduct a simulated operation test of the installation. During the same period, a Stevenson mechanical engineer and an apprentice engineer, Conor Moseley, were working together on the main engine exhaust system in the engine room.

Once the installation had been completed, and with the aerosol generators unplugged, a Stevenson electrical engineer, at the request of Ocean Engineering's lead technician, connected the vessel's 24V power supply to the FirePro system's PSU. At about 1530, the lead technician powered up the PSU and checked the control panel display. The control panel fault alarm activated. The trainee technician entered the engine room and told the Stevenson engineers that they were about to test the extinguishing system's pre-activation alarm. The lead technician then opened the control panel's protective cover, which released a microswitch and initiated the pre-activation alarm. The trainee technician went into the engine room space and confirmed that the alarm warning beacons were flashing and sounding. The lead technician then closed the control panel cover to stop the alarm and then returned to the engine room.

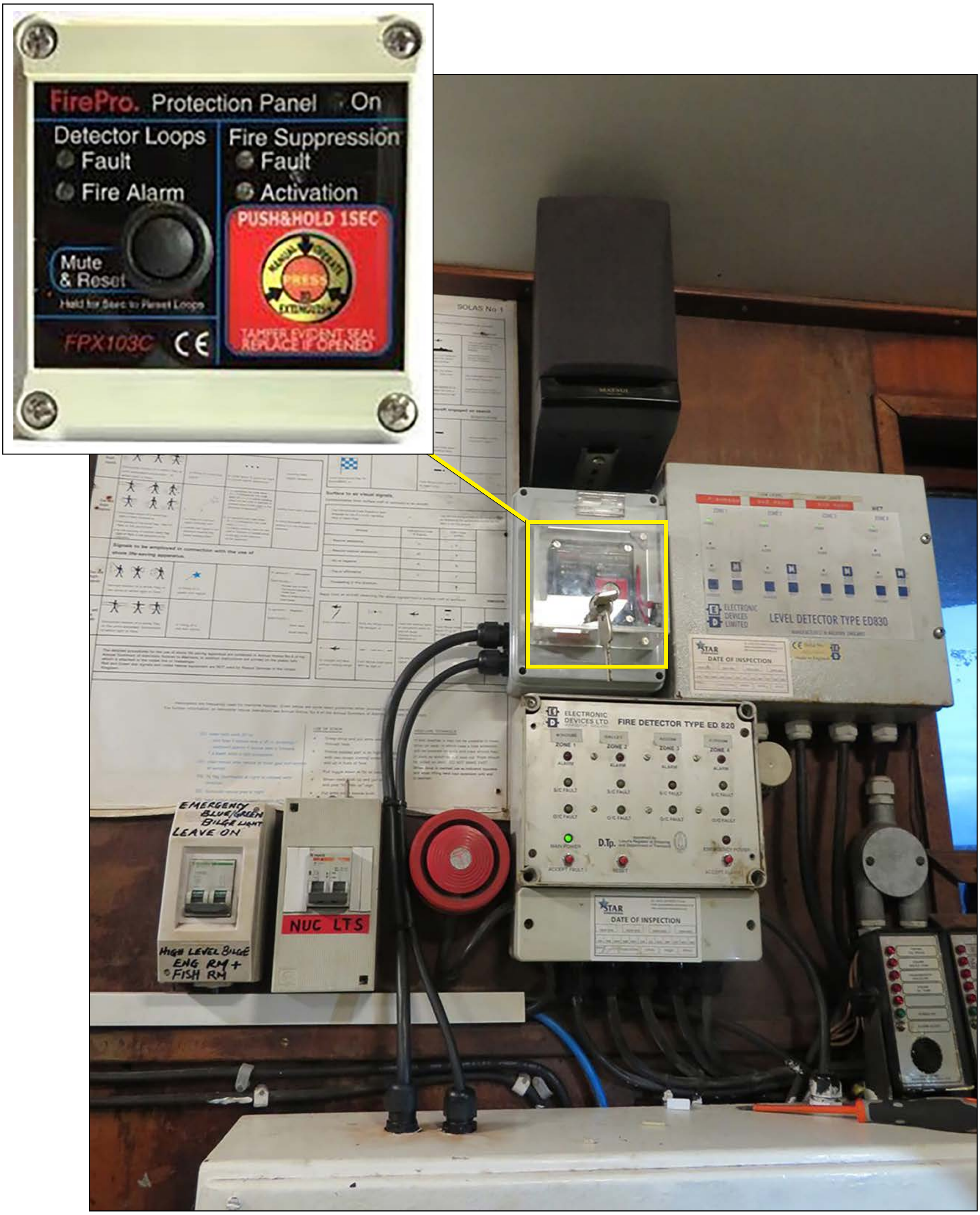

Figure 2: Fire protection control panel mounted in the wheelhouse

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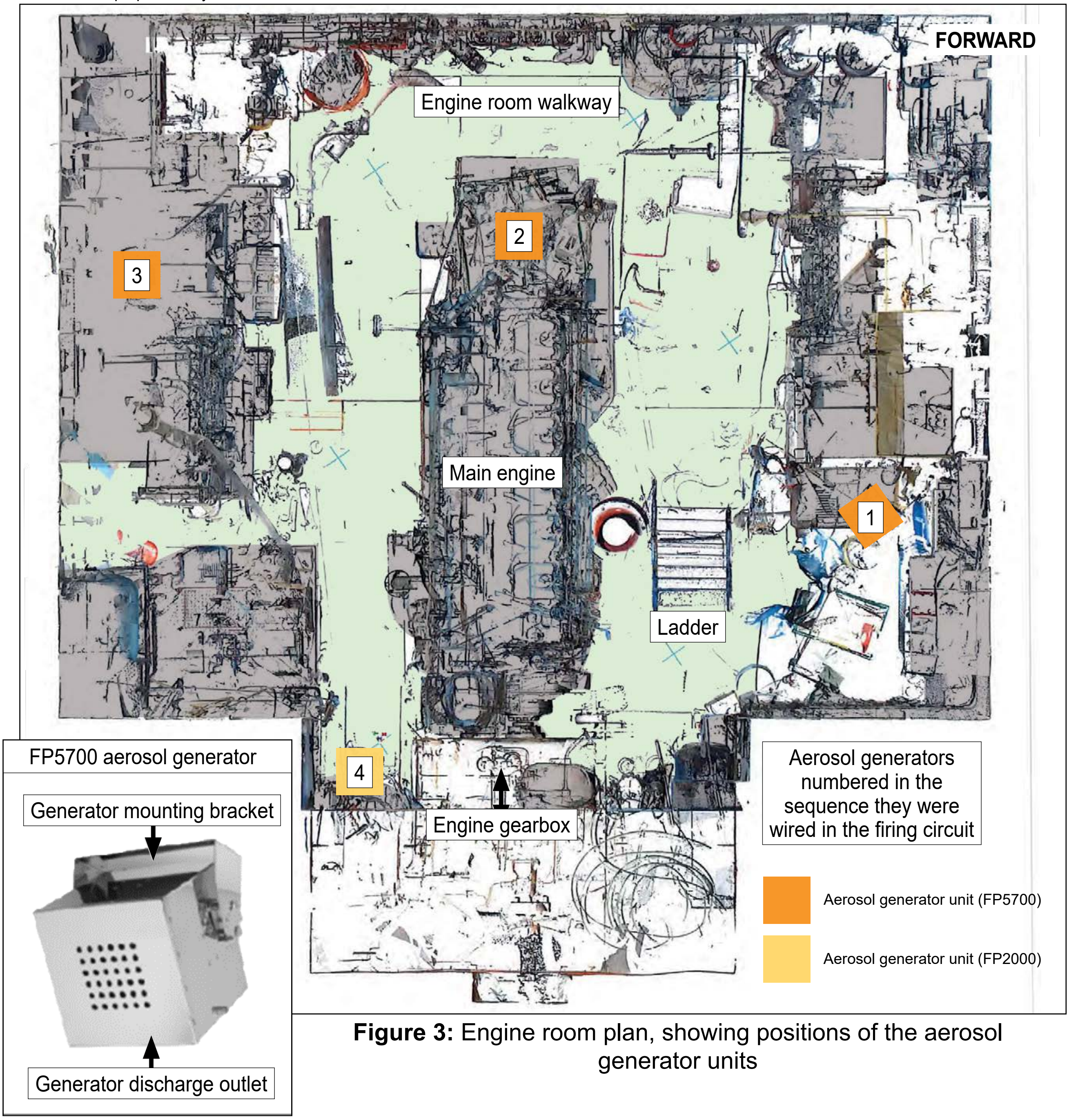

Figure 3: Engine room plan, showing positions of the aerosol generator units

At about 1535, the Ocean Engineering technicians began to plug the aerosol generators into the sockets fitted to the fire-extinguishing system's activation or firing cables. Both Stevenson engineers were working on the port side of the main engine, fitting new exhaust bellows.

While the trainee technician plugged in the aerosol generator adjacent to the access ladder (generator 1[3]), the lead technician sequentially connected the two forward units (generators 2 and 3) and then squeezed past the Stevenson engineers to get to the last generator (generator 4). By this time, the trainee technician had connected generator 1 and was making his way back to the wheelhouse **(Figure 4)**. At 1540, the lead technician plugged in generator 4 and almost immediately heard a loud hissing sound behind him. Realising that the system had activated, he unplugged the generator, jumped over the main engine gearbox and ran to the access ladder, shouting "*Get out*".

[3] The generator numbering convention is based on the order that the generators were reportedly connected in the period before the accident and has been adopted in this report for ease of reference.

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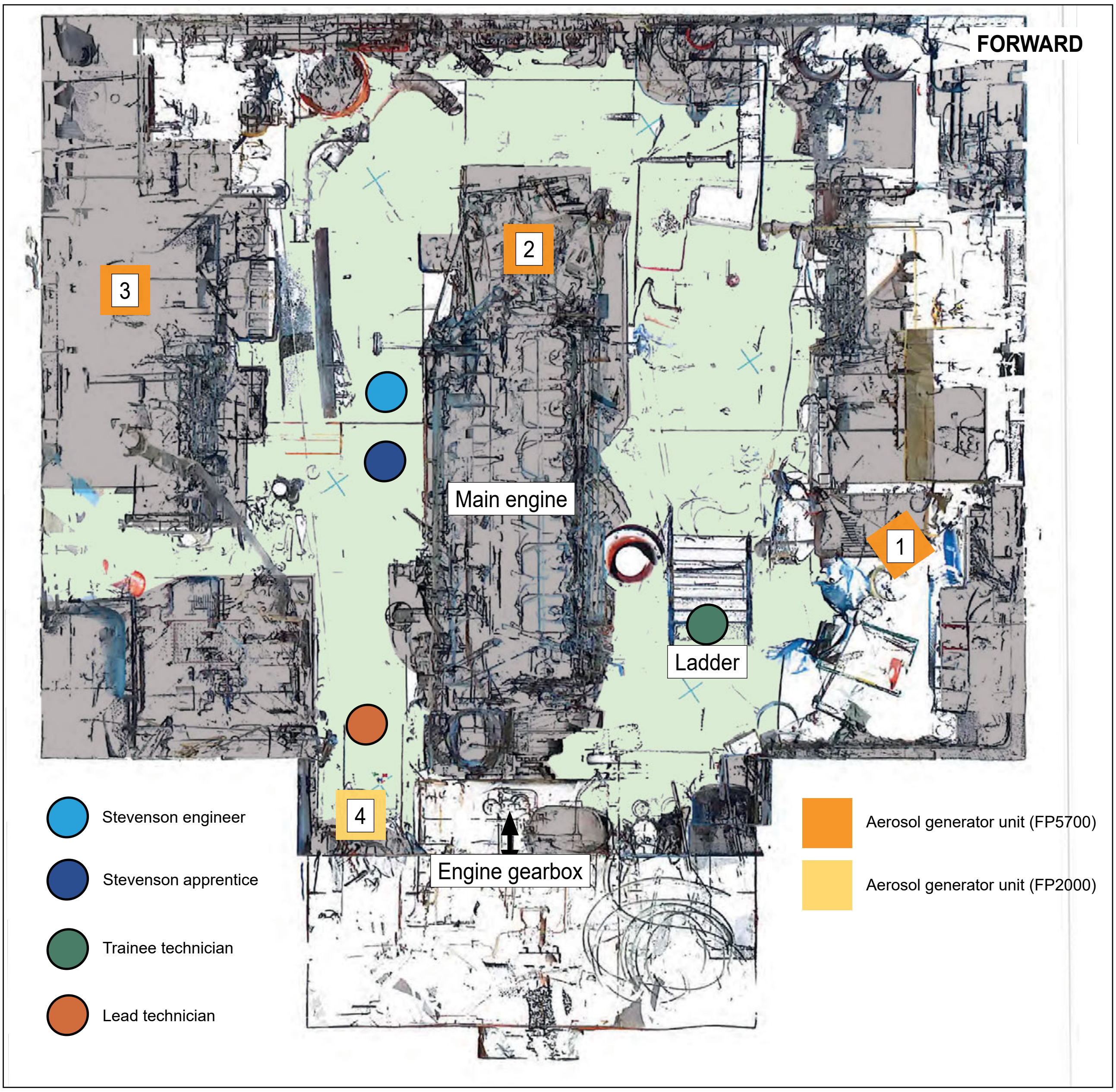

Figure 4: Positions of installation technicians and Stevenson engineers when the fourth aerosol generator was plugged in

The lead technician climbed the ladder as the space filled up with dense white condensed aerosol and followed the trainee technician, who was already at the top of the ladder, out on to the open deck. The Stevenson engineer grabbed the apprentice and guided him towards the access ladder. When they reached the ladder visibility in the engine room was zero and both were struggling to breathe. The engineer tried to help the apprentice onto and up the ladder. Thinking that he was following the apprentice, the engineer scrambled up the ladder and out of the engine room. When he emerged from the engine room on to the open deck he was on his hands and knees, coughing and spluttering, but quickly realised that the apprentice had not escaped.

Two Stevenson engineers and the engineering project manager on board a nearby vessel saw a dense cloud of aerosol particles coming from *Resurgam* **(Figure 5).** Initially thinking that a fire had broken out, they ran to the scene. When they arrived and realised what had happened, they asked the Ocean Engineering technicians if the aerosol was hazardous. The lead technician said he understood it was safe to breathe.

Figure 5: Cloud of aerosol particles seen coming from *Resurgam*'s engine room

One of the Stevenson engineers entered *Resurgam*'s engine room to search for the missing apprentice. Visibility was poor but, when the engineer reached the bottom of the engine room access ladder, he found the apprentice lying motionless on the floor plates behind it. He tried to lift the apprentice but soon began to suffer breathing difficulties and had to leave the space and return to fresh air. Once he had regained his breath, the engineer re-entered the engine room with a rope, which he placed around the apprentice's torso, but again he was overwhelmed by the atmosphere and had to return to the open deck.

Among the safety equipment carried on board *Resurgam* was a compressed air breathing apparatus set. This was found and an attempt was made to use it. However, the set was soon discarded on the deck as no one had any knowledge of how to operate it.

At 1550, having been alerted by a phone call, Stevenson's engineering and health and safety managers arrived on scene and told another employee, who was standing on the quayside, to dial 999 and request the help of the emergency services. The health and safety manager then boarded the vessel and attempted to enter the engine room to rescue the apprentice but, like the previous engineer, was unable to breathe properly and had to evacuate the space.

At 1555, two of the Stevenson engineers disembarked *Resurgam* and collected an electric fan, some ventilation trunking and an air filtered welding mask from the workshop. A further attempt was made to enter the space with the welding mask on, which again had to be aborted due to breathing difficulties. At approximately 1605, the fire and rescue service and ambulance service arrived as the fan and trunking were being set up and ordered everyone on board to evacuate to the quayside. Immediately afterwards, and wearing breathing apparatus, fire and rescue service officers recovered the apprentice to the open deck. The apprentice was unconscious and not breathing, and despite the attempts of ambulance paramedics he could not be resuscitated.

1.4 THE APPRENTICE ENGINEER

Conor Moseley was 20 years old. He joined Stevenson as a shore-based apprentice engineer and attended the local technical college as part of his apprenticeship.

1.5 CAUSE OF DEATH

The postmortem report identified that the apprentice's lungs were:

> *heavy with blotchy discolouration with intense congestion associated with haemorrhaging of the small air sacs within the lungs.*

Blood toxicology analysis established a carboxyhaemoglobin level of 31.7% consistent with exposure to high levels of carbon monoxide (CO). The pathologist's report concluded that, although the carboxyhaemoglobin level was high, it was not at a fatal concentration for an otherwise healthy individual.

A laceration and deep bruising at the back of the apprentice's head was consistent with an injury following a fall or collapse. Further neuropathological examination revealed no evidence of significant brain injury associated with the head injury.

The cause of death was recorded as:

> *Inhalation injury and carbon monoxide poisoning sustained following discharge of an aerosol based fire extinguishing system in a confined space.* [sic]

The pathologist concluded that:

> *Mr Moseley clearly died as a result of the effects of exposure to the aerosolised fire extinguisher. This was likely a combination of reduced respirable oxygen in the engine room, and inhalation of potentially hot gases and combustion products/chemicals resulting in carbon monoxide poisoning and direct injury to the respiratory tract.*

1.6 *RESURGAM*

Resurgam was a steel hulled beam trawler. It was built in 1969 in the Netherlands and purchased by Stevenson in 1987. Stevenson transferred *Resurgam* onto the UK fishing vessel registry; its overall and registered lengths were 26.22m and 23.22m, respectively.

The vessel's engine room was accessed only via a ladder from a lobby area at main deck level **(Figure 6)**. The lobby area also provided access to the vessel's winch room and could be accessed from both the main deck, via a small watertight door, and accommodation space.

Due to its registered length, *Resurgam* was required to comply with the Maritime and Coastguard Agency's (MCA) Merchant Shipping Notice (MSN) 1872 Amendment 1 (F) *The Code of Safe Working Practice for the Construction and Use of Fishing Vessels of 15m Length Overall to less than 24m Registered Length* (The

Code). The Code became mandatory on 31 December 2018 and required main machinery spaces to be fitted with a fixed fire-extinguishing system and have two means of escape. These requirements were first introduced in 2002.

Resurgam did not have a main machinery space fixed fire-extinguishing system or two means of escape from the engine room. As *Resurgam* was registered as a UK fishing vessel in 1987, the MCA had granted it several regulatory exemptions[4]. These exemptions included approvals to operate the vessel without a main machinery space fixed fire-extinguishing system and a second means of escape from the engine room. Following a review of *Resurgam*'s exemptions in 2019, the MCA informed Stevenson that it could no longer support the fire-extinguishing system exemption and told the company that one had to be installed.

At the end of July 2019, MCA surveyors inspected *Resurgam* in preparation for its 5-yearly UK fishing vessel certificate renewal. This resulted in the identification of several deficiencies, including the absence of an engine room fixed fire-extinguishing system. On 13 August 2019, the MCA issued a short-term UK fishing vessel certificate, which was valid until 1 November 2019 and only intended to allow sufficient time to rectify the deficiencies before the issue of a full UK fishing vessel certificate. This short-term certificate was later extended for a further month and was valid until 5 December 2019.

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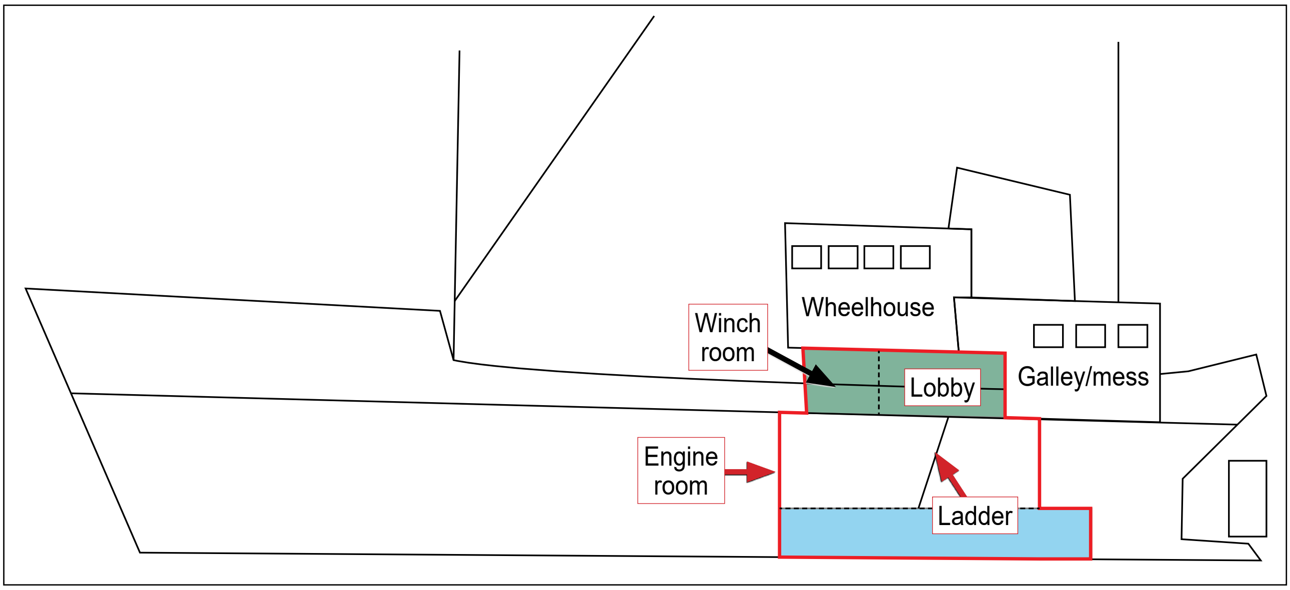

Figure 6: Schematic of engine room space, winch room and lobby area

1.7 W. STEVENSON & SONS LIMITED

Stevenson was a family-run business based in Newlyn, Cornwall. It owned and operated a fleet of 12 beam trawlers.

To maintain its fishing fleet, Stevenson operated a support workshop in Newlyn harbour that employed eight mechanical and electrical engineering staff. The support workshop was supervised by an engineering manager and an engineering project manager.

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[4] Often referred to as 'grandfather rights' because the vessel had not been built to current regulations.

Stevenson employed external contractors to carry out specialist or complex maintenance tasks and vessel modifications that were beyond the normal capability of its workshop team. The contract for the installation of *Resurgam*'s fixed fire-extinguishing system was awarded to Firewatch, which subcontracted the work to Ocean Engineering.

Firewatch had arranged for Ocean Engineering to assess the fitting of a fire suppression system to *Resurgam* and provide an estimated cost for the job. On 1 November 2019, Ocean Engineering carried out its onboard assessment and proposed the installation of the FirePro system. On 4 November 2019, Firewatch submitted a quote based on the fitting of four aerosol generators that Stevenson accepted. Stevenson's engineering project manager was the nominated point of contact for the Ocean Engineering installation technicians.

On Saturday 9 November 2019, Stevenson sent an email to the MCA informing it of the plan to fit a FirePro condensed aerosol system and advising that the installation would be undertaken by Ocean Engineering. In response, the MCA extended the short-term fishing vessel certificate by one month to 5 December 2019, which allowed time for the fire-fighting system to be fitted. The MCA had no further involvement in the installation and Stevenson did not query this.

1.8 OCEAN ENGINEERING (FIRE) LIMITED

Based in Penryn, Cornwall, Ocean Engineering was founded in 2004 and specialised in marine fire safety equipment installation and servicing. It had other branches across the south coast of England and in Scotland but most of its commercial activity focused on the south-west region of the UK. Ocean Engineering was listed on the FirePro UK Limited (FirePro UK) website as one of the latter's authorised distributors for the installation and servicing of FirePro systems. It serviced other types of condensed or powdered aerosol systems and was approved to install Fireaway Inc.'s Stat-X system.

The company had two directors, one responsible for operations and the other for commerce; each director held a 50% shareholding. The operations director's responsibilities included training installation engineers; he also designed proposed installation solutions and prepared plans and documentation for customers. The operations director was supported by a technical support manager and the service manager.

Ocean Engineering had been assessed by Det Norske Veritas and Lloyd's Register Quality Assurance as compliant with ISO 9001:2015, which was the International Organization for Standardization (ISO) standard for quality management systems.

1.9 FIREPRO

Trading under the name FirePro[5], the Cyprus-based company Celanova Limited designed, manufactured and distributed condensed aerosol fire-extinguishing systems. FirePro's marketing literature described the system as an environmentally friendly and safe alternative to halon-based systems, which were phased out due to their impact on the ozone layer. FirePro had a global network of distributors and operated in over 100 countries.

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[5] In Italy, Celanova Limited traded under the brand names Aerpro and FireBan.

1.10 FIREPRO UK LIMITED

FirePro UK was the sole importer and distributer of the FirePro systems in the UK. It was based in Surrey, England and had a network of authorised distributors and installers across the UK and Ireland. It required its distributors and installers to be third party accredited fire systems specialists. The recognised accreditation standard for land-based installations was either the British Approvals for Fire Equipment (BAFE) standard, *SP2303-03 – Fixed Gaseous Fire Extinguishing Systems*, or the Building Research Establishment Group, Loss Prevention Certification Board (LPCB), Loss Prevention Standard *LPS 1014.*

Both the BAFE and LPCB schemes required trainee installers to follow an accredited company training programme for fire-extinguishing system installation, including condensed aerosols. Once BAFE and LPCB accredited installers had completed the training, they were examined to assure satisfactory competence levels.

Equivalent accreditation for marine fire-extinguishing systems did not exist and Ocean Engineering was not accredited to either the BAFE or LPCB standard.

Ocean Engineering went into liquidation in 2022[6]

1.11 FIREPRO CONDENSED AEROSOL SYSTEM

1.11.1 Overview

In 1995, a group of Russian scientists developed a solid compound that, when ignited, produced an aerosol that was effective at extinguishing fires. In 1997, the FirePro condensed aerosol generator, which contained such a solid compound, was patented by Celanova Limited.

The key components of the FirePro system installed on board *Resurgam* were the aerosol generators, a control panel with protective cover and pre-activation microswitch, alarm warning beacons for the protected space, a PSU, junction box and electrical distribution cables.

1.11.2 Condensed aerosol generators

The solid compound within the FirePro aerosol generator consisted of potassium nitrate, potassium carbonate, magnesium, and an epoxy resin polymer. The potassium-based particulates generated when the solid compound was ignited disrupted the chemical chain reaction of combustion on contact with a flame to supress and extinguish a fire **(Figure 7)**.

The aerosol generators were fired by a pulse of electric current delivered following the activation of the fire protection control panel. The current heated a coil, which ignited the solid compound and initiated an exothermic chemical reaction that generated hot particles and gases. The particles and gases then passed over cooling material (alumina), which cooled the gases, before being expelled from the generator into the protected compartment **(Figure 8)**. The generators' discharge took 10 to 20 seconds.

6 As a result of the liquidation no MAIB recommendations were made

Image courtesy of FirePro (www.firepro.com)

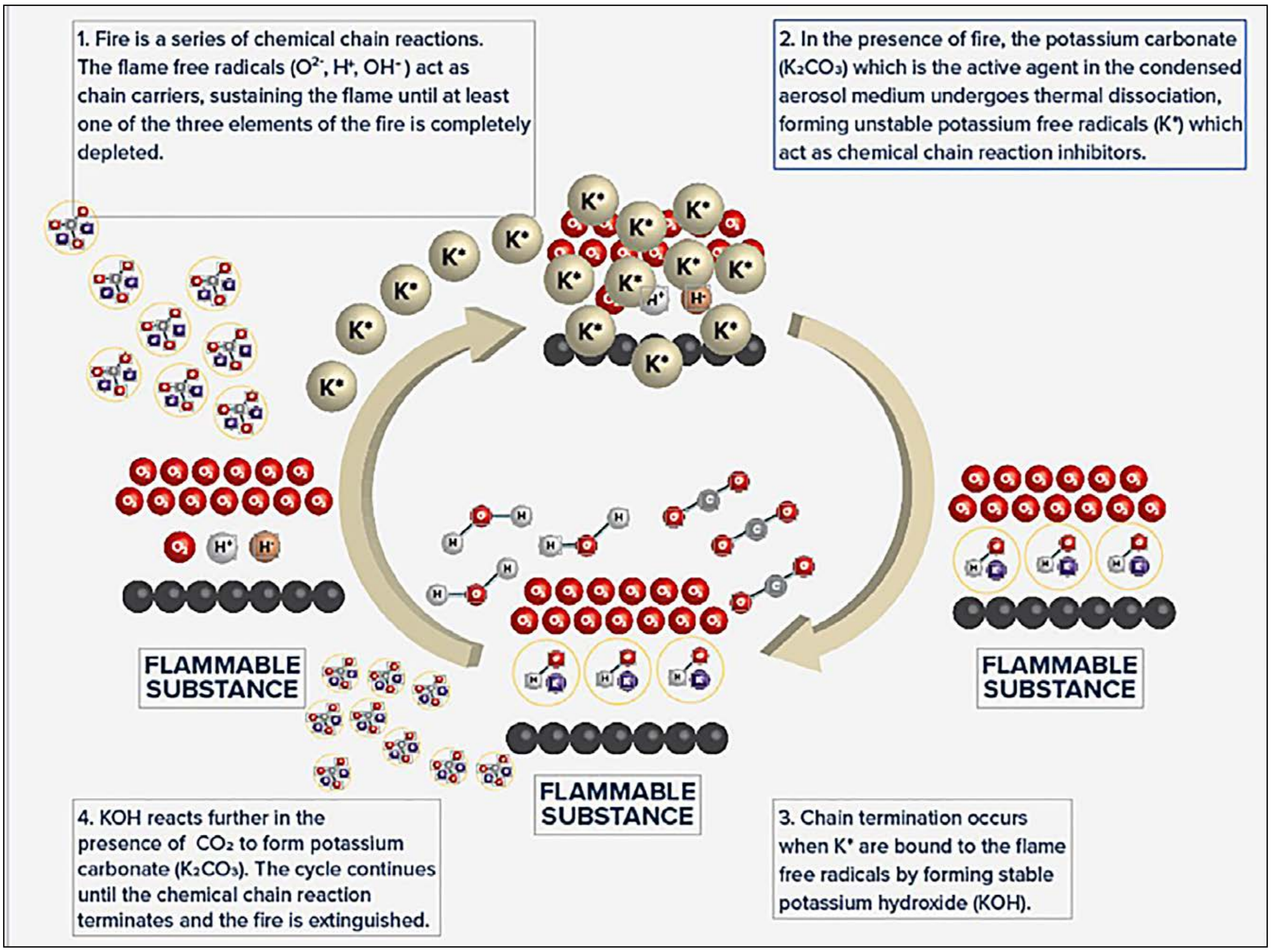

Figure 7: Fire-extinguishing action of condensed aerosol

Image courtesy of FirePro (www.firepro.com)

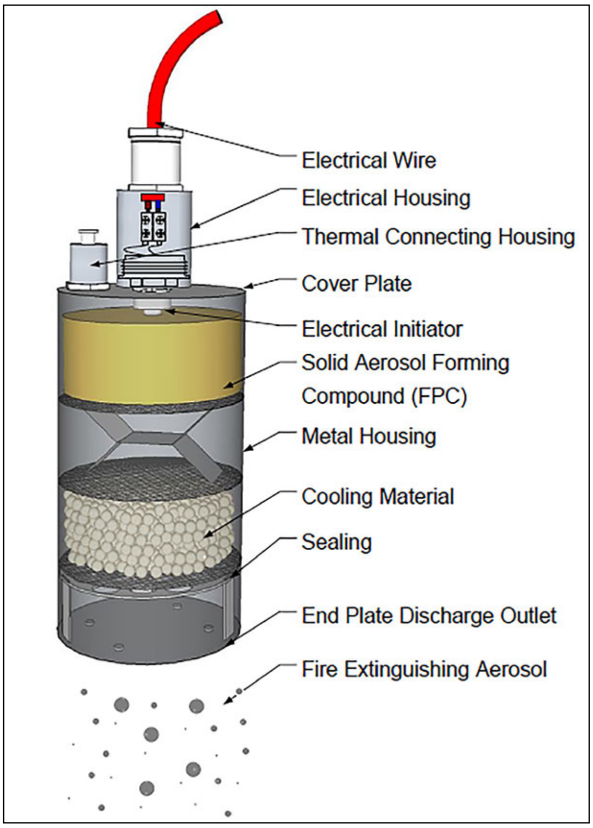

Figure 8: The component parts of a FirePro condensed aerosol generator

FirePro manufactured various models of aerosol generator units based on aerosol generating capacity. Three FP5700[7] units and one FP2000 unit were fitted on board *Resurgam* **(Figure 3)** and were mounted with their outlets facing down at a slight angle of approximately 15° to the horizontal. The FP5700 generator positioned next to the engine room access ladder was mounted at head height with its outlet 86cm from the closest edge of the ladder and walkway **(Figure 9)**. The other generators were mounted in close vicinity to the engine room's floor plate walkways, just above head height.

Figure 9: View of engine room looking aft, showing position of aerosol generator unit adjacent to the access ladder

1.11.3 Fire protection control panel

Ocean Engineering fitted a marine approved FirePro FPX103C dual loop (Auto/Manual) fire protection control panel, manufactured by Logician Ltd, on board *Resurgam* **(Figure 2)**. The panel could be powered by either a 12V or 24V supply and support up to four FirePro generators (24V supply). It could be configured **(Figure 10)** to provide:

- dual loop fire detection (two detector circuits)
- automatic and/or manual activation
- automatic pre-activation engine, fuel and ventilation shut down
- spin-down delay to allow time for machinery to stop before activation
- fault monitoring of fire detector loops and generator firing circuits.

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[7] FP stands for FirePro and the number denotes the net mass of the solid compound in grams: 1g of solid compound equates to 1 litre of aerosol.

Image courtesy of FirePro (www.firepro.com)

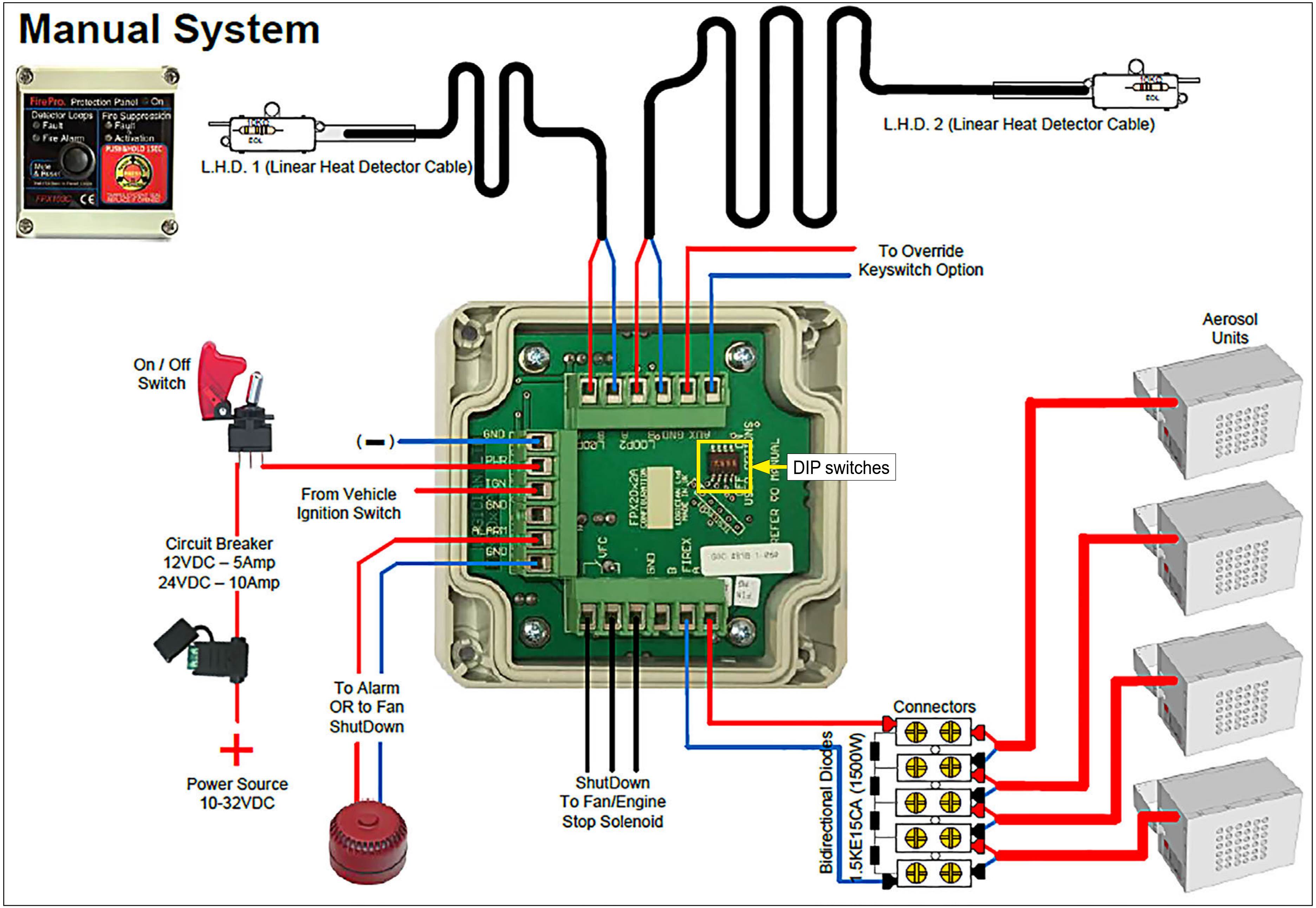


Figure 10: Typical layout of condensed aerosol unit firefighting system

The panel had five light-emitting diode (LED) indication lights, an internal audible alarm, a manual activation push button and a combined alarm mute and system reset push button **(Figure 2)**. The panel lights indicated:

- Green *protection panel on* LED: constantly illuminated – power on; double flashing when spin-down started; single flashing when system activated.
- Red *fire suppression activation* LED: normally off; flashing when spin-down started; constantly illuminated when system activated.
- Amber *fire suppression fault* LED: normally off; constantly illuminated if fault in firing circuit.
- Red/amber *detector loops fault* LED: normally off; flashing when detector loop fault.
- Red/amber *detector loops fire alarm* LED: normally off; flashing when detector alarm activated.

The red and yellow manual activation button had to be pressed and held in for 1 second to activate the system. To help prevent accidental activation, an anti-tamper tag, which needed be pulled off before the button was pressed, usually covered the manual activation button. The mute/reset button silenced the panel alarms when pressed. To reset the system, the mute/reset button had to be pressed and held in for 5 seconds.

A four-switch *dual in-line package* switch (DIP switch)[8] was attached to the printed circuit board within the control panel. DIP switches one to three were used to set the automatic activation spin-down times[9] or disable the automatic activation mode. DIP switch four was used to select single or dual loop fire detection alarm activation.

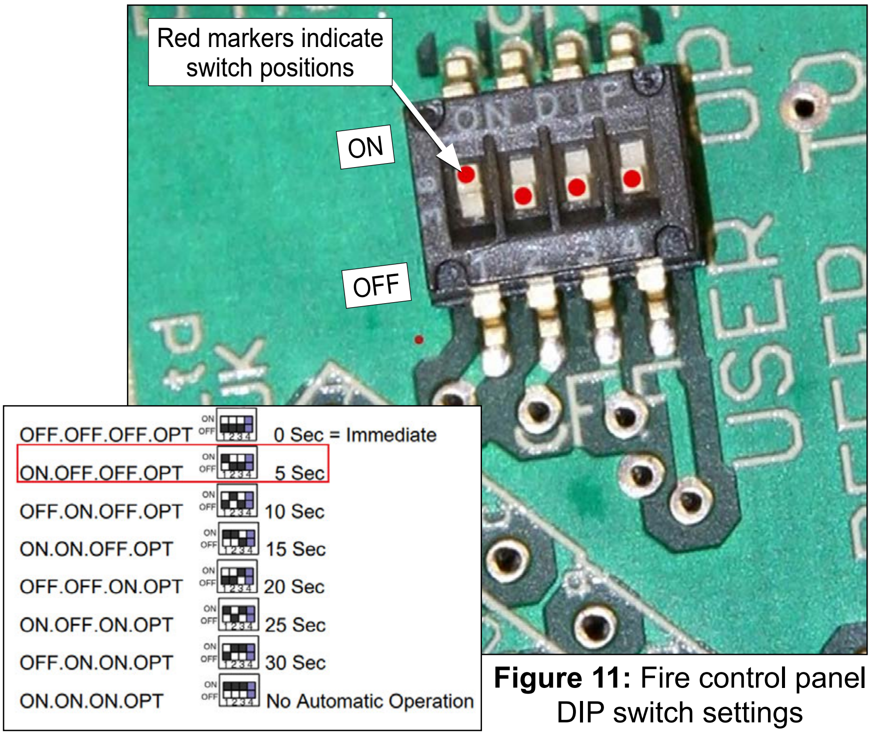


Figure 11: Fire control panel DIP switch settings

Resurgam's system was designed for manual operation only. The vessel had a separate fire detection system and therefore no detectors were connected to the FPX103C panel; instead, 10k ohm[10] resistors were connected across the printed circuit board's dual loop connections. The DIP switches were set to an automatic mode with a 5-second spin-down delay and dual loop activation **(Figure 11)**.

[8] DIP switches are designed to be mounted on printed circuit boards to provide a range of electrical inputs to an electronic device based on the position of the individual switches.

[9] Spin-down times could be set between 0 to 30 seconds in 5-second increments.

[10] An ohm is a unit of electrical resistance across a conductor. A 10k resistor is equivalent to 10,000 ohms.

1.11.4 Pre-activation alarm

A lockable hinged Perspex protective cover was fitted on the front of the FPX103C control panel **(Figure 2)**. The protective cover had to be unlocked and lifted to access the panel's push buttons. Lifting the cover released the microswitch that operated the pre-activation alarm warning beacons located in the protected space. The wiring circuit for the alarm warning beacons was separate to the system's control panel.

Two pre-activation alarm warning beacons were installed on board *Resurgam*; one in the main engine room space and one in the lobby area. The two audible and visual alarm warning beacons were intended to allow time for anyone in the protected spaces to evacuate before the aerosol was released.

1.11.5 Cabling and junction box

A four-core non-shielded electrical cable[11] from the control panel and pre-activation microswitch were run from the wheelhouse to a junction box mounted in the engine room lobby. A combination of three and two core non-shielded electrical cables were run from the junction box to the aerosol generators and the alarm warning beacons. Only two core cables were required to connect to the aerosol generators. In each case, the third core cable was not connected to anything and left loose in the junction box.

The four aerosol generators were wired in series and a bidirectional diode was connected in parallel with each generator. The diodes allowed current to flow in either direction when the potential difference across them exceeded 15V. This allowed the generators to be fired even when one or more were open circuit.

1.12 FIREPRO INSTALLATION GUIDANCE

FirePro's *Information, Instruction & User Manual Version 6, 24-06-16 Fire Extinguishing Aerosol Systems* (FirePro user manual) provided guidance to help calculate the number and sizes of aerosol generators needed to deliver optimum aerosol density for given classes of fire. The FirePro user manual was applicable to European inland waterway vessels as well as the UK and included regulation applicable to Europe. To aid installation planning, FirePro also supplied its distributors with a design calculation spreadsheet, comprised of a series of pages in which to input the size, shape and type of space to be protected. Once the measurements and requirements were entered, the spreadsheet recommended suitable aerosol generator models. It also indicated the models not to use.

The importance of choosing the correct generators and locating them at safe distances from structural components, combustible materials and people was explained in the manual and figures illustrating the length of the discharge streams and temperatures **(Figure 12)** were used to assist the process. The figures illustrated the total discharge stream lengths and three temperature-related discharge stream lengths for each generator model.

[11] A shielded cable or screened cable is an electrical cable that has a common conductive layer around its conductors for electromagnetic shielding. The shield acts as a Faraday cage – a surface that reflects electromagnetic radiation. This reduces both the interference from outside noise onto the signals and the signals from radiating out and potentially disturbing other devices.

For illustrative purposes only: not to scale

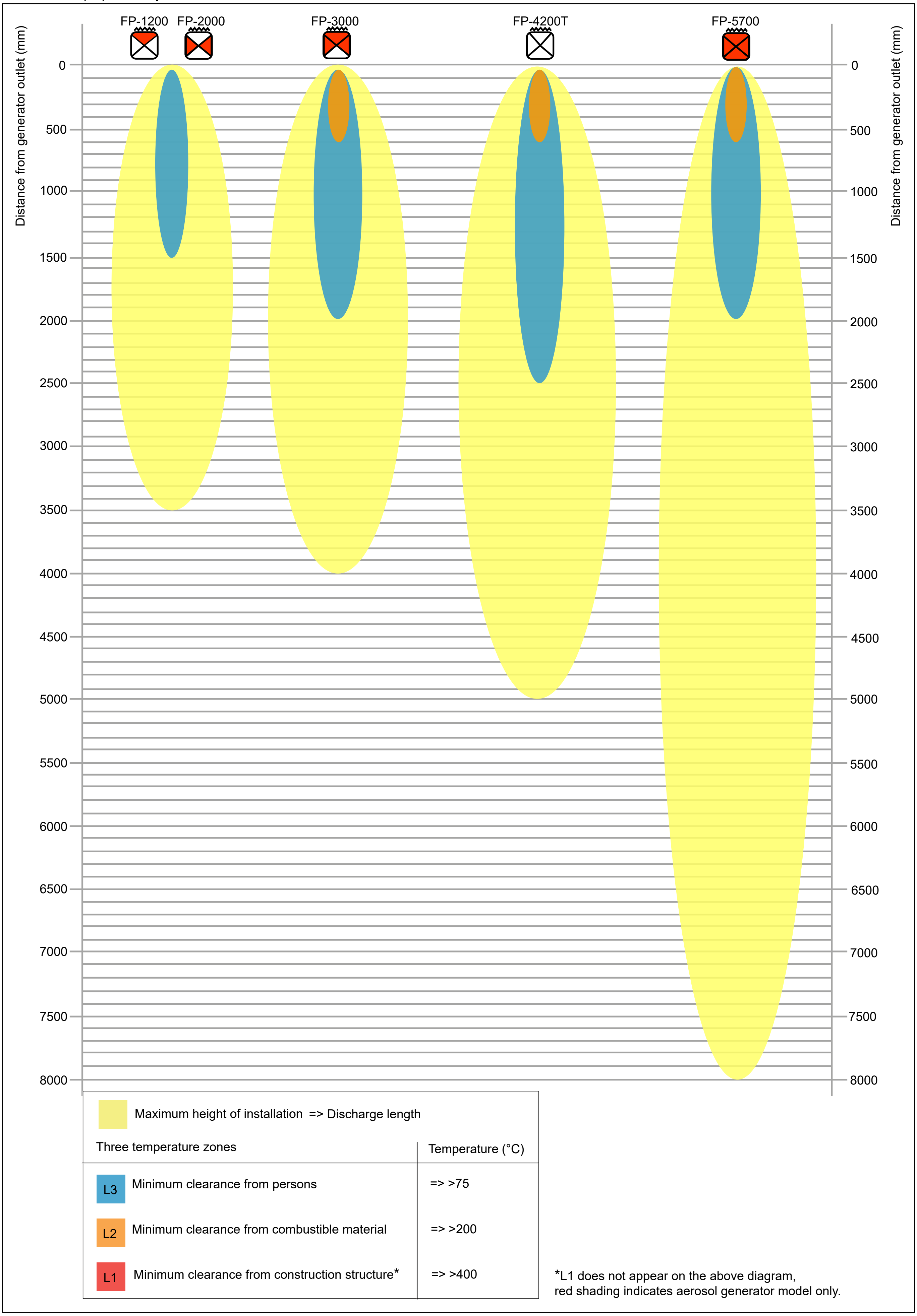


Figure 12: Condensed aerosol stream length and temperature illustration

The three lengths were:

- L1 = distance in metres away from the aerosol generator outlet where the discharge temperature did not exceed 400°C (minimum distance from construction structure);
- L2 = distance in metres away from the aerosol generator outlet where the discharge temperature did not exceed 200°C (minimum distance from combustible material);
- L3 = distance in metres away from the aerosol generator outlet where the discharge temperature did not exceed 75°C (minimum distance from persons).

FirePro's temperature/distance values were based on Paragraph 23 of the International Maritime Organization (IMO) Maritime Safety Committee Circular, MSC.1/Circ.1270: *Revised Guidelines for The Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing Systems, as Referred to in SOLAS 74, for Machinery Spaces*. The Circular stated that aerosol generators should be separated from escape routes and areas where people may be present by at least the minimum safe distance for exposure to temperatures of 75°C. The L3 values for the FP5700 and FP2000 aerosol generators were 2m and 1.5m, respectively **(Figure 12)**[12].

FirePro's user manual was supplemented by a marine annex[13] that contained specific guidance for marine applications. The first page of the marine annex reiterated the need for minimum safe distances between generators, escape routes and persons.

1.13 INSTALLATION DESIGN CALCULATIONS

Ocean Engineering's service manager and the trainee installation technician had measured the main machinery space (protected space) dimensions two weeks before the accident, during a visit to the Stevenson offices and *Resurgam* in Newlyn. The measured dimensions included the volume of the engine room, lobby area and winch room, which could not be isolated from one another and were linked by the engine room access ladder opening **(Figure 6)**. The height of the engine room was 2.3m. The gross volume of the protected space was calculated to be 153m^3. The net volume was calculated to be 138m^3, taking into account the volume of impermeable items such as machinery and tanks, of which 90m^3 (65% of net volume) was the engine room space alone.

Ocean Engineering's operations director used FirePro's design calculation spreadsheet to assess the number and models of aerosol generators required for the protected space. Page 1 of the spreadsheet listed the installation company's details. Pages 2 and 3 contained the design calculation and generator selection sheets.

The design calculation sheet **(Figure 13)** could be used to determine the volume of the protected space and the total mass of aerosol generating compound required to extinguish a fire. The operations director had already calculated the net volume of the space and entered it directly into the spreadsheet. He also entered *0.6m to 2.5m* as the required discharge stream length. The actual lengths, widths and heights

[12] L1 is not indicated on **Figure 12**, as the temperature of the stream was reported as being less than 400°C in the FirePro user manual.

[13] FirePro Annex 2 Marine Manual Version 1, 07-05-14 for Small Vessel Codes.

Image courtesy of FirePro (www.firepro.com)

Installer company

OCEAN ENGINEERING (FIRE) LTD

Design Calculation Sheet

VOLUME 1 (MCA Classification Society)

SELECT UNITS	Meters
VOLUME (if not to be calculated)	138

ROOM NAME & No.	Engine room
SPACE TYPE	Other Large Size Enclosure <4m Height
ROOM SHAPE	Rectangular

SECTION DIMENSION Length [ ] m x Width [ ] m x Height [ ] m = ***VOLUME*** = 138.000 m3

CLASS OF FIRE	Class B - Combustible Liquids
STREAM REQUIRED (m)	0.6<SL<2.5 m
SAFETY FACTOR (sf)**	1.3

****FOR ADDITIONAL SAFETY REPLACE CURRENT SAFETY FACTOR AS APPLICABLE**

TOTAL VOLUME THIS ROOM IN CUBIC METERS (m3) 138.00 m3

M (g)		V (m^3)	D (g/m^3)		
Mass of FirePro® Aerosol		Total Volume	EAD	SF	
Extinguishing Application Density (g)	=	138.00 m^3 x	100 g/m^3 x	1.3	= 17940.00 g

RECOMMENDED GENERATOR MODEL(S) SELECTION

Recommended Models by Stream Lenth:

Unable to Recommed Models - Pls Select Stream Length Required

Recommended Models by Volume:

FP-500S, FP-1200, FP-2000, FP-3000

CONFIRM STREAM LENGTH CORRECTNESS OF RECOMMENDED GENERATOR-ROOM HEIGHT Vs STREAM REQUIRED

CONFIRM SIZE CORRECTNESS OF GENERATOR RECOMMENDED - ROOM VOLUME Vs GENERATOR COVERAGE

IMPORTANT REMARKS:

1. THIS SOFTWARE IS ONLY A GUIDING TOOL - SELECTION OF GENERATORS IS THE USER's RESPONSIBILITY.
2. ABOVE SELECTION IS JUST A RECOMMENDATION. ENGINEERING JUDGMENT SHOULD BE APPLIED FOR PROPER SELECTION OF GENERATORS TAKING INTO CONSIDERATION ROOM HEIGHT(STREAM LENGTH), GENERATOR ORIENTATION IN RELATION TO THE VOLUME ARRANGEMENT, OPENINGS etc.
3. FOR PROTECTED VOLUMES EXCEEDING 4M HEIGHT GENERATORS SHOULD BE INSTALLED IN STAGGERED ARRANGEMENT TO ENABLE PROPER TOTAL FLOODING - PLEASE CONSULT MANUFACTURER.
4. ALWAYS CHECK CALCULATIONS FOR CORRECTNESS

TOTAL VOLUME THIS SECTION	**138.00 m3**
TOTAL FirePro® MASS REQUIRED FOR VOLUME 1	**17940.00 g**

Figure 13: Spreadsheet from calculation workbook

of the protected space were not entered. The spreadsheet calculated that, with a stipulated[14] safety factor of 1.3, *Resurgam*'s engine room required 17940.00g of solid aerosol forming compound.

The generator selection sheet contained a generator model selection table and listed the recommended models based on the volume of the protected space and the selected discharge stream length. Based on the volume of the protected space, the generator selection sheet recommended the use of models FP500S, FP1200, FP2000 and/or FP3000. The recommended generator models selected by stream length could not be displayed because the height of the protected space had not been entered on the design calculation sheet. Based on the mass of compound required, the operations director selected three FP5700 and one FP2000 generator. This equated to 19100.00g of solid compound, which was 6% higher than the required mass but within the 10% tolerance set by FirePro.

A note on the generator selection sheet's FP5700 cell stated: *select this model only if the room height exceeds 4m*. The bottom of the page carried the following warning, which was not included in the print area of the spreadsheet:

> ***DO NOT USE FP5700 – HEIGHT IS TOO SMALL***

The spreadsheet also contained advice about the installation and design, particularly the selected generator's size and its associated discharge stream lengths and positioning. This section of the spreadsheet explained that the FP5700 generator unit was designed for use in very large volumetric enclosures, typically exceeding 500m^3 and heights over 4m.

The operations director did not produce a job specific method statement or installation guidance for the installation on board *Resurgam*. Ocean Engineering did not confirm with either Stevenson or Firewatch that the proposed installation had not been approved by the MCA for fitting on board *Resurgam*. Ocean Engineering made no further pre-installation visits to *Resurgam* and the operations director did not verify the position of the aerosol generator units in the engine room with the installation engineers.

FirePro and FirePro UK had no procedures in place to scrutinise and approve its authorised installers' design calculations and installation plans.

1.14 VESSEL-SPECIFIC GUIDANCE MANUAL AND INSTALLATION DRAWINGS

Ocean Engineering had produced an information and guidance document titled *Manual and Specification for the Installation of a FirePro Aerosol Extinguishing System Onboard MFV Resurgam* and a simplified wiring diagram **(Figure 14)** for the *Resurgam* installation. The vessel-specific manual contained operating and maintenance instructions as well as various extracts from FirePro's instruction manuals, including a generic FirePro system wiring diagram **(Figure 15)**.

The operating instructions explained that although the FirePro aerosol was not hazardous to health in exposures of 5 minutes or less, it should be treated like other extinguishing systems and personnel should be evacuated from the space before operating. It specifically warned of the risk of disorientation due to loss of visibility and noise following sudden discharges.

[14] MSC.1/Circ.1270 - *Design application density (g/m³) is the mass of an aerosol forming composition per m³ of the enclosure volume required to extinguish a specific type of fire, including a safety factor of 1.3 times the test density.*

The vessel-specific manual also included extracts from the design calculation spreadsheet, showing the mass of aerosol compound needed to protect the space and the generator models selected to deliver the requirement. It omitted the spreadsheet's warning not to use the FP5700 aerosol generator.

One section of the vessel-specific manual described the FPX103C control panel; this was extracted from the manufacturer's guide but with errors, including a statement that the control panel supported up to six generators when the maximum was four.

The aerosol generators in *Resurgam*'s installation were connected to the system's wiring using inline plugs and sockets. This was contrary to the wiring diagrams and system illustrations within the FirePro user manual, its marine annex, the user manual for the FPX103C control panel or *Resurgam*'s documentation prepared by Ocean Engineering. All of these diagrams showed the firing cables connected directly to the generators and detailed guidance was provided in the FirePro user manual on how these connections should be made.

The vessel-specific manual also contained copies of the FirePro product material safety data sheet (MSDS) (see section 1.17 below), the MCA's product Certificate of Inspection and Tests, and some marine type approvals.

Stevenson was not given a copy of the manual or wiring diagram before the installation started and the installers did not have copies of them when they arrived on board.

Image courtesy of Ocean Engineering (www.oceanengineering.co.uk)

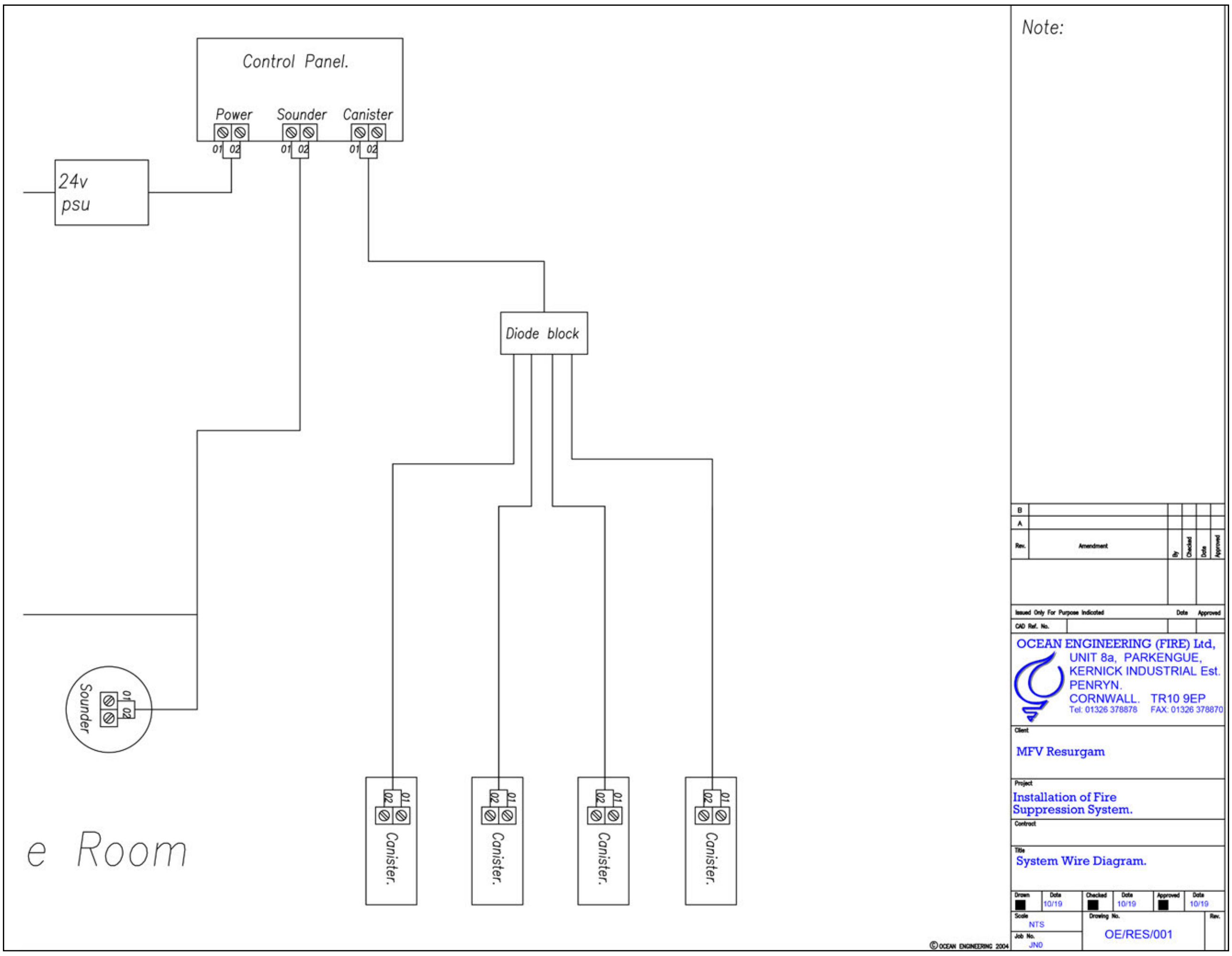
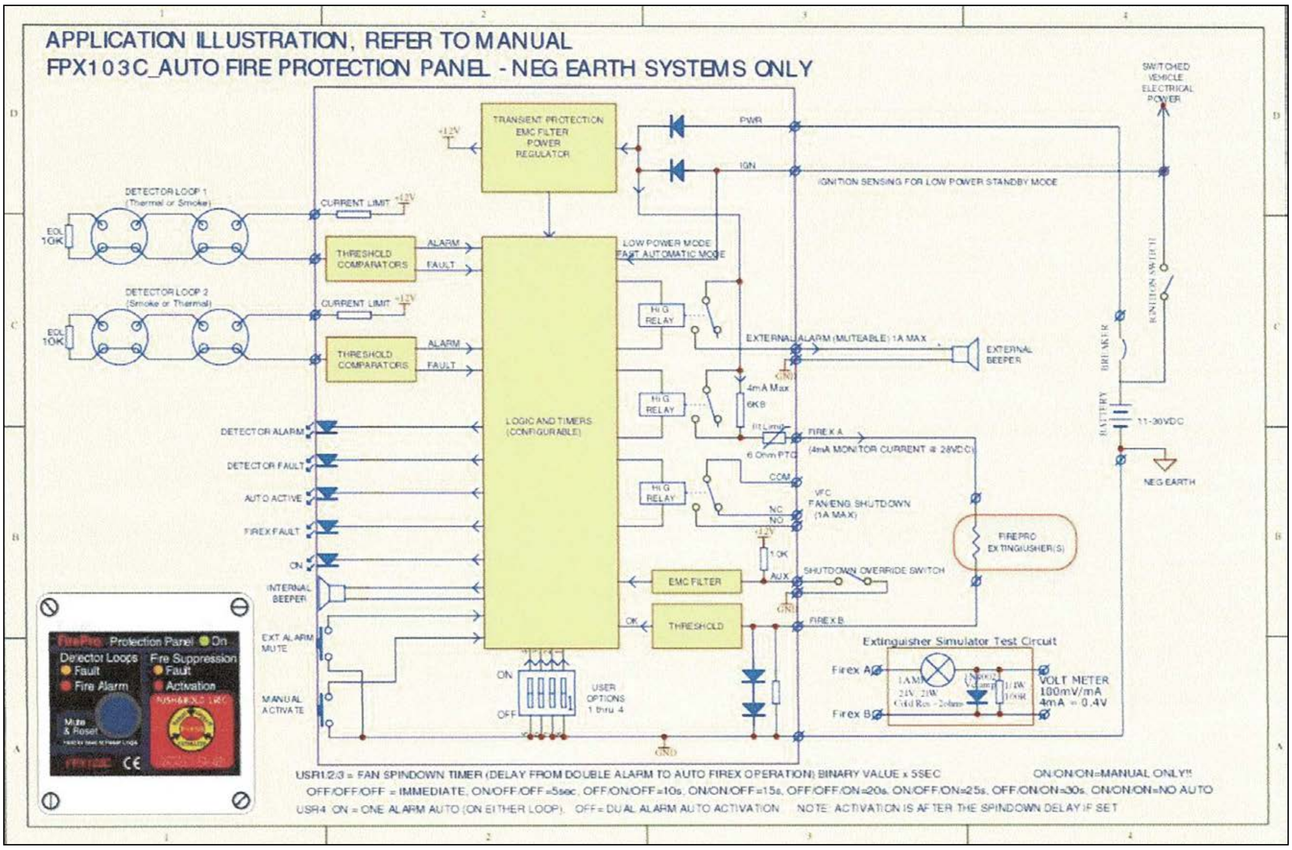


Figure 14: Ocean Engineering wiring drawing for *Resurgam* installation



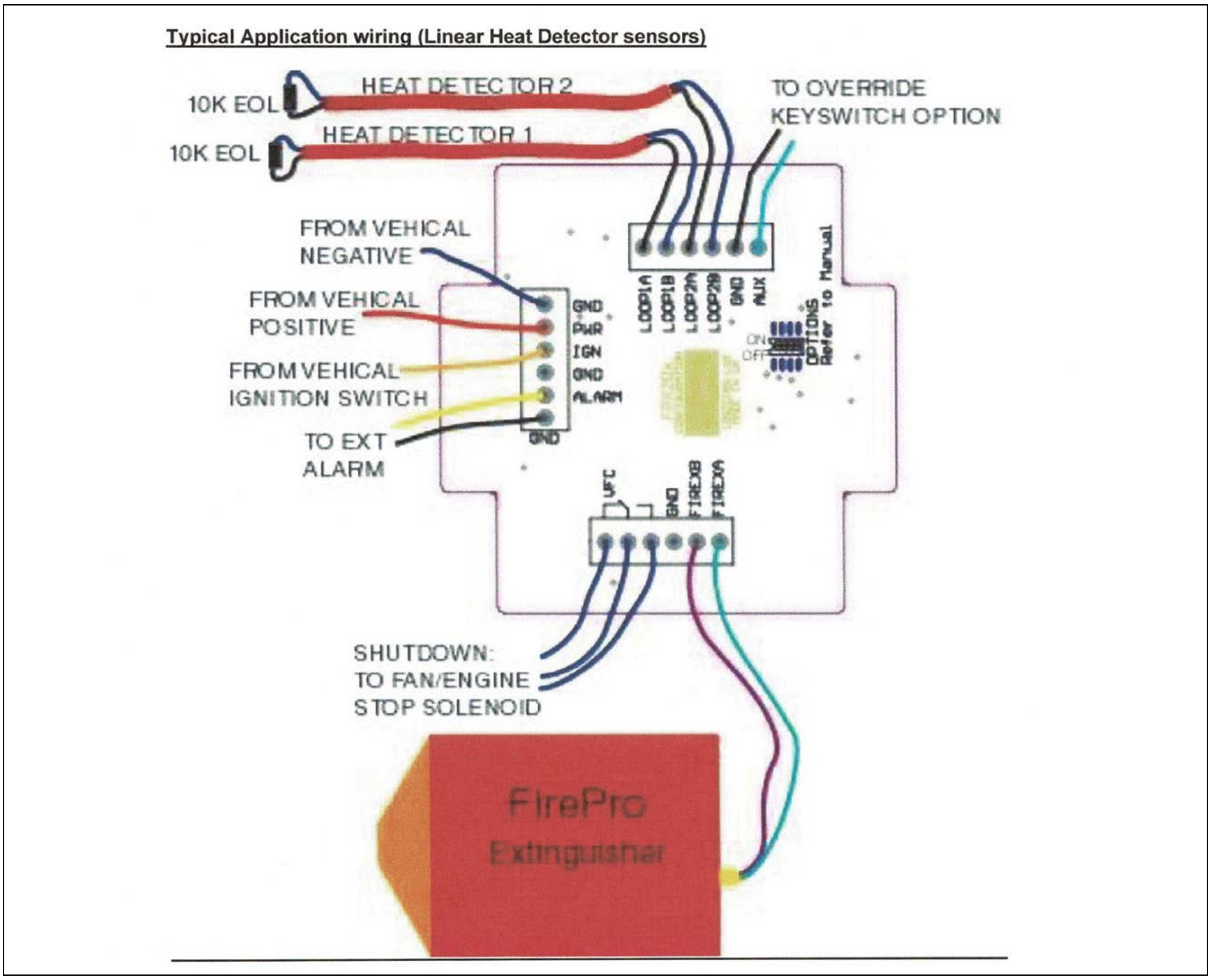


Figure 15: FirePro system wiring diagrams from *Resurgam*'s vessel-specific manual

1.15 INSTALLATION TESTING AND COMMISSIONING PROCEDURES

FirePro's FPX103C fire control panel user manual **(Annex A)** included installation and operational guidance intended for both land and marine applications. The manual included commissioning procedures to follow once the system's installation was completed. Part of the commissioning requirement was to test if the panel correctly identified faults in the extinguishing circuit and to simulate the activation of the installation. For both tasks, the manual stated that the aerosol generators had to be disconnected and replaced by simulation lamps **(Figure 16)**. Before doing this, the power to the whole system had to be isolated.

The commissioning instructions also detailed how to return the panel to its normal operating condition after the tests and simulation were complete. To do this, the panel had to be reset to normal operating conditions and the power isolated completely before removing the simulation lamps and reconnecting the generators.

Section 16 of the FPX103C manual referred to regulatory information relating to MCA approvals. The section included a copy of the MCA's Certificate of Inspection and Tests and excerpts from its Marine Survey Instructions for the Guidance of Surveyors *Fire Protection Arrangements (MSIS 12)*.

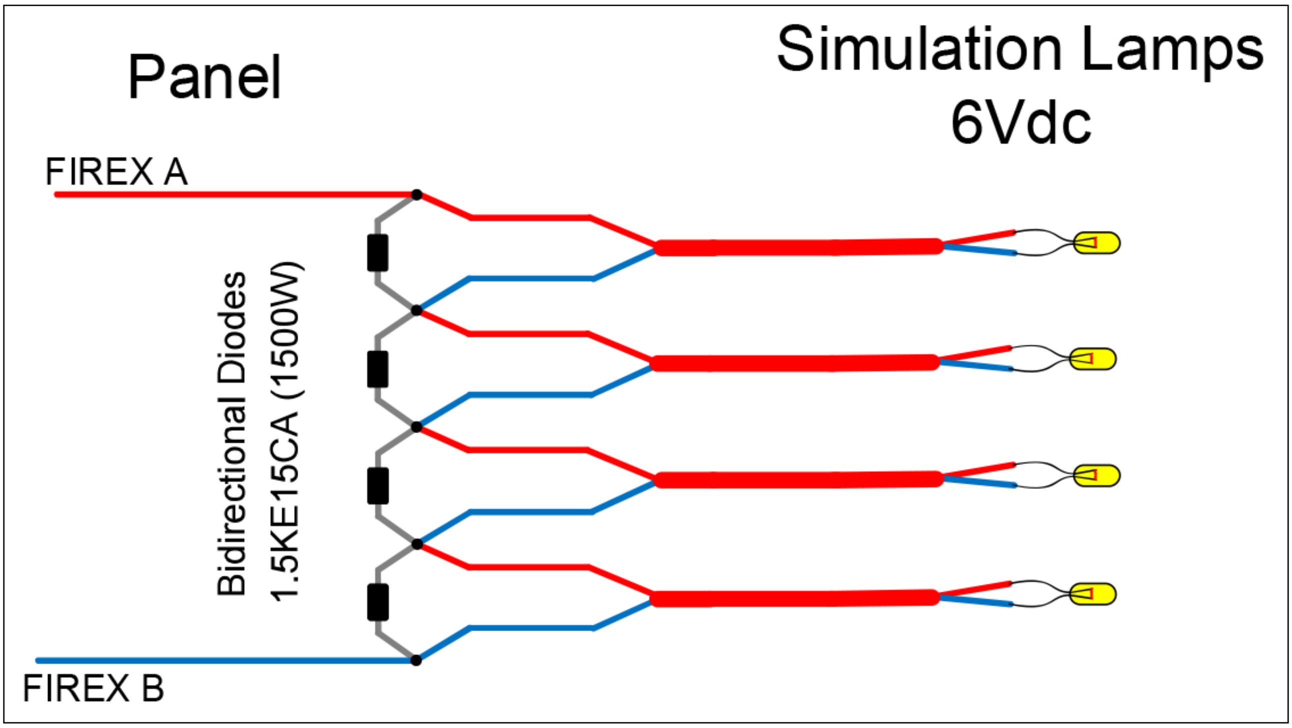


Figure 16: Aerosol generator firing circuit simulation lamps

1.16 TRAINING OF FIREPRO SYSTEM SERVICE AND INSTALLATION TECHNICIANS

The FirePro user manual described the project phases for a typical FirePro installation from system design to delivery. The manual stated that the installation phase should be carried out by *Certified Authorized Technical Technician Aerosol Systems* (CATTAS) trained personnel *on the basis of installation drawing, manual and standards*. This only applied to shore-based installations in Europe.

Ocean Engineering's installation technicians undertook a training programme that included health and safety and specialised installation and fire equipment servicing. Approved training providers were used if specific equipment manufacturer requirements existed.

For FirePro installations, Ocean Engineering did not have a formalised training programme to follow or written standards to achieve; instead, trainees were required to accompany more experienced installation technicians. When the trainee was judged to be proficient, the operations director conducted a verbal assessment to check they had sufficient knowledge to undertake unsupervised installation and maintenance.

The lead technician on board *Resurgam* had worked for Ocean Engineering for 4 years and held a City and Guilds Electrical Installation in Buildings Certificate. The operations director had deemed him competent to install and service FirePro systems. There was no formal reassessment to ensure standards were maintained.

1.17 FIREPRO HAZARD IDENTIFICATION

The IMO's MSC.1/Circ.1270 stated that:

> *Condensed aerosol systems for spaces that are normally occupied should be permitted in concentrations where the aerosol particulate density does not exceed the adverse effect level as determined by a scientifically accepted technique and any combustion products and trace gases produced by the aerosol generating reaction do not exceed the appropriate excursion limit for the critical toxic effect as determined in acute inhalation toxicity tests*[15]*.*

FirePro's marketing literature stated that the aerosol was:

> *Non Toxic (at design concentration), Non Conductive, Non Oxygen Depleting and Non Corrosive.*

One of the listed main advantages of the system was that *FirePro does not produce harmful toxic compounds or acidic fumes*. FirePro also described the transformation of the solid compound to a gaseous aerosol as non-pyrotechnic.

The MSDS **(Annex B)** in FirePro's user manual stated that the solid aerosol forming compound presented no hazard to humans. It also stated that hazards for humans related to the aerosol released during discharge had not been established because threshold limit values (TLV) were not applicable.

The MSDS recognised that accidental release of the aerosol was a foreseeable event but assessed that inhalation was an unlikely route of exposure and that respiratory protection was not needed. In circumstances when this might occur the recommended first aid measure was to remove the affected person(s) from the exposure area to fresh air.

The MSDS did not identify the composition of gases or particles generated during the condensed aerosol phase and stated that:

> *The TLV's (Threshold Limit Values) of the chemicals released in the aerosol phase are applicable only in case of long, as long as a complete professional life, exposure. This is not the case of a real life situation.* [sic]

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[15] MSC.1/Circ.1270 made reference to the United States' EPAs Regional Deposited Dose Ratio Program 'Methods of Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry'. EPA/600/8-90/066F October 1994.

FirePro UK's guidance leaflets stated that:

> *The FirePro agent is released as an aerosol made up of minute particles suspended in a blend of carrier gases. The agent is opaque in nature so visibility may be compromised. Although the area should have been vacated prior to discharge of the FirePro agent, extensive testing by independent accredited research facilities have shown that FirePro is safe to breath for an acute exposure, and does not reduce the oxygen content within the protected space. When discharged, residual and non-harmful amounts of CO [carbon monoxide], NO2 [nitrogen dioxide], NH3 [ammonia] and HCN [hydrogen cyanide] may be detected. These levels are very small and have been certified independently as not being life threatening for an acute exposure. Proper measures should be taken to minimise the exposure time.* [sic]

1.18 FIREPRO PRODUCT EVALUATION AND APPROVALS

1.18.1 Overview

To underpin sales and marketing, and to achieve global accreditation with flag states and classification societies, FirePro actively engaged with a range of laboratories to scientifically determine the environmental impact and hazards associated with its product.

In 2002, FirePro commissioned the Dutch environmental consultancy company Keuring van Elektrotechnische Materialen te Arnhem (KEMA) to undertake an evaluation of the aerosol generator's solid compound and the particulates released when it combusted. KEMA's analysis concluded that, in the open air, water vapour and carbon dioxide (CO_2) would be the only combustion by-products.

1.18.2 United States Environment Protection Agency

The *Montreal Protocol on Substances that Deplete the Ozone Layer*, which came into force in 1989, required some chemicals widely used to extinguish fires, such as halon, to be phased out. To help facilitate this, the United States Environmental Protection Agency (EPA) set up its *Significant New Alternatives Policy* (SNAP) programme.

In 2006, following FirePro submissions, the EPA concluded that the FirePro product did not pose a greater overall risk to human health or the environment when compared to similar acceptable products. The EPA accepted the FirePro condensed aerosol, subject to use conditions, as a halon 1301 substitute for total flooding agent uses. The EPA listed the FirePro agent, along with two other FirePro trade named brands, FireBan and FirePro Extinguish, as *Powdered Aerosol E*. As requested by FirePro, the use of its condensed aerosol system was limited to normally unoccupied spaces.

Because of the risk of accidental release of the aerosol generators, the EPA recommended that personnel wear goggles, gloves, and particulate removing respirators while performing installations and/or maintenance activities.

The EPA also approved the Stat-X product, which was listed as *Powdered Aerosol D* and was also approved for use in normally unoccupied spaces. The Stat-X product was subject to worker safety recommendations similar to those of FirePro.

A legal definition of a normally unoccupied space, relating to the use of halon gases, can be found in *European Union Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer (recast)*, as amended by Commission Regulation (EU) No. 744/2010 of 18 August 2010:

> *A protected space that is occupied for limited periods only, in particular for undertaking maintenance, and where the continual presence of persons is not necessary for the effective functioning of the equipment or facility.*

It defined a normally occupied space as:

> *A protected space in which it is necessary for persons to be present most or all of the time in order for the equipment or facility to function effectively.*

1.18.3 United States Coast Guard

In 2006, the United States Coast Guard (USCG) Research and Development Center evaluated three condensed aerosol extinguishing systems for marine machinery space applications[16]. A FirePro system containing 1.1kg of solid compound was one of those selected for evaluation.

Part of the USCG's evaluation process was to identify and monitor the gases produced during combustion. It determined that the aerosol comprised potassium-based particulates and a combination of gases consisting of CO, CO_2, water vapour and nitrogen. The CO production was assessed as 0.8%, equal to 8000 parts per million (ppm) and it was noted that the compartment's oxygen fell to 19.1%.

1.18.4 The Institute of Environmental Hygiene and Toxicology

In 2016, FirePro commissioned the Institute of Environmental Hygiene and Toxicology in Gelsenkirchen, Germany, to assess the condensed aerosol system. A 200g disc of solid compound was ignited in a 2.43m^3 enclosure. The solid compound was not in an aerosol generator casing and the enclosure's atmosphere was monitored for temperature, oxygen, CO_2 and CO.

The results indicated that, post combustion, the oxygen levels fell to 19.3% and CO_2 was present at 1.2% by volume of the compartment. CO was recorded at less than 0.1% by volume (1000ppm). The enclosure's temperature rose by approximately 4.5°C. It was reported that the estimated visibility in the chamber was between 20cm and 30cm.

In October 2018, based on the institute's assessment results, the EPA revised its 2006 SNAP assessment and accepted the FirePro systems for use in normally occupied spaces. The EPA also removed its specific recommendation that goggles, gloves and particulate removing respirators be worn during installation and maintenance activities; instead, it referred users to the OSHA[17] technical manual for personal protective clothing. The Stat-X system had been approved for use in normally occupied spaces in 2014.

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[16] An Evaluation of Aerosol Extinguishing Systems for Machinery Space Applications Final Report, February 2006, Report No. CG-D-03-06.

[17] Occupational Safety and Health Administration – a regulatory agency of the United States Department of Labor.

1.18.5 Marine type approvals

The FirePro fire-extinguishing system had been type approved and certified for use on board ships by a number of bodies, including the MCA and four members of the International Association of Classification Societies: American Bureau of Shipping (ABS); Bureau Veritas; Registro Italiano Navale; and Croatia Register of Shipping.

ABS had approved the FirePro system for use in normally occupied machinery spaces up to a maximum volume of $500m^3$. The conditions placed on the system included:

- maximum height of protected space 5m
- minimum design density of the aerosol $120g/m^3$
- minimum clearance from persons and escape routes 1.8m
- provision of a means providing an automatic pre-activation audible and visible alarm in the protected space that will allow sufficient time to evacuate the space before the aerosol is released. This time should not be less than 20 seconds.

ABS also stated that automatic release of the system was not allowed on board SOLAS ships or vessels above 500GT. The other classification society type approvals had similar conditions.

1.19 APPROVAL OF THE FIREPRO SYSTEM FOR USE ON BOARD UK REGISTERED VESSELS

The MCA was the approving authority for the installation, operation and maintenance of fixed fire-extinguishing systems on board UK registered vessels. In July 2016, it approved the FirePro system for use on board UK vessels of under 24m in length. The MCA also approved the use of two other condensed aerosol systems, Stat-X and Pyrogen.

The MCA's Certificate of Inspection and Tests **(Annex C)** approved the use of the FirePro system in *normally unoccupied spaces*, where the space to be protected did not exceed a deck height of 4m or an area of $64m^2$. It also included the conditions to be met for the planning, installation and operation of the system. The certificate also listed two control panels manufactured by Logician Ltd, the FPX103C and FPX104C, which were suitable for systems with up to four aerosol generators. The MCA described the FPX103C as a basic panel used for automatic and manual activation. It described the FPX104C as a control panel used for manual activation.

The Certificate of Inspection and Tests defined a normally unoccupied space as:

> *…an area that is not occupied by humans under normal circumstances but may be entered occasionally for brief periods. Whenever the space is entered then the isolation method is to be used to de-activate the generators within the protected enclosure.* [sic]

It also stated that:

> *In some cases, it will be a requirement for the discharge of a FirePro aerosol generator to be prevented by means of an isolation switch, or other means, that shall be manually operated when personnel are present within the protected engine enclosure, or adjacent areas, which could be rendered hazardous by the discharge of the system.*

Before the MCA approved the FirePro system, various scenarios were trialled to test how effective the system was in combatting fires. The MCA's certificate described FirePro as:

> *…a fire extinguishing aerosol system consisting of a non-pyrotechnicaerosol forming solid compound together with the non-pyrotechnic natural mineral coolant and egress chambers which are contained within a non-pressurised canister with one or two discharge outlets.* [sic]

It also explained that:

> *The FirePro non-pyrotechnicaerosol forming solid compand is made up mainly of potassium nitrate 77%, potassium carbonate 4%, magnesium 1% and an epoxy resin polymer 18%. Once activated the SBK solid compound is turned into a rapidly expanding aerosol gas comprising of nitrogen(N2), Carbon dioxide (CO2) water vapour (H2O) and solid particles of potassium salts (K2C03).* [sic]

The MCA required plans to be submitted before installation and the installation to be completed to the satisfaction of one of its surveyors. The MCA also required the system's installation, maintenance, testing and operation instructions to be provided on board.

Section 7.7 of MSIS 12 provided instructions and guidance for MCA surveyors on both condensed and dispersed aerosol systems. It advised its surveyors that condensed aerosols were created in pyrotechnical generators[18] and were typically non-corrosive, non-toxic and non-conductive. Despite this, the guidance warned that:

- *The minimum quantity should not be greatly exceeded as powdered aerosols are typically composed of multiple soluble and insoluble compounds. Acute inhalation exposure to very high concentrations of these compounds can induce a variety of adverse effects in humans, such as eye irritation and inhalation toxicity. Unnecessary exposure to aerosol media, even at concentrations below an adverse effect level, should be avoided.*
- *Aerosol particles cause obscuration and possible hazards resulting from being unable to see while evacuating the space.*
- *Accidental exposure to the aerosol should be limited to 5 minutes as high levels of carbon monoxide may be generated. For these reasons aerosols may have approval for 'normally unoccupied spaces' only.*

These warnings were omitted from the MSIS 12 excerpts quoted in the FPX103C fire control panel manual. Of note, FirePro's FPX104C fire control panel manual included an instruction to ensure that all power was off and that all persons were removed from the protected space before connecting aerosol generators to the firing circuit.

MSIS 12 contained some contradictory guidance regarding normally occupied spaces but explained that automatic activation was only acceptable for spaces of 170m^3 or less. Where automatic operation was used for spaces large enough to enter, an isolation switch had to be fitted close to the entry point.

[18] The MCA explained that dispersed aerosols were non-pyrotechnically generated, but stored in containers with carrier agents (inert gases or halocarbon agents).

1.20 POST-ACCIDENT INSPECTIONS, LABORATORY TESTS AND TRIALS

1.20.1 Initial inspection after the accident

Examination of the FirePro condensed aerosol system installation on board *Resurgam* after the accident found the following:

- The doors to the electrical distribution cabinet in the wheelhouse that contained the PSU were open **(Figure 17)**. A length of cable had loosely been led from a miniature circuit breaker on the mounting rail and connected to the PSU. The circuit breaker was in the off position and the system was depowered.
- The FirePro FPX103C control panel's **(Figure 18)** protective Perspex cover was closed and locked; its key was inserted in the lock. The anti-tamper tag had not been attached and was lying at the bottom of the protective cover. The pre-activation alarm microswitch was detached from the protective cover wall. None of the panel's indicator lamps were illuminated and no audible alarms were sounding.
- The cover for the junction box **(Figure 19)** in the engine room lobby was off. The generators were wired in series in the order 4, 3, 1, 2.
- The FP5700 generator 1 **(Figure 3)**, mounted adjacent to the engine room access ladder, had discharged. Its firing cable plug/socket coupling was connected.
- The FP5700 generator 2 **(Figure 3)**, mounted near the forward end of the main engine, had not discharged. Its firing cable plug/socket coupling was disconnected.
- The FP5700 generator 3 **(Figure 3)**, mounted near the port forward corner of the engine room, had discharged. Its firing cable plug/socket coupling was connected.
- The FP2000 generator 4 **(Figure 3)**, mounted in the port aft corner of the engine room, had discharged. Its firing cable plug/socket coupling was disconnected.
- The two pre-activation alarm warning beacons were inactive.

It is unknown when or how the pre-activation alarm microswitch became detached from the wall of the control panel's protective cover.

1.20.2 Observations on powering up the system

On 21 November 2019, the FirePro system was powered up on board *Resurgam* in the presence of an HSE Her Majesty's Specialist Inspector (Electrical Engineering). All of the condensed aerosol generators were unplugged before the 24V power supply was switched on.

When power was applied, the green *protection panel on* LED illuminated. The control panel's amber fire suppression fault LED also illuminated and its audible alarm sounded. The pre-activation alarm warning beacon audible alarms sounded in the engine room and their warning lights flashed. The pre-activation alarms had activated because the microswitch had detached from the control panel cover and was in its open position. The alarms stopped when the microswitch was closed.

The fire suppression system voltage in the lobby junction box was measured at 22.4V.

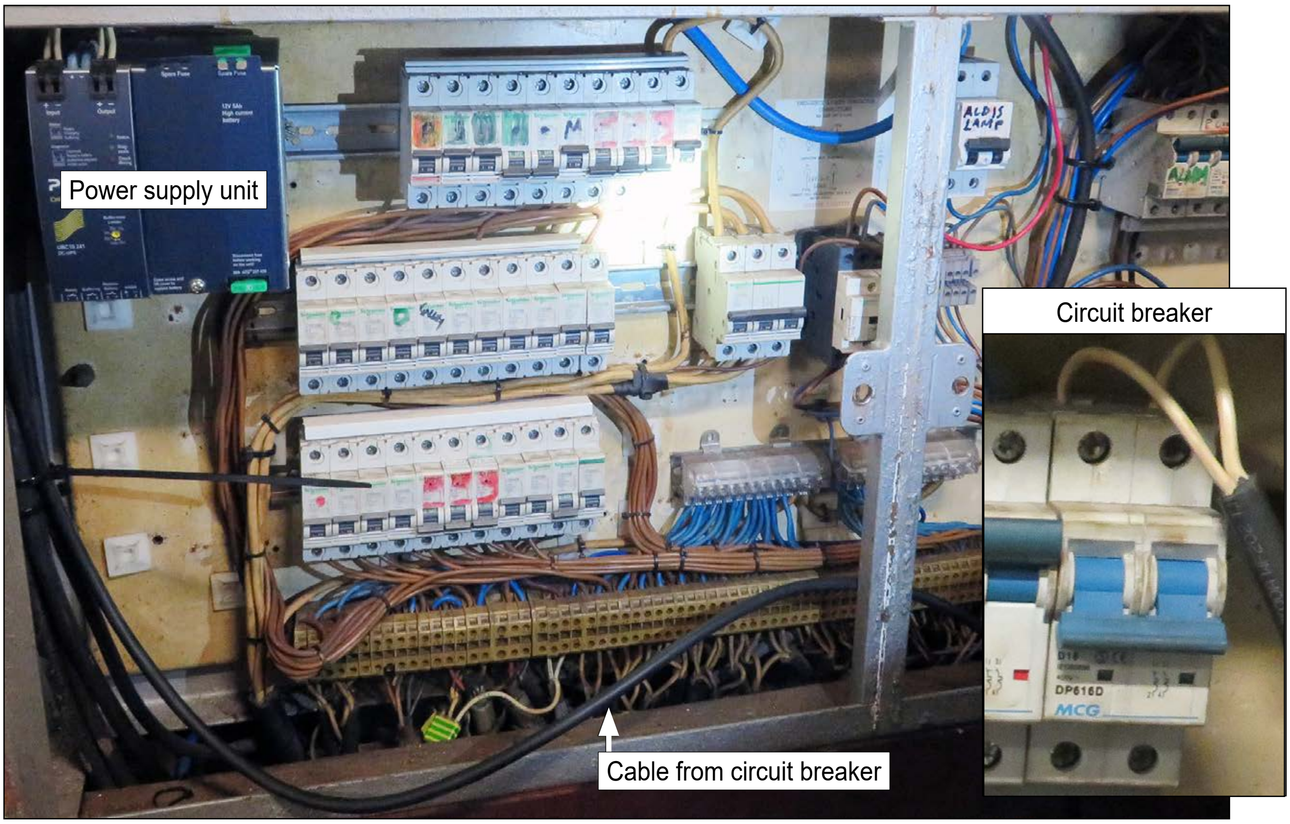

Figure 17: Power supply unit installed in the electrical distribution cabinet in the wheelhouse

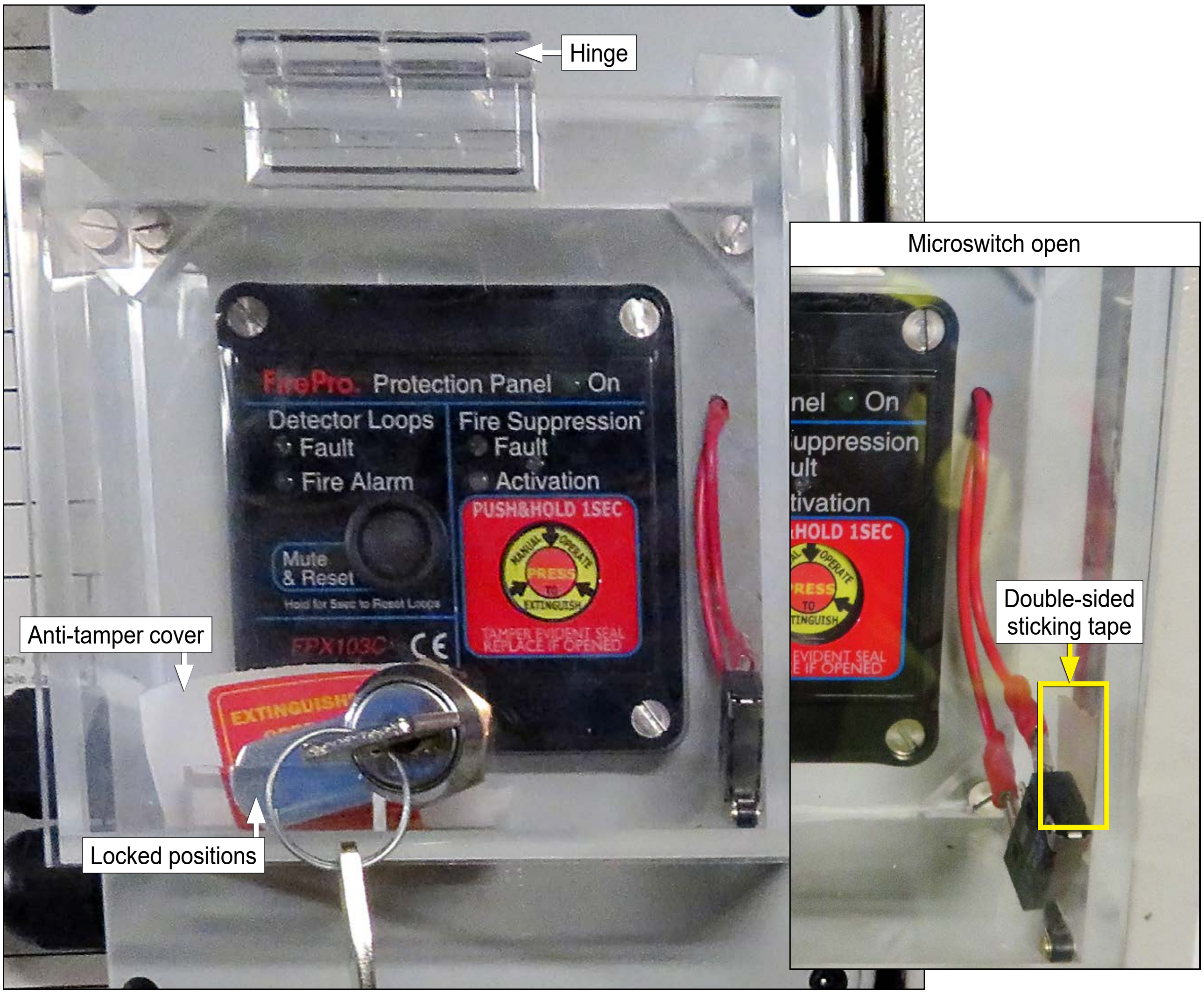

Figure 18: FPX103C control panel on board *Resurgam* following the accident

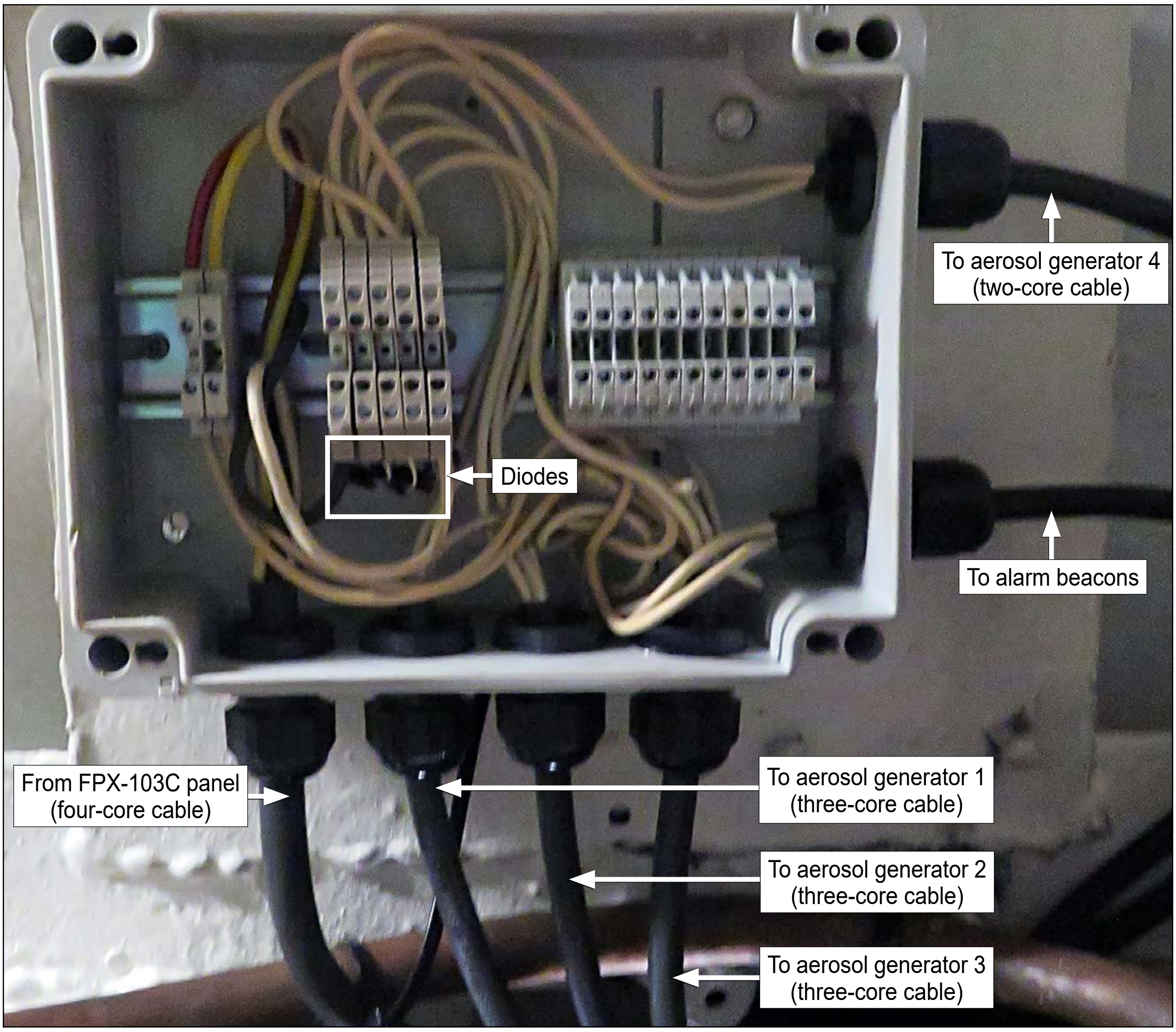

Figure 19: Junction box in engine room lobby on board *Resurgam* following the accident

1.20.3 Laboratory tests and trials

Following the accident, *Resurgam*'s FirePro system was dismantled and transported for forensic examination to the HSE Science and Research Centre in Buxton, Derbyshire. The HSE commissioned it to examine and test *Resurgam*'s FirePro system and conduct aerosol generator discharge trials.

The aim of the system examination and tests was to determine the causes of the accidental discharge. The aim of the generator discharge trial was to identify and measure the combustion gases created during the ignition of the solid compound and to measure the stream length temperatures. MAIB inspectors witnessed the system tests and discharge trials.

1.20.4 Electrical circuit testing

Resurgam's FirePro system electrical components and cabling were examined and tested by the HSE Science and Research Centre, and no faults were found. The components were then reconnected under laboratory bench test conditions as they were found on board *Resurgam*, but with simulation lamps connected to the firing circuit instead of the aerosol generators. A manually operated switch was connected in series with each test lamp to simulate fault conditions and the connection and disconnection of the aerosol generators.

When a 24V power supply was connected to the FPX103C control panel with the firing circuit switches closed (generator connected condition), the green *protection panel power on* LED illuminated and lamps simulating the aerosol generators remained unlit. Opening any or all the switches caused the amber fire suppression fault LED to illuminate and the panel audible alarm to sound.

When the manual activation button was pressed and held for 1 second, with the four simulation lamp switches open (generator disconnected condition), the panel's audible alarm beeped and the red fire suppression activation lamp flashed for 5 seconds (spin-down period). After the 5-second spin-down time elapsed the panel's audible alarm sounded and the red activation LED illuminated constantly; the green power on LED light began to flash. The panel remained in this state until the detector loop mute/reset button was pressed and held in for 5 seconds.

The test was then repeated without resetting the panel. With the control panel in its activated state the simulation lamp switches were closed one at a time in the order the generators were connected on board *Resurgam*. During the test, no current flowed until the final switch was closed. The current caused all four test lamps to illuminate.

The sequence was repeated in the next test, but the switch for the lamp simulating the generator that did not discharge (generator 2) was left open. Again, current only flowed when the final switch was closed; the current caused the three connected test lamps to illuminate.

Two key findings stated in the HSE's electrical testing report[19] were:

- *With the FirePro protection panel*[20] *in the activated state connecting aerosol generators No.1, No.2 and No.3 had no effect, however subsequently connecting No.4 discharged all four aerosol generators.*
- *The roller-actuated microswitch connected to the audible-alarm located in the engine room was completely separate from, and had no effect on, the FirePro FPX103C protection panel and its associated aerosol generators.* [sic]

1.20.5 Carbon monoxide production – theoretical analysis

CO gas had been identified as a significant contributory factor in the fatality and the HSE carried out analysis to determine its source. The first step was to theoretically analyse CO production, which found that converting solid potassium nitrate into potassium carbonate in an aerosol form was a pyrotechnical reaction[21]. It was then possible to calculate the potential amount of CO produced when the reaction occurred.

The theoretical calculations were based on the stoichiometric[22] reaction of potassium nitrate with epoxy resin and assumed a hot stream at the generator's outlet. The calculations showed that, when enclosed in an FP5700 generator canister, the composition of potassium nitrate and epoxy resin would burn fuel-rich, leading to incomplete combustion and producing CO **(Annex D)**. It was possible

[19] HSE Report EM/20/15, 22 April 2020.

[20] Referred to in this report as the control panel.

[21] A pyrotechnical substance, as defined by UN Model Regulations Volume 1 Annex Part 2 Classification, is one designed to *produce an effect by heat, light, sound, gas or smoke or a combination of these as the result of non-detonative self-sustaining exothermic chemical reactions*.

[22] Concerned with, involving or having the exact proportions for a particular chemical reaction.

to generate 0.08kg to 0.13kg of CO for every 1kg of potassium nitrate, resulting in potential exposure to CO of between 160,000 and 290,000ppm in the concentrated, undiluted stream of aerosol from the generator's outlet.

1.20.6 Aerosol generator practical trials

On 1 September 2020, practical trials were carried out at the HSE Science and Research Centre to determine the combustion products and temperatures reached during the activation of a FirePro FP5700 aerosol generator. The combustion trials took place in a 27m^3 test cell with an array of thermocouples and gas sampling points at a series of distances from the aerosol generator **(Figure 20)**.

Three FP5700 generators, including the unit from *Resurgam* that had not fired, and two FP2000 generators were activated. Within the volume of the test cell, the three FP5700 generators created 9700ppm, 9900ppm and 11600ppm of CO gas, respectively. The FP2000 generators each produced 2206ppm of CO. The pyrotechnic loading density in the 27m^3 test cell measured 195g/m^3 for the FP5700 generators and 68.5g/m^3 for the FP2000 generators. The temperature of the stream of gases discharged from the FP5700 generators was also monitored and the following values were calculated against FirePro's documented temperature/distance conditions:

- L1, temperature not exceeding 400°C = 0.2m
- L2, temperature not exceeding 200°C = 1.0m
- L3, temperature not exceeding 75°C = 3.25m

These results demonstrated that, for each of the temperature points, the measured temperature values in the HSE trials exceeded the distance values given in FirePro's documentation **(Figure 12)**. The distance for the key temperature value of 75°C for the FP5700 generators was exceeded by 61% and measured 3.25m instead of 2.0m.

Image courtesy of Health and Safety Executive (www.hse.gov.uk)

Figure 20: Set up of HSE condensed aerosol generator test

Oxygen levels within the test cell were also monitored and fell to 19.1 percent by volume.

1.20.7 Health and Safety Executive technical review

Following its tests and trials, the HSE undertook a full technical review of FirePro's aerosol generator system, which considered the theoretical analysis, trial results and documentary evidence review. It concluded that:

- FirePro's description of the aerosol generators as non-pyrotechnical was inappropriate.
- The solid compound's composition was fuel-rich, with the potential to yield high levels of CO.
- FirePro's combustion testing was based on burning in the open air; such test results were not relevant to the combustion conditions in the enclosed FirePro unit. Regulatory bodies appeared to have accepted the manufacturer's claims that CO production was low.
- HSE testing had demonstrated that FirePro aerosol generators produce high concentrations of CO, that could significantly reduce the chance of escape.
- There should be prominent warning about the toxicity of fume products.
- Stream temperatures and the range of thermal effects appear to have been underestimated in the FirePro manuals.

1.20.8 Post-accident trials conducted by FirePro

In January and February 2021, FirePro commissioned its own trials to assess CO production[23]. These took place at the Albarubens SRL laboratory in Saronno, Italy and produced two reports. MAIB inspectors did not attend due to COVID-19 travel restrictions that were in place at the time.

In the first trial an FP5700 generator was discharged in a sealed space of 57m^3 volume to create the design concentration of 100g/m^3 of condensed aerosol. Fourier transform infrared spectroscopy sampling equipment measured a CO level of 2400ppm, which was evenly distributed in the space.

FirePro's second set of trials took place in a specially constructed test chamber with a 15.1m^3 internal volume. A fan mixed the atmosphere in the chamber with two CO sampling points. FP2000, FP1200 and FP500 aerosol generators were used in the trials. The FP2000 generators produced 3213ppm of CO at 132.5g/m^3 density and the FP1200 produced 2786ppm CO at 79.4g/m^3 density. The FP500 trial activated three F500 aerosol generators simultaneously in the sealed chamber, which resulted in 2776ppm of CO at 99g/m^3 density.

1.21 EFFECTS OF EXPOSURE TO CARBON MONOXIDE GAS

CO is a toxic, colourless, odourless, flammable gas produced as a by-product of combustion. When inhaled, CO binds with blood haemoglobin to form carboxyhaemoglobin that binds more efficiently to blood cells than oxygen, preventing the carriage of oxygen around the body.

[23] The temperature zones and length of discharge plume were not monitored in the FirePro trials.

The workplace short-term exposure limit[24] (15-minute reference period) for CO is 100ppm. **Table 1** describes the physiological effects of CO on humans at various concentration levels.

Carbon monoxide concentration (ppm)	Physiological effects
1500	Headache after 15 minutes, collapse after 30 minutes, death after 1 hour
2000	Headache after 10 minutes, collapse after 20 minutes, death after 45 minutes
3000	Maximum exposure for 5 minutes, danger of collapse in 10 minutes
6000	Headache and dizziness in 1 to 2 minutes, danger of death in 10 to 15 minutes
12800	Unconscious after 2 to 3 breaths, danger of death in 1 to 3 minutes

Table 1: Effects of carbon monoxide exposure (NORSOK Standard Z-013)

Blood toxicology describes blood carboxyhaemoglobin levels as a percentage, which is a function of both the concentration level and exposure time. **Table 2** describes the physiological effects of CO on humans based on their blood carboxyhaemoglobin levels. The apprentice engineer's blood carboxyhaemoglobin level was 31.7%.

Blood carboxyhaemoglobin levels (%)	Physiological effects
5-10	Visual light threshold slightly increased
10-20	Tightness across forehead and slight headache, breathlessness, abnormal vision
20-30	Headache, easily fatigued, impaired judgement, possible dizziness and dim vision, impaired manual dexterity
30-40	Severe headache with dizziness, nausea and vomiting
40-50	Headache, collapse, confusion, fainting on exertion
60-70	Unconsciousness, convulsions, respiratory failure and death
80+	Rapidly fatal

Table 2: Effects of carboxyhaemoglobin in blood[25]

[24] HSE publication EH40/2005 Work Place Exposure Limits - Containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended).

[25] Health and Safety Executive - SPC/Tech/OSD/30 - Indicative human vulnerability to hazardous agents, paragraphs 74 & 75.

1.22 HEALTH AND SAFETY MANAGEMENT

1.22.1 Overview

The primary piece of legislation covering occupational health and safety in the United Kingdom is the *Health and Safety at Work etc. Act 1974, as amended* (HSW Act). It is based on the principle that those who create risks to employees or others in the course of carrying out work activities are responsible for controlling those risks. An employer has a general duty to ensure, *so far as reasonably practicable*, the health and safety of its employees and anyone else who may be affected by their work activities.

Secondary legislation also applied under the HSW Act to the work being undertaken in *Resurgam*'s engine room. This included *The Management of Health and Safety at Work Regulations 1999*, which required employers to carry out risk assessments. Employers with five or more employees were required to record significant findings of their risk assessments.

1.22.2 W. Stevenson and Sons Limited

Stevenson operated two safety management systems, one for its vessels and crew and one for its shore activities. The company's managing director had overall responsibility for the safety management systems. The role of the health and safety manager was to coordinate health and safety activities on board Stevenson's vessels, in its workshops and on its premises. The health and safety manager was appointed the fleet's designated person responsible for:

- *Ensuring the safe operation of each company vessel.*
- *Providing a link between those in shore-based operations and vessels.*
- *Monitoring the safety and pollution aspects of the operation of each vessel.*
- *Ensuring adequate resources and shore-based support are applied as required.* [sic]

The shore workers safety induction manual provided an overview of the safety requirements and site rules that all workers must abide by. It instructed workers to refer to the company's Health & Safety Handbook and its site-specific risk assessments before work started. It also stated that:

> *All W. Stevenson & Sons Ltd employees and contractors must use the clocking card system when accessing and leaving site.* [sic]

The Ocean Engineering installation technicians were not given a site safety brief and did not clock in and out when accessing and leaving the vessel. A specific risk assessment was not completed for the installation of the FirePro system on board *Resurgam*.

1.22.3 Ocean Engineering (Fire) Limited

Ocean Engineering had documented safety guidance for its employees and safety was included in its induction training process. The documentation provided to MAIB during its investigation included a risk assessment for the installation of the FirePro system **(Figure 21)**. The FPX103C control panel was also used, under a different brand name, for Stat-X systems in marine applications. For Stat-X systems, the panel could support six aerosol generators.

RISK ASSESSMENT JSA NR:

		(L/hood) LIKELIHOOD OF OCCURRENCE				
		V.LOW	LOW	MED	HIGH	V.HIGH
(Sev) HAZARD	NEGLIGIBLE	LOW	LOW	LOW	LOW	MED
	MODERATE	LOW	LOW	LOW	MED	HIGH
	SERIOUS	LOW	LOW	MED	HIGH	HIGH
	MAJOR	LOW	MED	HIGH	HIGH	HIGH
	CATASTROPHIC	MED	HIGH	HIGH	HIGH	HIGH

(Risk) RISK RATING	
LOW	No immediate action required, Proceed with care.
MEDIUM	Hazard to be investigated in conjunction with line manager / supervisor with a view to reducing the risk
HIGH	Task must not be undertaken. Immediate action must be taken to eliminate the risk or substantially reduce the risk.

Location: | Job: INSTALL Firepro system

TASK	HAZARD	PERSONS AFFECTED	RISK			CONTROL MEASURES	RISK		
			L/hood	Sev	Risk	List those provided and required	L/hood	Sev	Risk
Disconnect existing panel Connect new panel	Electric shock	OE Electrician	M	M	L	Disconnect and tag out system	VL	M	L
Testing system	Alarms generated, Unwanted evacuation of vessel slips trips and falls	All personnel on vessel	M	S	M	Inform all personnel of likely alarms before commencing.	L	M	L
Testing system	Accidental discharge of system	All personnel on vessel	L	M	M	Ensure panel is fully reset before making system Live and connecting canisters.	L	M	L
All	Slips, trips and falls	All personnel on vessel	L	MO	L	Wear correct PPE Follow Manual Handling Procedures Good Housekeeping, Vessel Familiarisation	L	L	L

ASSESSOR(S):	SUPERVISOR'S SIGNATURE	DATE OF ASSES:	10/7/16
		DATE OF REVIEW	
Comments:		REVISION NUMBER: 1	TPB

Figure 21: FirePro control panel risk assessment

The FirePro risk assessment identified the accidental discharge of the system as a hazard and stated that all persons on board a vessel could be affected by such an event. Ocean Engineering assessed the likelihood of an accidental discharge to be low but the potential consequence to be major. The control measure stipulated in the risk assessment to mitigate the consequences of the hazard to medium and the risk rating from medium to low was: *Ensure nobody in protected space when system is being made live.*

Ocean Engineering had a generic method statement that detailed 19 steps for the installation[26] of an aerosol system **(Figure 22)**. The initial steps required the installers to report to an onsite supervisor and ensure the system was electrically isolated and tagged out before commencing work. Steps 9 to 17 stated that the installer should:

9. *Check continuity of wiring between cannisters and panel*
10. *Connect the panel to the power supply (without cannisters connected)*
11. *Connect cannisters*
12. *Check for faults*
13. *Disconnect cannisters*
14. *Carry out test of panel to ensure correct alarms are given*
15. *Carry out test of panel to ensure firing mechanisms are operational*
16. *Power down panel and reconnect cannisters*
17. *Power up panel and check for faults* [sic]

[26] The method statement refers to the term 'cannister'; for consistency, this report refers to 'aerosol generator' throughout.

Image courtesy of Ocean Engineering (www.oceanengineering.co.uk)

OCEAN ENGINEERING (FIRE) Ltd

METHOD STATEMENT

Date		Name of Installation	Aerosol	Representative	
Scope of Work	Installation of aerosol System				
Status of work area	Wheelhouse	Special Precautions			

Item		Frequency
1	Report to supervisor on arrival	BC
2	Isolate current system electrically and tag out before commencing if appropriate	BC
3	Disconnect existing panel if appropriate	
4	Remove from bulkhead	
5	Remove all cables and brackets not required for new installation	
6	Mount new panel on bulkhead	
7	Mount cannisters on deckhead within protected space	
8	Run cable between cannisters and panel if existing cable not present	
9	Check continuity of wiring between cannisters and panel	
10	Connect panel to power supply (without cannisters connected)	
11	Connect cannisters	
12	Check for faults	
13	Disconnect cannisters	
14	Carry out test of panel to ensure the correct alarms are given	OC
15	Carry out test of panel to ensure firing mechanisms are operational	
16	Power down panel and reconnect cannisters	
17	Power up panel and check for faults	
18	Leave panel in working order	
19	Report to vessel supervisor and inform him of the status of the system	
SYSTEM STATUS DURING WORKS		
Codes	D - Daily , BC-Before commencing work, ES -End of Shift ,OC On completion	

Prepared By: Sign .... Print .... Accepted By: Sign .... Print ....

Figure 22: Ocean Engineering's generic method statement for the installation of an aerosol system

On completing the work, step 19 of the method statement required the installers to report to the vessel supervisor and inform them of the status of the system.

Ocean Engineering also had a work instruction in place for working on board ships, the purpose of which was to ensure procedures for safe working were met. The work instruction required the installation supervisor to contact the relevant ship's officer or maintenance manager and discuss the scope of work to be carried out and the safety issues associated with it.

The installation technicians were unfamiliar with the risk assessment and did not take a copy of this or the method statement to *Resurgam*; neither did they discuss the documents with Stevenson's engineering manager or engineering project manager.

1.23 USE OF CONTRACTORS AND SUBCONTRACTORS

The HSE's leaflet INDG368 *Using contractors – a brief guide* helped employers understand their duties towards contractors and subcontractors and how best to discharge them. The guide directed companies to satisfy themselves that the contractors they chose could do the job safely and listed examples of questions to ask them, including:

- *What arrangements will you have for managing the work?*
- *Will you be using subcontractors?*
- *What is your recent health and safety performance?*

- *Do you have a written health and safety policy?*
- *Can you provide existing risk assessments for similar jobs?*
- *What qualifications, skills and experience do you have in this type of work?*
- *What health and safety information and training do you provide for your workers?*

It further suggested asking a potential contractor whether they would produce a safety method statement for the job to support safe working practices and minimise risks to health.

The guide also explained the importance of the contracting company meeting with the contractor *to consider any risks from each other's work that could affect the health and safety of the workforce or anyone else*. It went on to emphasise that measures to control risk and how the work would be managed and supervised must be agreed before the work started.

1.24 WORKING IN CONFINED SPACES

Although located within the structure of a ship, engine rooms and machinery spaces are usually ventilated and are not considered to be enclosed or confined spaces. The Confined Spaces Regulations 1997, applicable to shore-based workers and other workers when the vessel is not under the control of a master or their representative and is undergoing maintenance, defined a confined space as:

> *...any place, including any chamber, tank, vat, silo, pit, trench, pipe, sewer, flue, well or other similar space in which, by virtue of its enclosed nature, there arises a reasonably foreseeable specified risk.*

Guidance provided by the HSE in its L101 *Safe work in confined spaces – Confined Spaces Regulations 1997 – Approved Code of Practice (ACOP) and guidance*, added that:

> *...a confined space <u>must</u> have <u>both</u> of the following features:*
>
> *a) It must be a space which is substantially (though not always entirely) enclosed; and*
>
> *b) one or more of the specified risks must be present or reasonably foreseeable.*

The specified risks were:

> *a) serious injury to any person at work arising from a fire or explosion;*
>
> *b) without prejudice to paragraph (a)*
>
> *i. the loss of consciousness of any person at work arising from an increase in body temperature;*
>
> *ii. the loss of consciousness or asphyxiation of any person at work arising from gas, fume, vapour or the lack of oxygen;*
>
> *c) the drowning of any person at work arising from an increase in the level of liquid; or*
>
> *d) the asphyxiation of any person at work arising from a free flowing solid or the inability to reach a respirable environment due to entrapment by a free flowing solid.*

The ACOP also cautioned that:

> *a place not usually considered to be a confined space may become one if there is a change in the conditions inside or a change in the degree of enclosure or confinement, which may occur intermittently. For example, an enclosed space may be free of contaminants and have a safe level of oxygen but the work to be carried out in it may change this…*

The ACOP contained a flow chart **(Figure 23)** to help employers and employees identify if an area should be considered a confined space.

Regulation 4 of the Confined Spaces Regulations 1997 referred to working in confined spaces. The ACOP required the development and use of safe systems of work that considered elements such as supervision, communications, ventilation, access, emergencies and rescue.

Regulation 5 required that arrangements be put in place for the rescue of persons in the event of an emergency situation. The arrangements were to cover: rescue and resuscitation equipment, raising the alarm and rescue, safeguarding the rescuers, fire safety plant control, first aid, public emergency services and training.

Image courtesy of Health and Safety Executive L101

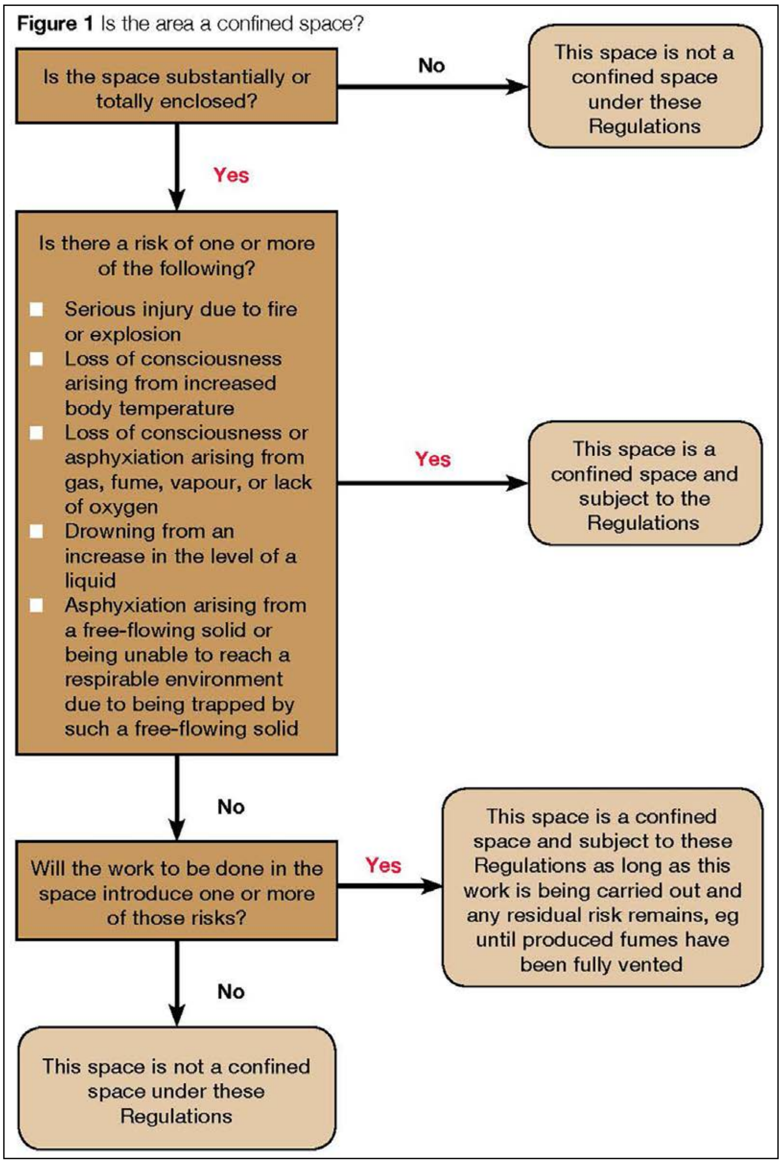

Figure 23: Approved Code of Practice flow chart: *is the area a confined space?*

1.25 PREVIOUS SIMILAR ACCIDENTS

1.25.1 Previous inadvertent discharges of fixed fire-extinguishing systems during Ocean Engineering (Fire) Limited servicing activities

Ocean Engineering had experienced several fixed fire-extinguishing system accidental discharges before the accident on board *Resurgam*. Earlier in 2019, the lead technician for the *Resurgam* installation accidentally activated a Stat-X aerosol generator while testing the system during a routine service on another vessel. He had forgotten to isolate one of the system's two generators before testing the activation process. The lead technician had experienced another accidental discharge of a condensed aerosol system but did not know why it happened. Neither incident had been reported to the MAIB.

On 23 August 2011, a shore-based service engineer was seriously injured on board the tug *SD Nimble* when six CO_2 cylinders were accidently discharged. The engineer was employed by Ocean Engineering and was testing components of the vessel's fixed CO_2 fire-extinguishing system.

The MAIB investigation report (MAIB report 23/2012[27]) found that the release of the CO_2 was caused by a failure to isolate the pilot lines from the system control cabinet. It concluded that this omission was likely to have been the result of an incorrect plan of action rather than a misidentification of the system's components.

The investigation also found that the service engineer's training was ineffective, and that the tug's crew and service engineers worked in isolation, which led to a hazardous situation. Ocean Engineering reported that it had fully implemented an MAIB recommendation to improve the monitoring of its service engineers and the adoption of safe systems of work.

1.25.2 Other reported incidents of discharges of in service FirePro systems following this accident

In September 2020, a FirePro system was activated without warning on a fish feed barge with people in a compartment. Everyone escaped without suffering any ill effects. The system was an automatic initiation system type, activated by the fire detection system. However, the fire detection system had not been activated before the incident occurred. Personnel were working in the compartment without operating the FirePro system isolation switch.

In November 2021, a FirePro system unintentionally activated on a twin-hulled workboat in one of the engine compartments, which was unmanned at the time of the release. An examination of the system by the manufacturer's service engineers found that no apparent reason could be determined for the activation of the FirePro system.

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[27] https://www.gov.uk/maib-reports/accidental-discharge-of-carbon-dioxide-when-testing-the-fixed-co2-fire-extinguishing-system-on-tug-sd-nimble-at-hm-naval-base-faslane-scotland-with-1-person-injured

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 OVERVIEW

Stevenson's apprentice engineer, Conor Moseley, died because he was working in *Resurgam*'s engine room when three condensed aerosol generators accidentally discharged during the installation of the vessel's FirePro fixed fire-extinguishing system. He collapsed during his attempt to escape from the engine room and succumbed to the adverse effects of the atmosphere created by the pyrotechnical release of the condensed aerosol before he could be rescued.

This section of the report will examine the causes and circumstances of the accidental discharge of three condensed aerosol generators during the installation of a FirePro fixed fire-extinguishing system on board *Resurgam*. The reasons why the apprentice engineer was unable to escape from the engine room and died will also be analysed. The underlying factors that contributed to both events will also be discussed.

2.3 THE ACCIDENTAL DISCHARGE OF THE AEROSOL GENERATORS

The Ocean Engineering technicians were in the latter stages of installing and commissioning *Resurgam*'s FirePro fire-extinguishing system when three of the system's four aerosol generators accidentally discharged into the engine room space. The system's fire protection control panel, PSU, pre-activation alarm warning beacons and electrical cabling were all in place, and the aerosol generators had been mounted in their brackets ready to be plugged into the firing circuit. Power had been supplied to the control panel and the protected space alarm warning beacons had been tested. The final steps were to check that the fire protection control panel identified faults in the fire suppression circuit and to conduct a system activation test using simulation lamps. This was not completed and the aerosol generators were instead plugged into the firing circuit. It is unknown why the simulation test was not completed. However, the installation technicians neither had the equipment to carry out the test or detailed installation guidance with them. It is possible that the test was not carried out through lack of experience and the disinclination to return to Ocean Engineering offices to collect the equipment.

The investigation's onsite examinations of the FirePro system installation on board *Resurgam* and subsequent laboratory tests found no electrical component or circuit connection faults. As a result, several hypotheses were explored to identify the most likely cause of the accidental discharge. These included the potential effects of induced currents from adjacent power cables and circuit earth faults.

One hypothesis considered the deliberate or inadvertent activation of the system by pressing the manual activation button after the power had been supplied to the fire protection control panel and before the generators had been connected to the firing circuit. To explore this and other possible scenarios, *Resurgam*'s installation was reconstructed at the HSE's Science and Research Centre using the as fitted electrical components and simulation lamps instead of aerosol generators. In-line switches were added to the circuit to simulate connecting and disconnecting the aerosol generators; the initial state was for the switches to be in the open position to simulate the aerosol generators disconnected from the circuit.

Power was applied to the fire protection control panel, the amber fault and green power LED illuminated and the internal sounder activated. The manual activation button was pressed and the control panel was activated after the spin-down delay time had elapsed. The red activation LED flashed for 5 seconds. The power to the fire suppression circuit was active.

The fire protection control panel remained in its activated state until the mute/reset button was pressed and held in for 5 seconds or the power to the fire protection panel was removed.

The simulation lamps were connected to the firing circuit by closing their associated switches in turn. The first three simulation lamps did not illuminate when they were connected to the firing circuit in the same sequence as the generators on board *Resurgam*. All four simulation lamps illuminated when the fourth light was connected. The trial validated the hypothesis; however, because the undischarged generator activated as designed during later trials it was unclear why only three generators discharged on board *Resurgam*. It is possible that this happened because the lead technician unplugged generator 4 before generator number 2 could be triggered **(Figure 24)**.

Previous procedural errors by Ocean Engineering technicians during the installation and maintenance of fixed fire-extinguishing systems had resulted in accidental system discharges [Section 1.25.1]. However, the investigation found no evidence to indicate that the manual activation button had been deliberately or accidentally pressed during the installation and commissioning processes on board *Resurgam*. Furthermore, had the control panel's manual activation button been pressed and not reset, the trials showed that: the control panel's amber fire suppression circuit fault and red activation LEDs would have been illuminated; the green power on LED would have been single flashing; and the internal audible alarm would have sounded in the control panel in the wheelhouse. This was inconsistent with the accounts given; the installers had tested the pre-activation alarm but this was independent of the control panel's activation and fault detection circuits.

There was no one reported to be in the wheelhouse immediately before or during the accident; both installation technicians were in the engine room space when the generators began to discharge and therefore no one saw which LEDs were illuminated in the moments before the fourth generator was connected. The post-accident trials suggested that the most likely cause of the discharge was the inadvertent or deliberate activation of the system's firing sequence when the disconnected generators were subsequently connected during the installation process. Regardless of the direct cause, it was evident that *Resurgam*'s installation design and system commissioning processes differed from those prescribed by FirePro and would have contributed to the accidental discharge.

2.4 EVACUATION OF THE ENGINE ROOM FOLLOWING THE ACCIDENTAL DISCHARGE

Resurgam had one escape route from its engine room, which was via the compartment's normal access ladder located on the starboard side of the main engine. When the generators started to discharge, the Stevenson engineers were

For illustrative purposes only: not to scale

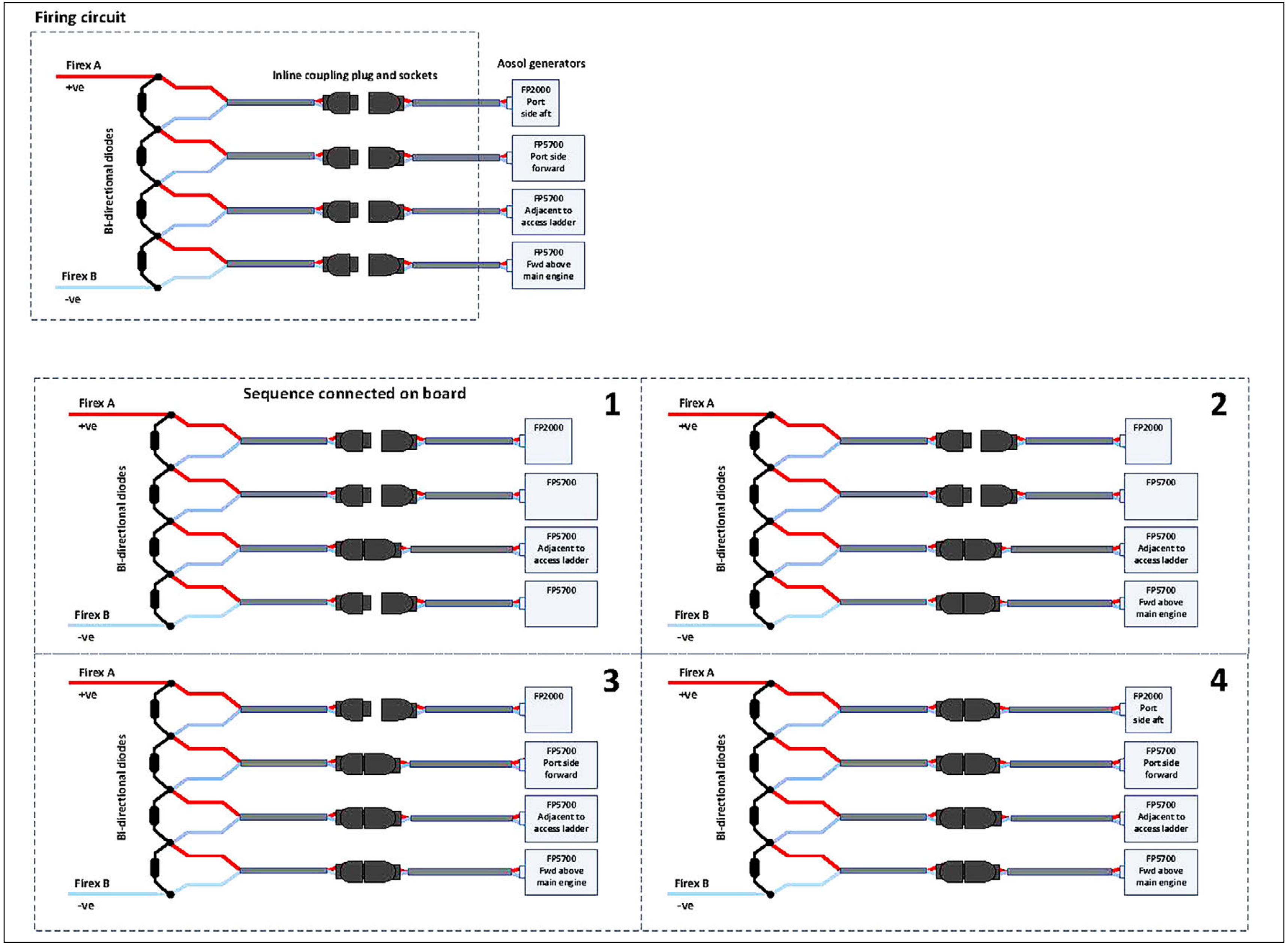

Figure 24: Sequence the FirePro generators were connected to the firing circuit during the installation

working on the port side of the engine, the lead installation technician was directly aft of them, and the trainee technician was in the lobby area at the top of the access ladder.

When the lead technician heard the first generator start to discharge, he knew what was about to happen and immediately jumped over the engine gearbox and climbed up the access ladder. Both he and the trainee technician escaped onto the open deck without inhaling significant amounts of the FirePro condensed aerosol. The Stevenson engineers had little or no understanding of what was going on and had a further distance to cover to reach the access ladder.

The engine room space filled rapidly with hot condensed aerosol particles and pyrotechnic gases when the system activated. The aerosol was opaque and reduced visibility within the space to almost zero, which would have disorientated the engineers and adversely affected their ability to escape. Both Stevenson engineers inhaled significant amounts of aerosol particles and hot gases as they made their way to the access ladder, which ultimately led to the collapse and death of the apprentice engineer.

Given that the lead technician heard a generator activating behind him when he plugged in generator 4, it is likely that generator 3 activated first, followed by generator 4 then generator 1 adjacent to the access ladder. The location of the Stevenson engineers when working on the engine exhaust system placed them less than 2m from two of the discharging aerosol generator outlets on the port side of the engine room. Their escape route forward of the main engine took them into the direct path of the discharging FP5700 generator 1 adjacent to the access ladder on the starboard side of the engine room **(Figure 25)**.

It is possible that the apprentice engineer was closest to the generator discharges on the port side of the engine room when the system was activated. It is likely that his face was in the direct path of the discharging generator, mounted just under 1m from the access ladder, immediately before he collapsed. At this distance, and based on the results of the HSE trials, the discharge stream temperature would have been about 120°C and would account for his severe inhalation injuries.

Close proximity to the discharging aerosol generators for even a brief period would result in exposure to high levels of CO. Given that the apprentice was unconscious but breathing when his workmates first attempted to rescue him, it is considered most likely that he was initially exposed to a concentration of CO in excess of 12800ppm **(Table 1)** when inhaling the discharging condensed aerosol stream. The apprentice would have been exposed to sustained lower levels of CO for about 20 minutes afterwards, probably around 2400ppm[28]. He could not be resuscitated when he was removed from the space about 20 minutes later.

The apprentice collapsed at the bottom of the ladder because he was overcome by the effects of inhaling large quantities of hot condensed aerosol particles and pyrotechnic combustion gases. The postmortem toxicology report stated that his carboxyhaemoglobin levels were high but this alone would not have been fatal. It was the combination of severe inhalation injuries, CO poisoning and reduced oxygen levels that caused his death. The Stevenson engineer, who made a determined attempt to guide the apprentice out of the space, suffered a reaction following his

[28] The closest comparison with the accident was FirePro's post-accident test of an FP5700 generator, which created a sealed space CO level of 2400ppm and 100g/m³ aerosol density.

exposure and was immobilised for a short period after escaping onto the open deck. It is fortunate that he did not also succumb within the protected space and fail to escape.

For illustrative purposes only: not to scale

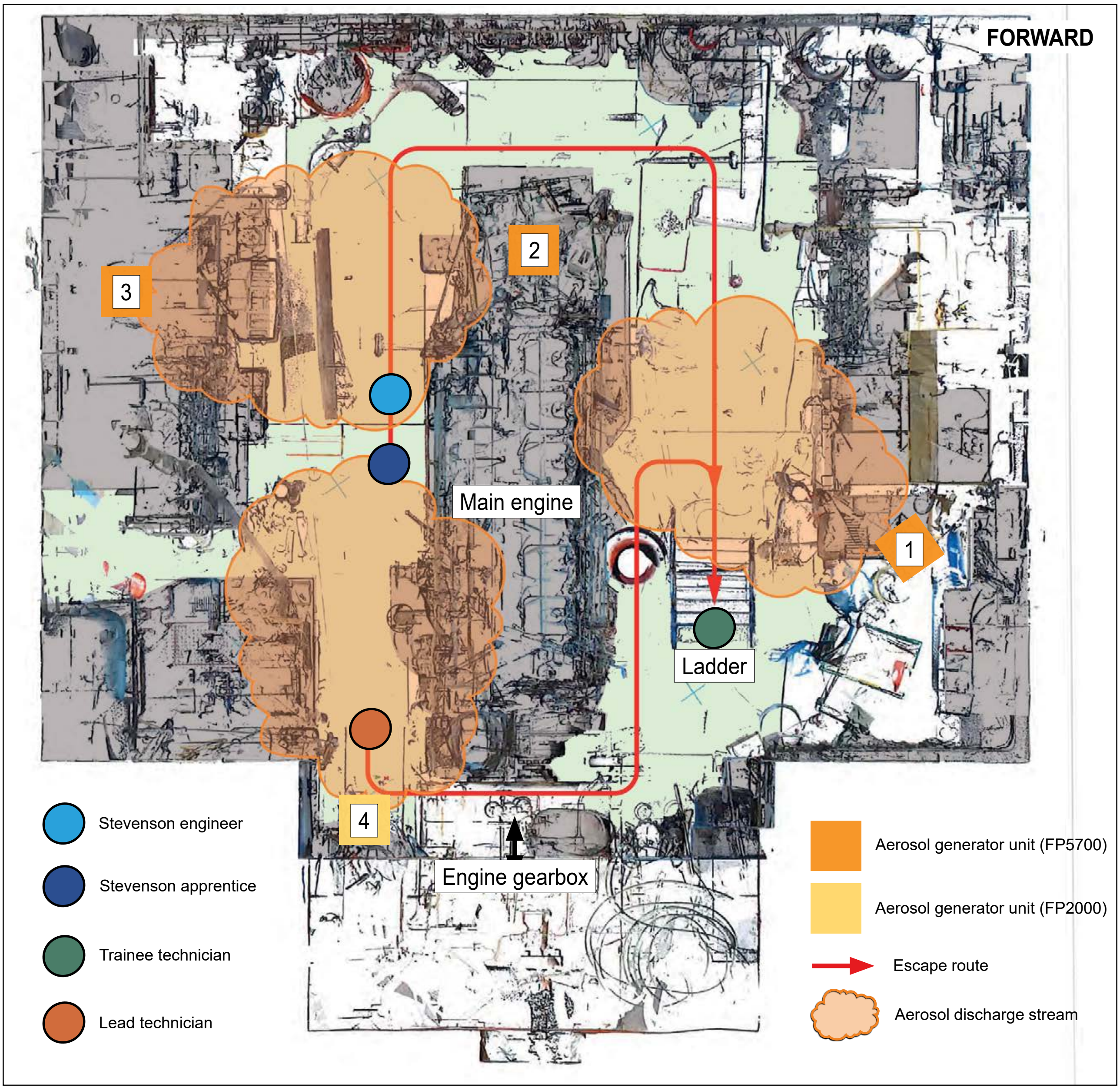

Figure 25: Escape route through aerosol discharge streams

2.5 EMERGENCY RESPONSE

The first responders to the emergency were Stevenson employees working on board another vessel, who arrived to investigate the white aerosol cloud emanating from *Resurgam*'s engine room. Their initial actions, and those of the Stevenson health and safety manager, were brave and well-intentioned but unsuccessful in rescuing the apprentice engineer. The first responders put themselves in danger by entering the enclosed engine room without respiratory protection and made multiple entries despite being driven back by the noxious atmosphere. The situation was only brought under control when the emergency services arrived at the scene and fire and rescue service officers employed breathing apparatus to recover the apprentice engineer from the engine room.

The personnel working on board *Resurgam* and those responsible for the management of safety during the vessel's maintenance period had not anticipated the likelihood of an accidental discharge of the FirePro system and did not understand the potential consequences of such an event. The Ocean Engineering technicians thought that discharged aerosol was non-hazardous, which might explain the 10-minute delay in calling the emergency services.

The first people to respond did have access to a compressed air breathing apparatus set, which was found discarded on *Resurgam*'s open deck. However, none of them had been trained in the use of compressed air breathing apparatus nor had any knowledge of how to operate the set. As a result, the breathing apparatus set was not used.

Those working on board *Resurgam* were not fully aware of the risks associated with an accidental discharge of the FirePro system and had not been briefed on the initial actions to take in the event of an emergency. They were therefore unprepared to respond to the situation. The apprentice engineer was unconscious but still breathing when the first attempts were made to rescue him. It is unknown whether he could have survived if the emergency services had been alerted earlier, but his chances of survival would have significantly increased had the initial rescue attempts been successful.

2.6 HAZARD AWARENESS

In the process of acquiring technical approvals for its product, FirePro sought to identify, through testing and laboratory evaluation, the hazards associated with both the solid compound and the aerosol it created on ignition. The tests focused on the condensed aerosol's respirable particles when evenly distributed at the design density. Although the results varied dependent on the circumstances of the trial, the consensus was that the solid compound was largely harmless and that the aerosol's by-products were primarily CO_2, water vapour and low levels of other, harmless, gases. Based on this evidence, FirePro marketed the solid compound as harmless and the post-combustion aerosol as safe to breathe, with the oxygen content of the compartment largely unaffected. This assessment of low risk levels associated with the product was reflected in FirePro's MSDS, which was reproduced in its entirety as part of Ocean Engineering's local documentation. However, the HSE's post-accident analysis demonstrated that there was a significant CO hazard, particularly in enclosed environments where CO production was greater than found in open air trials. It also identified that the discharge of the aerosol depleted the oxygen levels within the protected space.

The inadvertent or accidental discharge of FirePro and other condensed aerosol fixed fire-extinguishing systems had occurred on other installations. It was also widely recognised that the likelihood of this happening was highest during initial installation and system maintenance. However, based largely on FirePro's assessment of the research it commissioned and the information provided in its MSDS, the hazards associated with an accidental discharge into a protected space that was occupied by people was limited to the loss of visibility and the effects of heat and noise generated during the combustion process.

Despite FirePro's marketing and safety assessments, several external organisations, including the MCA and USCG, were aware that the pyrotechnic combustion of the solid compound generated significant levels of CO and that the aerosol particles should be treated as a respirable dust. Although the MCA Certificate of Inspection and Tests referred to the aerosol forming process as non-pyrotechnic and repeated many of the assurances given by FirePro in its guidance documents, unlike other marine certifying authorities, the agency only approved the use of the FirePro system in normally unoccupied spaces. Furthermore, the MCA's MSIS 12 guidance to its surveyors specifically warned of the potential inhalation hazards presented by the aerosol and made particular reference to the production of high levels of CO. However, the hazards listed in MSIS 12 were not listed in section 2 of the Certificate of Inspection and Tests and there was no mention of CO in the certificate.

In describing the aerosol generators as non-pyrotechnic, FirePro alluded to the fact that the transformation of the solid compound to a gaseous aerosol was not an exothermic reaction. This led to the conclusion that CO was not a by-product caused by the aerosol generator's activation. The solid compound's ignition and combustion process required oxygen to sustain it; CO gas is produced if the available oxygen is insufficient to fully support the solid compound's combustion.

FirePro was aware of the observations made and warnings given by the MCA to its surveyors several years before the *Resurgam* accident. It was apparent that the manufacturer applied a degree of selective bias when it chose to omit the safety messages published in MSIS 12 from the excerpts used in the marine annex of its user manual. Consequently, installers of the FirePro system, such as Ocean Engineering, may not have been aware of all the actual hazards posed by the activated aerosol.

The FirePro condensed aerosol system can undoubtedly provide effective fire-extinguishing capability; however, this accident highlights the potentially fatal hazards of being exposed to the discharge from an aerosol generator, especially at close range. The apprentice engineer almost certainly inhaled the full products of combustion during his attempt to escape, and the atmosphere within *Resurgam*'s engine room was unable to support life for many minutes after the discharge was complete. The dangers of inhaling the condensed aerosol particles and hot gases generated during discharge are clear and should be highlighted in the FirePro MSDS and guidance documents. Without easy access to this information, installers, service technicians, ship operators and crew cannot properly assess the risk and put appropriate control measures in place.

2.7 INSTALLATION STANDARDS

2.7.1 System installation

The number of FirePro aerosol generators required for *Resurgam*'s fixed fire-extinguishing system was calculated by Ocean Engineering based on the dimensions of the spaces to be protected. For the FirePro system to extinguish a machinery space fire, the condensed aerosol had to achieve the predetermined density of 100g/m^3. This was done by calculating the mass of solid compound needed to produce the required aerosol density and then choosing the appropriate number and size of aerosol generators. The number of aerosol generators that could be used on board *Resurgam* was limited to four, which was the maximum number of generators the FPX103C fire protection control panel was designed to activate.

Once the dimensions of *Resurgam*'s engine room spaces had been measured and the net volume calculated, Ocean Engineering's operations director used FirePro's planning spreadsheet to determine that 17940.00g of solid compound was needed to protect the space. The only way to achieve this using the FPX103C control panel was to install one FP2000 and three FP5700 aerosol generators. However, this configuration was flawed from the outset given the dimensions of the engine room spaces. Warnings on the calculation spreadsheet not to use the FP5700 generator because the height of the space was insufficient were ignored and they were not visible in the extracts of the spreadsheet included in *Resurgam*'s FirePro installation manual.

The protected space was split over two decks, as the engine room spaces could not be isolated from each other. The main engine machinery space, which constituted 65% of the net volume, was on the lower deck level and the lobby area and winch room were on the deck above. However, all four generators were mounted in the main engine space. This would almost certainly have resulted in the accumulation of much higher concentrations of aerosol particles and combustion gases than intended in the main engine space. It would also have reduced the likelihood of design concentrations being reached in the lobby area and winch room.

The stated discharge stream length of the FP5700 aerosol generator was 8m and, under internationally set discharge temperature limits, the outlet should have been mounted no closer than 2m from escape routes and areas where people might be present. The discharge stream length of the FP2000 aerosol generator was 3.5m and the outlet should have been mounted no closer than 1.5m from areas where people might be present. These limits were not met on board *Resurgam* and all four generators were mounted close to areas where people could be expected to occupy and near floor plates that would be used as an emergency escape route. Two of the generator outlets were pointing directly toward the area where the Stevenson engineers were working and one was positioned at head height level less than 1m away from the floor plate area at the bottom of the engine room's main access ladder, which was the only escape route.

The positions of the generator units contravened the discharge temperature/distance rules stipulated by the IMO and set out in several marine approval authority certificates for escape routes and areas that people might occupy. The inappropriate positioning of the generator outlets might have been the consequence of the installers' lack of knowledge; however, it would almost certainly have been influenced by the size of the compartment and the space available to mount them.

Other system installation anomalies were identified during the investigation. These included:

- The use of the FPX103C control panel with its DIP switches set in automatic mode with a 5-second spin-down delay.
- The use of inline coupling plugs to connect the aerosol generators to the firing circuit.
- The use of non-shielded cabling and a combination of three-core and two-core cables in the firing circuit.

Resurgam's fixed fire-extinguishing system was designed for manual activation only. The MCA's Certificate of Inspection and Tests listed the FPX103C and FPX104C control panels as suitable for use in marine applications. The MCA's certificate explained that the FPX103C control panel was suitable for both manual and automatic activation systems, and that the FPX104C control panel was for manual activation systems only. Ocean Engineering used the FPX103C control panel, but the post-accident examination of the control panel revealed that the DIP switches were set to an automatic mode position rather than the manual mode position. The rationale for this decision is unknown. At the time of the activation of the aerosol generators the full installation had not been completed and the system was not fully commissioned. It is possible that the DIP switches may have been set to the manual position at the time of the accident. It is also possible that the 5-second delay was intended to provide an additional delay between opening the cover of the control panel and the activation of the fire suppressant system. If this was the case, the decision to set a 5-second DIP switch delay was illogical; the condition of most marine approvals was for a minimum activation delay of 20 seconds for an automatic system.

Ocean Engineering's use of inline coupling sockets to plug the aerosol generators into the firing circuit appeared to be a local arrangement that made it easier to connect and disconnect generators. However, it also made it possible to connect and disconnect the generators to the control panel with the power supply turned on.

The electrical cables used for the FirePro system on board *Resurgam* did not comply with the standards set out in FirePro's guidance specifications and varied randomly between two-core and three-core cabling. Post-accident examinations of the electrical circuits concluded that these anomalies were not critical to the system's operation; however, they were indicative of a lack of planning and attention to detail.

FirePro had approved Ocean Engineering to install and service its fire-extinguishing systems. As such, it was expected to design bespoke systems for a wide range of vessels. Ocean Engineering was an established company with a third party approved quality management system. However, it did not produce detailed installation plans, accurate wiring drawings or a vessel-specific instruction and guidance manual that accurately reflected the system installation on board *Resurgam*. Furthermore, safety critical decisions relating to the location of aerosol generators were left to the judgement of the installation technicians while on site. Neither FirePro nor FirePro UK were required to have procedures in place to scrutinise and approve its authorised installers' design calculations and installation plans. This function fell to the MCA as the approval authority for coded vessels.

Resurgam's fixed fire-extinguishing system installation did not meet the requirements and standards set by the IMO, marine certifying authorities or the equipment manufacturer. Given the size and layout of the protected space on board *Resurgam*, it is questionable whether a safe and compliant FirePro system could have been designed for the fishing vessel. Regardless, it is evident that the design of these systems can be very complex and it is therefore essential that detailed installation design plans are produced. These plans need to be properly scrutinised for compliance with the manufacturer's guidance and other appropriate standards before being submitted for approval to the MCA or other certifying authorities.

2.7.2 Installation and commissioning process on board *Resurgam*

Ocean Engineering did not produce a comprehensive risk assessment or method statement for the installation, commissioning and maintenance of the FirePro system, and a specific risk assessment had not been carried out for the *Resurgam* project. However, a risk assessment for the installation of a FirePro system and a generic method statement for the installation of condensed aerosol systems did exist.

The two Ocean Engineering technicians were not involved in the planning and design of *Resurgam*'s fire-extinguishing system and had not been given Ocean Engineering's locally produced documentation or the equipment manufacturer's installation and commissioning instructions. Because of this, the lead technician had to use his personal judgement to position the control panel in the wheelhouse and aerosol generators in the engine room. He also had to rely on his previous experience to commission the system.

To check the function of the fire suppression circuit fault alarm, the lead technician powered up the system with the aerosol generators disconnected. This caused the fire suppression fault LED on the fire protection panel to illuminate and the panel's audible alarm to sound. The aim of connecting the generators with the power still on was to clear the alarm and therefore prove the panel's fault identification function. This process was not in accordance with FirePro guidance **(Annex A)**, which stated that the fault test should be conducted using simulation lamps and that the power to the system should be isolated whenever connecting and disconnecting the generators. However, the steps taken by the technicians did broadly follow those set out in Ocean Engineering's generic aerosol system installation method statement.

The lead technician had been directly involved in two previous condensed aerosol generator accidental discharges and was aware of the risk of this event occurring during the installation, commissioning and maintenance of the system. Although he was unaware of the potentially fatal consequences of an accidental discharge, when he heard the first generator begin to ignite he knew the engine room spaces were about to fill rapidly with dense aerosol particles and immediately ran to the escape ladder. This hazard was recognised in the FirePro risk assessment and the control measure identified was the removal of all personnel from the protected spaces. Despite the lack of awareness of the respirable hazards posed by the aerosol discharge, the implementation of this control measure would have prevented the loss of life.

2.8 MARITIME AND COASTGUARD AGENCY OVERSIGHT

As the certifying authority for fishing vessels less than 24m in length, the MCA approved the FirePro system for use in fishing vessel engine rooms and maintained oversight of the planning and installation process. A critical component of the approval process to fit the FirePro system was the requirement to notify MCA of the intent to install the system and submit plans ahead of the installation. The installation also had to be completed to the satisfaction of an MCA surveyor. The MCA certificate of approval required that the installation was in line with the manufacturer's manual.

Stevenson advised the MCA of its intent to install a FirePro system three working days before Ocean Engineering started the FirePro installation, but Ocean Engineering did not submit any plans or drawings for approval. This omission and the short timescale before Ocean Engineering began the installation denied the MCA the opportunity to scrutinise and challenge Ocean Engineering's flawed system design. The MCA, on receiving notification of the intention to install a FirePro system, did not prompt Stevenson to submit plans for prior approval before the installation work commenced.

The MCA's MSIS 12 contained important information to aid its surveyors when inspecting condensed aerosol systems. However, the hazards listed in MSIS 12 were not listed in section 2 of the Certificate of Inspection and Tests.

2.9 INSTALLATION STANDARDS

Without a national or international training standard for the installation of condensed aerosol fire-extinguishing systems on coded marine vessels, it falls to employers to ensure training standards are developed and maintained for their technicians.

Ocean Engineering's operations director managed the company's training programme, which was not based on agreed competencies; instead, trainees doubled-up with more experienced technicians before a verbal assessment that relied on the operations director's knowledge of the FirePro system. Moreover, the core competency of *Resurgam*'s lead technician was that of an electrician. This installation required specific knowledge of the aerosol generators' characteristics and fitting requirements. Without general arrangement and electrical drawings, supported by a detailed method statement and risk analysis, Ocean Engineering's director could not give assurance to either Stevenson, as the operator, or the MCA, as the approving authority, that the FirePro system was installed in accordance with the manufacturer's design intent.

As a comparative analysis, installers of land-based FirePro systems were required to complete a nationally-accredited training programme through either BAFE or LPCB. Such schemes added a layer of assurance that the installers met the recognised competence standard required by FirePro for its accredited installation companies.

Correct installation of critical safety systems such as the FirePro aerosol generators required a consistent and high standard of competence. Without a national or internationally agreed standard, consistency of safe installation could not be assured for coded marine vessels.

2.10 WORKING WITH CONTRACTORS AND SAFE SYSTEMS OF WORK

Ocean Engineering did not share its generic installation risk assessment or method statement with Stevenson. Stevenson's engineering manager and engineering project manager were familiar with Ocean Engineering but did not hold safety discussions with its installation technicians or request sight of its risk assessments or method statement.

A method statement describes in a logical sequence exactly how a job is to be carried out in a safe manner and without risks to health. An associated risk assessment should consider all the risks identified and the measures needed to control those risks. This allows the job to be properly planned and resourced. Ocean Engineering had not prepared a specific risk assessment or method statement for the installation and commissioning of the FirePro system on *Resurgam*, nor did its technicians understand the risks associated with installing the system. In this case, a discussion between Stevenson and Ocean Engineering about the risks and control measures for the installation of the FirePro system might have ensured that no personnel were in the engine room when the generators were connected, and when power was first applied to the system.

Similarly, discussions between Stevenson and Ocean Engineering should have alerted all parties to the need to put in place a capability to rescue people from the space if the installers intended to connect and disconnect the aerosol generators with the power on. Although *Resurgam*'s engine room was substantially enclosed it was not considered a confined space under normal circumstances because it had adequate ventilation. However, the work being undertaken by Ocean Engineering presented the risk of introducing one of the specified risks listed in the Confined Spaces Regulations 1997 i.e. *the loss of consciousness or asphyxiation of any person at work arising from gas, fume, vapour or the lack of oxygen.* The controls required under such circumstances would again have increased the levels of safety applied and improved the workers' preparedness to deal with any accidental discharge.

Although Stevenson had a written policy and procedure for contractors working on its site, it did not have a robust formal process for the safety management and control of contractors working on its vessels; instead, reliance was placed on the health and safety manager or the engineering project manager talking to the contractors to ascertain what work was being undertaken and whether Stevenson needed to provide resources. There was no process to deconflict work in hazardous situations or identify risks. This accident demonstrates the importance that should always be placed on the sharing of safety information and understanding and agreeing safe systems of work to ensure that the opportunities to avoid serious accidents such as this are not lost.

2.11 NORMALLY OCCUPIED AND NORMALLY UNOCCUPIED SPACES

Some marine certifying authorities had approved the FirePro and other condensed aerosol systems for use in normally occupied spaces. However, based on its assessment of the hazards presented during discharge, particularly the production of CO, the MCA only approved the system for use in normally unoccupied spaces on coded vessels.

The definition that the MCA used for normally unoccupied spaces differed from that used by other bodies; it is arguable whether *Resurgam*'s engine room, winch room and lobby area met the criteria for a normally unoccupied space, especially during maintenance periods and refits when these spaces could be continually occupied.

The FirePro system, along with other condensed aerosols, is very effective at extinguishing fires and almost certainly less hazardous to life than a CO_2 system when discharged. However, this accident demonstrated the potentially fatal consequences of people being in a protected space during a release of this condensed aerosol system. It is therefore important that controls are put in place to minimise the risk to personnel from inadvertent activation of a FirePro system.

SECTION 3 – CONCLUSIONS

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

1. Stevenson's apprentice engineer, Conor Moseley, died because he was working in *Resurgam*'s engine room when three condensed aerosol generators accidentally discharged during the installation of the vessel's FirePro fixed fire-extinguishing system. [2.2]

2. The system was inadvertently activated because the FirePro condensed aerosol generators were connected to a live electrical system, initiating combustion. The manufacturer's design and installation procedures were not followed, which would have contributed to the accidental discharge. [2.3]

3. The condensed aerosol generators discharged accidentally because the system's fire protection control panel was in its activated state when the last generator was connected to the firing circuit. It could not be determined when or how the control panel was activated during the installation process. [2.3]

4. The apprentice engineer collapsed at the bottom of the ladder during his attempt to escape from the engine room because he was overcome by the effects of inhaling large quantities of hot condensed aerosol particles and pyrotechnic combustion gases. The combustion gases included high levels of CO, which along with the severe inhalation injuries contributed to his death. The other Stevenson engineer, who tried to help the apprentice engineer escape, suffered from the effects of exposure to the aerosol and was fortunate to escape. [2.4]

5. Those on board *Resurgam* and the first responders to the accident were unaware of the respiratory hazards posed by the aerosol and were therefore not properly prepared to deal with the emergency situation. [2.5]

6. The apprentice engineer's chances of survival would have significantly increased if the initial rescue attempts had been successful. [2.5]

7. Despite being aware that the MCA's guidance to surveyors warned about the potential inhalation hazards and high levels of CO associated with the aerosol, FirePro's information and guidance documents and its MSDS did not accurately represent the hazards posed by the condensed aerosol particles and combustion gases produced during generator discharge. [2.6]

8. *Resurgam*'s fixed fire-extinguishing system installation did not meet the safety criteria set by the IMO, marine certifying authorities and the equipment manufacturer. In particular, the aerosol generator outlets were located too close to areas that people could be expected to occupy and to the escape route [2.7.1]

9. Given the size and layout of the spaces to be protected by the fixed fire-extinguishing system on board *Resurgam*, it is questionable whether a safe and compliant FirePro system could have been designed for the fishing vessel's main machinery space. [2.7.1]

10. Ocean Engineering had not produced detailed installation plans, accurate wiring drawings or a vessel-specific instruction and guidance manual before the installation of the FirePro system. Installations can be complex and plans need to be properly scrutinised and approved by the equipment manufacturer before they are sent to the MCA or other certifying authorities for approval [2.7.1]

11. The system installation and its commissioning process were not carried out in accordance with the manufacturer's guidance. This was because the installation technicians did not have access to clear plans and instructions and the lead technician relied on his previous experience and personal judgement while positioning the system components. [2.7.2]

12. An opportunity to identify flaws in Ocean Engineering's system design was missed because the plans were not submitted to the MCA for approval. [2.8]

13. Correct installation of critical safety systems such as the FirePro aerosol generators required a consistent and high standard of competence. Without a national or internationally agreed standard, consistency of safe installation could not be assured for coded marine vessels. [2.9]

14. Ocean Engineering did not share its generic installation risk assessment and method statement with Stevenson's engineering project manager. Stevenson did not hold safety discussions with Ocean Engineering's installation technicians or request sight of its risk assessment or method statement. This, combined with Ocean Engineering not properly understanding the risks, meant an opportunity to ensure the engine room was evacuated before applying power to the system and connecting the aerosol generators was lost. [2.10]

15. Although Stevenson had a written policy and procedure for contractors working on its site, it did not have a robust formal process in place for the safety management and control of contractors working on its vessels. [2.10]

16. This accident has demonstrated the potentially fatal consequences of being in a protected space during a release of a FirePro system and the need for it to be treated in a similar manner to CO_2 fire suppression systems during installation and servicing. [2.11]

3.2 OTHER SAFETY ISSUES NOT DIRECTLY CONTRIBUTING TO THE ACCIDENT

Neither FirePro nor FirePro UK had procedures in place to scrutinise and approve its authorised installers' design calculations and installation plans as FirePro and FirePro UK could not approve installations on marine vessels. [2.7.1]

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

The MCA's MSIS 12 contained important information to aid its surveyors when inspecting condensed aerosol systems. However, the hazards listed in MSIS 12, including the generation of CO, were not listed in section 2 of the Certificate of Inspection and Tests. [2.8]

SECTION 4 – ACTION TAKEN

4.1 MAIB ACTIONS

The **MAIB** has:

- Issued a safety bulletin **(Annex E)** that warned of the inadvertent discharge of a FirePro condensed aerosol system and included a recommendation (S2020/144) to FirePro UK to issue a safety alert to the owner/operators of vessels fitted with its systems and its network of marine installation/maintenance engineers, highlighting the circumstances of this accident and advising them of appropriate measures to take to reduce the risk of exposure to fire-extinguishing particles.
- Issued a safety flyer to the fishing industry **(Annex F)**.

4.2 ACTIONS TAKEN BY OTHER ORGANISATIONS

FirePro UK has:

- Issued a safety alert to the owner/operators of vessels fitted with its systems and its network of marine installation/maintenance engineers highlighting the circumstances of this accident and advising them of appropriate measures to take to reduce the risk of exposure to fire-extinguishing particles.
- Issued a safety bulletin to all marine distributors of the FirePro system highlighting the requirement to provide a safe system of work when installing the FirePro system. This is to include method statements, risk assessments and the requirements for working in confined spaces.
- Issued basic guidance information in the form of a quick start guide highlighting the requirements for designing, installing and commissioning of the system, including periodical inspection and testing.

FirePro has:

- Undertaken qualitative and quantitative assessment of the by-products of FirePro aerosol generators in a total flooding application.
- Updated its Annex 2 Marine Manual for small vessels to include a more comprehensive description of the installation of FirePro systems, including maintenance and inspection.
- Issued a safety bulletin worldwide to all master distributors highlighting the dangers of exposure to the suppressant agent as it is discharged from the aerosol generator and the requirement to follow the FirePro installation information.

The **Maritime and Coastguard Agency** has:

- Issued two safety bulletins (SBI022 & SBI023) highlighting the hazards of unintentional activation of fixed aerosol fire suppression systems and the requirement to ensure the wiring system is in accordance with the manufacturer's requirements.
- Included a statement in the current Certificate of Inspection and Test for FirePro that warns about CO generation:

  9.7 Aerosol Fire Suppression systems may in certain circumstances carry the risk of producing potentially fatal quantities of Carbon Monoxide (CO) as the system activates and produces the aerosol. Sufficient care should be taken during installation and maintenance to ensure the risk of exposure is as low as reasonably practicable and deliberate activation must only occur when the space is confirmed to be evacuated. [sic]

- Published Marine Guidance Note (MGN) 659 (M+F) *Amendment 1 The Merchant Shipping and Fishing Vessels (Entry into Enclosed Spaces) Regulations 2022*. This MGN supports the interpretation of the underpinning regulations set out in T*he Merchant Shipping and Fishing Vessels (Entry into Enclosed Spaces) Regulations 2022* (Statutory Instrument 2022 number 96) which are applicable to UK vessels, including non-SOLAS vessels and fishing vessels.

SECTION 5 – RECOMMENDATIONS

The **Maritime and Coastguard Agency** is recommended to:

2023/116 Take steps to improve the standard of installation of safety critical fire-extinguishing systems in vessels operating under codes of practice (i.e. non-SOLAS vessels) to ensure that, specifically:

- Vessel owners are aware of the obligation to notify the Maritime and Coastguard Agency in advance of the installation, in order to obtain pre-installation approval.
- Equipment installation is undertaken in accordance with manufacturers' instructions and the relevant statutory requirements.
- In collaboration with industry stakeholders, introduce a competency standard for the installers of systems on vessels.
- The information provided in the Marine Survey Instructions for the Guidance of Surveyors for Fire Protection Arrangements (MSIS 12) and the Certificate of Inspections and Tests is consistent.

FirePro is recommended to:

2023/117 Undertake a specific risk assessment for the installation and operation of each of its fire-extinguishing systems to identify and mitigate all of the associated hazards, including those identified as part of this investigation, to a level that is considered as low as reasonably practicable.

2023/118 Review its safety-related documentation for its fire-extinguishing systems (including, but not limited to, the installation and operational guidance and material safety data sheet) to:

- Incorporate the hazards identified as part of this investigation, specifically those associated with carbon monoxide generation and risk of inhalation injury, and the required control measures.

W. Stevenson & Sons Limited is recommended to:

2023/119 Update its safety management system for vessels alongside, specifically to include the control and safe management of contractors, including the provision of rescue plans for people working on board.

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

Marine Accident Report