Modelling of the HMAS Westralia Fire

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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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ABSTRACT

The HMAS Westralia fire incident of 5 May 1998, involved the combustion of a quantity of diesel fuel in the engine compartment. Four sailors were killed and the ship disabled.

This paper presents the results of a series of fire engineering calculations, material measurements together with a computer based simulation of the HMAS Westralia fire. The modelling is used to give an insight into the behaviour of the fire and physical phenomena observed.

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MODELLING OF THE HMAS WESTRALIA FIRE

Executive Summary

The HMAS Westralia fire incident of 5 May 1998 lasted 90 minutes during which four sailors were killed. The fire was caused by the rupture of a flexible fuel return line on cylinder number nine starboard engine. This sprayed diesel fuel onto a hot indicator cock, which ignited a spray fire. The scope of this report is limited to presenting the results of modelling which provides an insight into the size, duration and effects of this fire.

The modelling revealed that the damage to the engine compartment is consistent with a fire in which 30 litres of diesel fuel was consumed in a spray fire lasting for approximately one minute.

The engine compartment on HMAS Westralia, a replenishment tanker, has a volume of 2600 m^3 which is large compared with engine compartments of warships. The calculations show:

- Rapid filling of the compartment with hot smoke which quickly reduced visibility to near zero.
- High levels of carbon monoxide requiring that fire fighters within the compartment should wear breathing apparatus.
- Badly sited escape ladders requiring crew to move through hot gases to escape from the compartment.

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Stephen Kennett graduated from the University of Melbourne with a B.Sc. (Hons) in 1976, a M.Sc. (Nuclear Physics) in 1978 and a Ph.D. (Nuclear Astrophysics) in 1981. He commenced with the Department of Defence, Materials Research Laboratory, now the Aeronautical and Maritime Research Laboratory, Defence Science and Technology Organisation (DSTO) in 1981 and has undertaken research in interaction of lasers with materials, atmospheric optical propagation and laser eye protection. Since 1989 he has lead a research team working in the area of naval fire research.

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Contents

1. Introduction

HMAS Westralia is a 40870 tonne Leaf Class underway replenishment tanker. The ship was designed as a commercial tanker for the Hudson Fuel and Shipping Company and was launched in 1974. In 1989 the Royal Australian Navy (RAN), leased the ship and exercised an option to buy the vessel in 1994.

The ship is powered by two SEMT Pielstick P C2.2V14 Engines which are housed at the bottom of an engine room that extends from the bilge to the funnel. A series of mezzanine floors containing diesel generators and auxiliary machinery lie within the space. The machinery control room (MCR) and the switchgear room lie four meters above the top of the main engines on the forward section of the engine room. Figure 1 shows the location of the engine room in HMAS Westralia and Figure 2 shows the location of the major pieces of machinery within the engine room. The fridge flat level is seen at the aft of the compartment above the boiler (level with the top of the MCR).

The HMAS Westralia fire incident of 5 May 1998, involved combustion of a quantity of diesel fuel in the engine room. Four sailors were killed. The incident continued for 90 minutes before the smoke was cleared. The initial fire source was diesel fuel which sprayed from a damaged fuel line on cylinder number 9 starboard main engine ingniting on a nearby indicator cock.

DSTO staff were allowed by the RAN Board of Inquiry (BOI) to have access to the compartment to inspect the fire damage prior to the commencement of repair work. The observed fire damage was restricted to the top of the starboard engine, the wall immediately adjacent to the engine and the structures under the MCR including cable trays, structural beams and the three-tonne-lifting rail. A smaller amount of fire damage was located in the bilge area imediately adjacent to the starboard engine.

Other damage due to smoke and heat was distributed around the whole of the compartment. This was mainly restricted to the melting of light fitting diffusers and damage to paint work.

This report presents the results of the application of fire engineering models and computer simulation, which describe the fire incident and some of the associated physical phenomena.

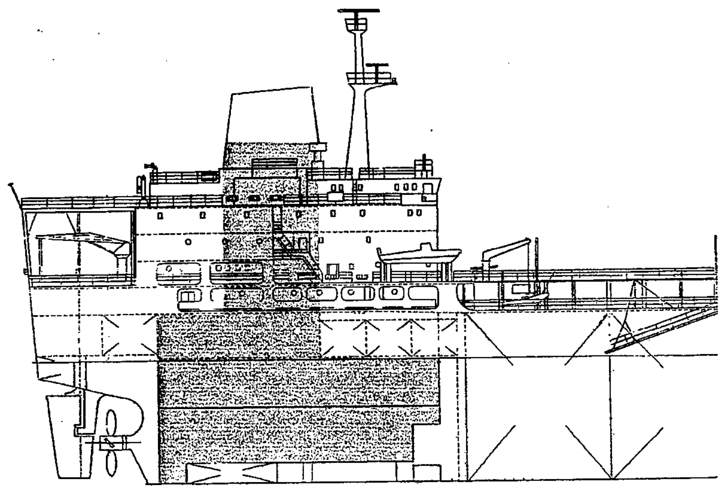

Figure 1. The location of HMAS Westralia's engine compartment and stack is indicated in green in this drawing of the aft end of the vessel.

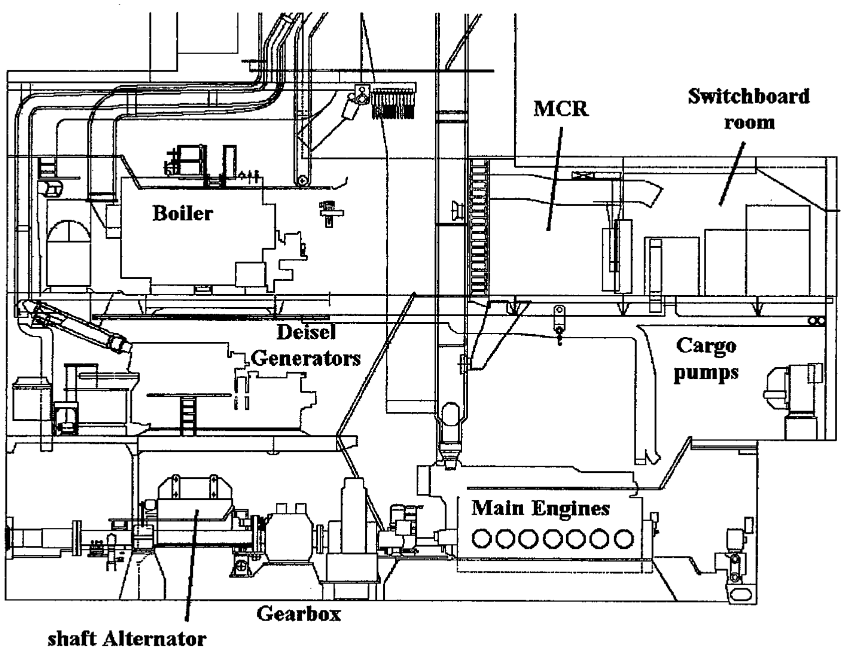

Figure 2. The location of the main machinery within Westralia's engine room is shown in this sectional view of the vessel. The MCR and switch gear rooms are included here to show their relative position to the main engines.

2. Duration

The exact duration of the fire is under some doubt as thick smoke filled the engine compartment and obscured the flames and there was no direct means of monitoring the extent or duration of the fire.

The physical damage to the structure within the compartment indicates a short duration fire. Indication lamps melted on one side only, light fittings melted and flowed yet remained as stalactites and a wooden notice board did not show charring although attached to the starboard wall immediately adjacent to the fire source.

The simplest assumption for fire duration is that the fuel source was shut off when the engine was shut off. This is not strictly true as the evidence provided to the BOI suggested that 18 minutes had passed before all valves associated with the supply lines were closed. However the pressure to the fuel line would have been substantially reduced and this would allow the material arround the hole in the hose to contract and the flow of fuel to be effectively cut off.

Conversations with crew members, who were both in the space and in the MCR at the time of the fire, suggest that there was a duration of between 20 seconds and 1 minute before the crew acted to cut the diesel fuel supply to the starboard main engine.

It seems reasonable that for the purposes of modelling the fire spray duration was 60 seconds.

3. Fuel Load

3.1 Primary Fire

The localised flame damage and low overall temperatures indicated a short duration fire involving mainly the spilt diesel fuel. The quantity of fuel involved in the fire can be estimated by making a few assumptions

A first approximation of the total fuel load consumed in the Westralia incident can be obtained by considering the available volume of air involved. The engine compartment on HMAS Westralia has a volume of approximately 2600m^3. For a typical diesel fuel, the ratio of the mass of air to the mass of fuel for combustion to proceed is typically 14:1 for a fuel rich mixture. If the compartment can be considered closed then an upper limit to the fuel load is approximately 180 L of deisel fuel (F76). This is an upper limit as it implies no mixing of the combustion products with the air and all the volume of the compartment is involved.

A second estimation of the fuel load can be had from the observed damage, which can provide an estimate of the temperatures within the compartment, and hence the fuel load. The polycarbonate covers on the fluorescent light fittings through out the compartment show varying degrees of melting. Polycarbonate starts to flow at a temperature of about 130°C. A temperature of near that 220°C would have caused a discolouration in the material. Few of the fittings show discolouration of the polycarbonate indicating that the average temperature is likely to be less than 200°C. The fact that a large number melted indicates an average temperature over 130°C. An average air temperature near 150°C seems reasonable. The natural exhaust ventilation of the compartment is through a 2.5m diameter opening in the top of the compartment. This is not a large opening and for the purposes of estimating the fuel load can be neglected. Therefore the total energy content of the fire can be estimated from the volume of air in the compartment (2600 m^3) and the average temperature (150°C) by ignoring heat losses to the surrounding materials and assuming a well-mixed volume. This calculation results in a lower limit estimated fuel load of 11 L.

The supply pump to meet the fuel requirements of the diesel engine the fuel lines must be able to supply 6ml per injection per cylinder at the maximum 520 rpm and 80 psi. It is understood that the diesel fuel also acts as a coolant to the injection system and the supply pumps are typically designed to supply two to three times the maximum fuel required [1]. This corresponds to about 1.11 L/s to the system. The hole in the fuel line could have opened up to about 1cm diameter. This could allow a flow of about half of the total fuel flow to spray out, 0.56 L/s, giving a total fuel load to the fire of 34 L.

There was little evidence of pooling of fuel near the starboard engine. Both the walkways adjacent to the engine on the starboard side near the bilge and near the top of the engine showed any significant pooling residue. This suggests that the fire consumed the fuel as it was introduced into the compartment. At a comsumption rate of 0.5 L/s the primary fire would have had a heat release rate of near 22 MW.

3.2 Secondary Fires

During the inquiry, it was suggested that a second source of fire existed in the bilge for a long duration.

It is unlikely that a large fire existed in the bilge, as the resultant damage to the bilge area would be substantial. The fire damage below the starboard engine is limited in area to within a metre or so of the point directly below cylinder number 9 of the starboard engine. This would tend to suggest a maximum sized pool fire of about 1 metre in diameter and, a heat output of 2.3 MW or less as estimated using the BRE package ASKFRS [2,3]. The reduced oxygen levels in the compartment would produce a lower heat output.

The small size of a secondary fire less than 10% of the heat output of the spray fire would allow such a fire to be neglected from the modelling. This is not to say that a secondary fire or fires did not continue to burn for a long period. However it is suggested that the heat output is greatly diminished after the spray fire is ended so that the calculations can neglect the secondary fires.

4. Temperature Estimation

Temperature estimates based on the observed damage can be obtained from the thermal properties of the materials within the compartment. The relevant thermal properties of a number of samples taken from the engine room have been determined. The following tables show the results for the samples taken.

Light Fitting diffuser

The light fitting diffuser is formed by injection moulding of polycarbonate at a temperature of 160°C. The polycarbonate light fitting diffusers over the fluorescent tubes in the compartment will melt at approximately 140°C and burn at temperatures of 270°C.

120°C	still hard
130°C	starts to soften
150°C	slow flowing
165°C	flows
220°C	discolours
270°C	Burning/ breakdown

Light fitting - Aluminium bracket

The aluminium bracket, which attaches the light fitting to the structure, will soften at 400°C and melt near 660°C.

400°C	softened
660°C	Melting point

Plastic Label

A plastic label attached the cargo pump number 3 was sampled. This label during the fire had softened to allow bubbles to form in the plastic arising from breakdown products of the adhesive below. This label was the lower of the two attached to that pump. The upper was blackened and burnt. The data below indicates the tops of the pumps were exposed to temperatures of greater than 180°C.

85°C	Softened
135°C	Bubbles form from glue in label
160°C	Slow colour change
175°C	Bubbles/ blackens
185°C	Softens/blackens rapidly

Rubber floor mat

A sample of the rubber floor mat in the MCR was taken. This mat was observed to have undergone heat softening. The floor of the MCR appears to have been heated to between 130°C and 150°C. The rubber floor matting did not appear to have been charred suggesting a temperature below 165°C and a chair's plastic castor resting on the painted metal floor, in the switch room adjacent to the MCR, was melted suggesting a temperature greater than 130°C. The painted metal floor did not show blistering which also indicates a temperature less than 150°C.

165°C	Chars surface

Paint

The standard paint used in RAN vessels involves a alkyd paint scheme. The paint is applied using white spirits as thinner. A trace of the thinner is retained in the dry paint. The blistering of the paint is indicative of the boiling point of the solvent used in the application of the paint. Typically this is white spirits which has boiling point of between 150°C and 300°C and an auto ignition point at 254°C.

0-155°C	No visible change
160°C	smoking
190°C	Colour changes, starting to char
260°C	Burns to carbon

5. Observed damage

The primary damage appears to be due to a spray of burning diesel fuel from the injection return line to cylinder 9 of the starboard engine. The fuel appears to have been directed slightly forward at an angle of approximately 45 degrees to the horizontal towards the bulkhead adjacent to the engine.

An estimate of the temperatures experienced by this bulkhead derived from observation of the damage to the paint and fittings on this bulkhead are shown in Figure 3. Similar estimates of the maximum temperatures experienced at the top of the port escape ladder are shown in Figure 4.

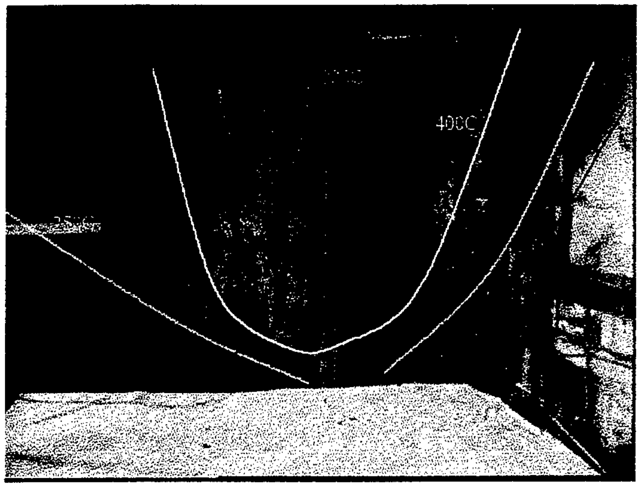

Figure 3. The wall adjacent to the starboard engine is shown together with approximate fire isotherm values from observed damage. Notice the two light fittings. The light fitting on the left has experience temperatures near 250°C and the polycarbonate diffuser has melted and flowed away. The fitting of the right has experienced temperature in excess of 400°C and this has resulted in the destruction of the aluminium support as well as the burning of the polycarbonate diffuser.

The 150°C line is the lowest level at which the paint is observed to blister. The 250°C line is the lowest level at which the paint is discoloured. The 450°C line is the line at which the paint is completely burnt. The 800°C line is an estimate beyond which no paint residue remains. Some of these estimates are time dependent and could be out by 20%.

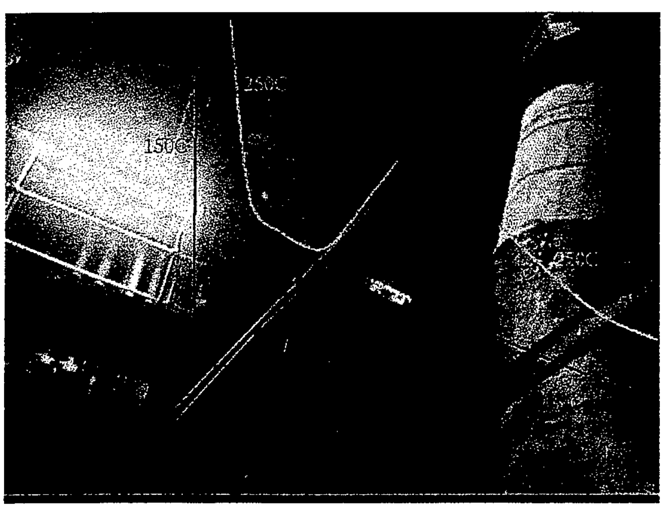

Figure 4. The port side bulkhead looking towards the port escape ladder from the 1st platform. Approximate isotherms values are shown.

6. Estimation of Carbon Monoxide production

The major cause of death in fires is the build up of carbon monoxide (CO) due to incomplete combustion. CO is an insideous gas in that the dose is cummulative. There is an irreversable reaction between CO and the oxygen bearing haemoglobin in the blood stream that reduces the oxygen bearing capacity of the blood. An approximate rule of thumb has been found [4] for a fatal dose of CO this is,

$$\text{Fatal dose} \sim 35000 \text{ ppm - min.}$$

This rule must be applied with caution at high concentrations as progressively lower doses can be tolerated.

The maximum concentration of CO would occur if all the carbon in the fuel were converted to CO. If 30 L of diesel fuel were consumed and converted to CO then this would release approximately 50 kg of carbon monoxide. 50 kg corresponds to a volume of 50 m^3 and this in turn for a compartment volume of 2600 m^3 corresponds to an average CO concentration of 19000 ppm. The conversion to CO in the Westralia fire would not have been complete and a concentration of near 10% of the maximum seems reasonable.

The physiological response to the build up of carbon dioxide (CO_2), the end product gas of burning carbon, is a rapid increase in the breathing rate. For mixtures of CO_2 and CO the time to incapacitation has been shown to reduce by 50% in CO_2 concentrations of 5% [4].

Even with an adaquate air supply, a fire burning with a very sooty, highly luminous flame can have 2%-4% of carbon monoxide in the smoke [5].

At a concentration of 1900 ppm a fatal dose can be achieved in 18 minutes at 20000 ppm this is reduced to less than 2 minutes.

7. Estimation of the Oxygen concentration.

There was some discussion at the BOI as to the level of oxygen after the release of the carbon dioxide (CO_2) flooding system into the compartment ten minutes into the incident.

The oxygen level in the compartment, can be estimated from the behaviour of one of the diesel generators, which remained running in the engine compartment, at idle, during the whole incident. Ten minutes into the fire incident, the CO_2 flood system was released to extinguish the fire. Some time later, the television footage taken by the channel 7 helicopter showed that the diesel was puffing smoke rings from its exhaust.

The diesel was under no load and therefore usually would be running under a lean mixture with an air fuel ratio of near 40:1. The smoke rings indicate a rich mixture and a ratio near 14:1 where a diesel would be close to stall. The volume of air inducted into the idling diesel is constant. Therefore the changed behaviour is due to the reduced oxygen level in the air. The change in the ratio coresponds a change in the oxygen level from 23% to 8%. This level is below the level that would sustain normal combustion.

8. Estimation of the smoke filling time

The time for the smoke from the spray fire to fill the Westralia engine compartment can be estimated, from the size of the fire and the compartment, using a simple plume model and a fluid-filling concept. Hinkley [5] produced an equation to do this for a pool fire,

$$t_{fill} = 20.8\frac{A_{comp}}{P_f}\left(\frac{1}{T_L}\right)\sqrt{\left(\frac{T_O T_f}{g}\right)}\left(\left(\frac{1}{\sqrt{z}}\right)-\left(\frac{1}{\sqrt{h}}\right)\right) \qquad (1)$$

Where, A_{comp} is the compartment floor area, h its height, P_f the fire perimeter, T_L layer temperature, T_f the flame temperature, T_0 the ambient air temperature and Z the distance from the floor to the base of the smoke layer.

For the fire in the engine compartment of Westralia a number of simplifications and approximations can be made

The area of the floor, A_{comp} = 360 m²,
The temperature of the smoke layer estimated, T_l = 800°K,
The flame temperature, T_f = 1500°K,
Gravitational constant, g =10 m/s²,
Ambient air temperature, T_0 = 300°K,
Height above the deck of interest, Z = 2 m,
The fire perimeter, P_f = 5.5 m,
The effective height, h = 7.22 m, derived from the volume of the compartment, 2600m³, divided by the floor area, A_{comp}.

Substituting the above information into equation (1) gives a time of 120 seconds for the compartment to be filled with smoke down to head height above the hull plates. This estimate is only indicative as a result of the complex geometry of the compartment and the uncertainties of the size of the fire.

9. Computational Fluid Dynamics simulation.

This section presents a computational fluid dynamics simulation of the fire incident onboard the HMAS Westralia.

An approximation to the engine compartment was created for the computational fluid dynamics program, FLOW3D [8]. Isometric projections of this compartment are shown in Figure 5. Only the main bulkheads and decks were approximated. The curvature of the hull and any bulkhead was ignored. All machinery and piping were neglected. All space and machinery below the level of the top of the main diesel engines are assumed not to significantly contribute to the fire or the airflow in the event and were ignored. The large size of the space allows the air to move almost unimpeded by the piping and equipment and it was felt an unnecessary complication to include these in the model.

An isobaric boundary condition was aplied to an area of 6.25 m^2 on the top of the stack during the calculation. This simulates the opening at the top of the stack.

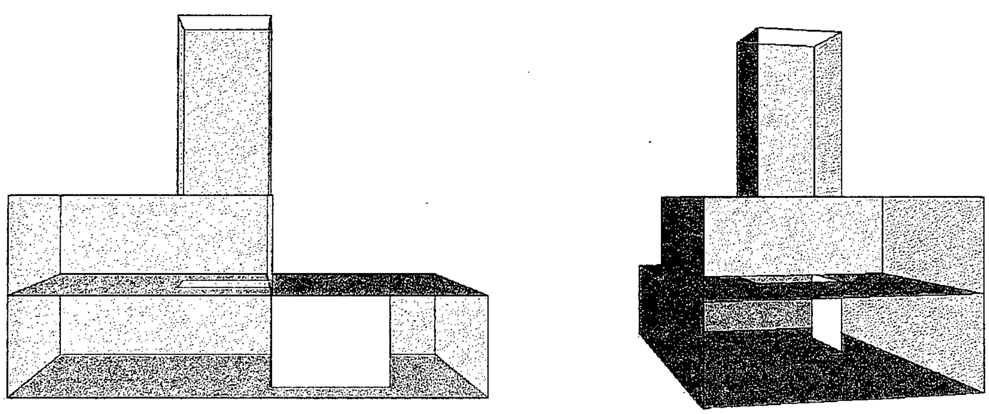

Figure 5 Isometric projections of the model compartment. The yellow bulkhead is the bulkhead djacent to the fire source. The fire source is indicated by an orange dot.

The properties assigned to the bulkheads and deck were not those of steel. However during the first minute of the event little heat is transferred to the hull in both reality and in this model prediction. The results here are not considered sensitive to the bulkhead material properties.

The location of the fuel source is indicated as an orange dot in Figure 5. A flow of fuel was directed at an angle of 45 degrees to the horizontal towards the starboard wall. The flow rate of fuel was set to 0.5 L/s. The flow of fuel was cut off after 60 seconds giving a total fuel load of 30 L of diesel equivalent.

The initial calculation was halted at sixty seconds of simulated real time and subsequent calculations after 4 minutes. Although the effects of this fire incident had a much longer duration than this the size of the calculation precluded solving these at this time.

Computational time for each calculation was between 2 and 8 days on a DEC Alpha computer network system. The program calculated the concentration of the fuel in the plume, the oxygen concentration in the compartment, the carbon dioxide concentration in the compartment, the temperature and the movement of air in the compartment.

10. Results

The results of the computations are presented in a series of coloured contour plots. FLOW3D is able to predict the concentrations of oxygen, carbon dioxide, fuel, temperature and airflow throughout the compartment volume.

10.1 Predicted Temperatures

10.1.1 Starboard bulkhead

The starboard bulkhead adjacent to the fire source and the deckhead directly above the fire source (the deck of the MCR) were subjected to the most intense heat. Figure 6 depicts the predicted temperature distribution 1 minute into the model incident for a plane through the model along the starboard bulkhead adjacent to the starboard engine. Temperatures of greater than 1200°C are predicted near the top of the wall.

The damage observed on the starboard bulkhead can be compared with the predicted temperature distribution. In figure 7, the first picture shows a view of the bulkhead taken from the port side lower platform and the second has the FLOW3D temperature distribution at 1 minute superimposed on it. The shape and size of the temperature distribution matches well with the shape the size of the damaged area. In the modelled scenario the fuel is cut off after 1 minute which results in the temperature distribution on the wall being at its maximum. For the real fire, the damage to the wall is in effect a snapshot of the maximum temperature.

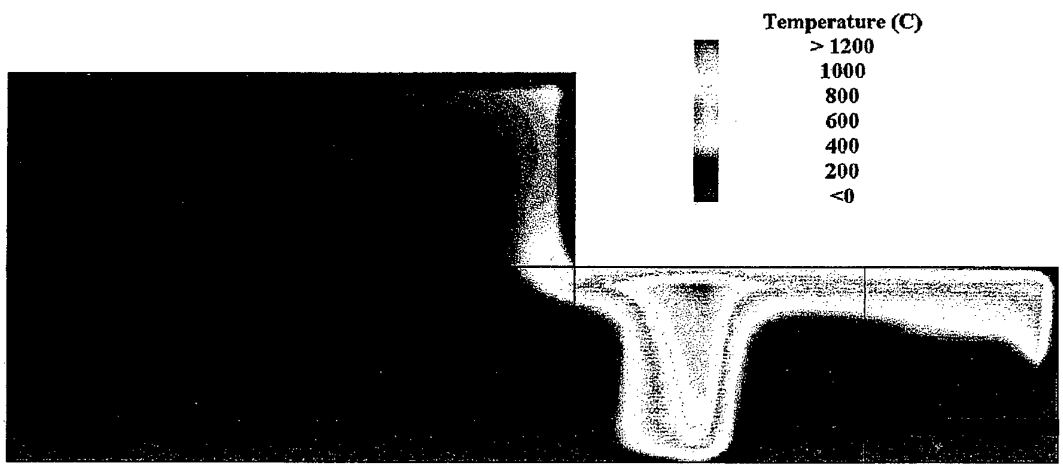

Figure 6. The temperature distribution of the fire incident on a section through the wall adjacent to the starboard engine is shown. Viewed from the starboard side. The thick black lines indicate the positions of the lower and upper mezzanine floors.

The paint blister line drawn in figure 3 matches well the line corresponding to the transition from purple to blue (150°C) in figure 7. The line marking the transition from blackened paint to a whitish residue matches the green (450-500°C). Both give confidence in the assumptions made in creating the model.

Two aluminium light fittings were attached to the starboard wall 2.5m above the level of the top of the engines. The aft fitting can be seen in the top image of Figure 7 to be reduced to a steel bracket. As seen in the lower image of Figure 7, the model predicted this fitting to be exposed to temperatures of 600 to 800°C (green-yellow). Aluminium melts at near 660°C. The forward fitting can be seen in the top image of Figure 7 to be reduced the aluminum backing and bracket. The polycarbonate diffuser and the plastic fittings have melted away completely and the tube has fallen away. The model results predict a temperature of near 150°C (purple-blue) consistent with the damage observed.

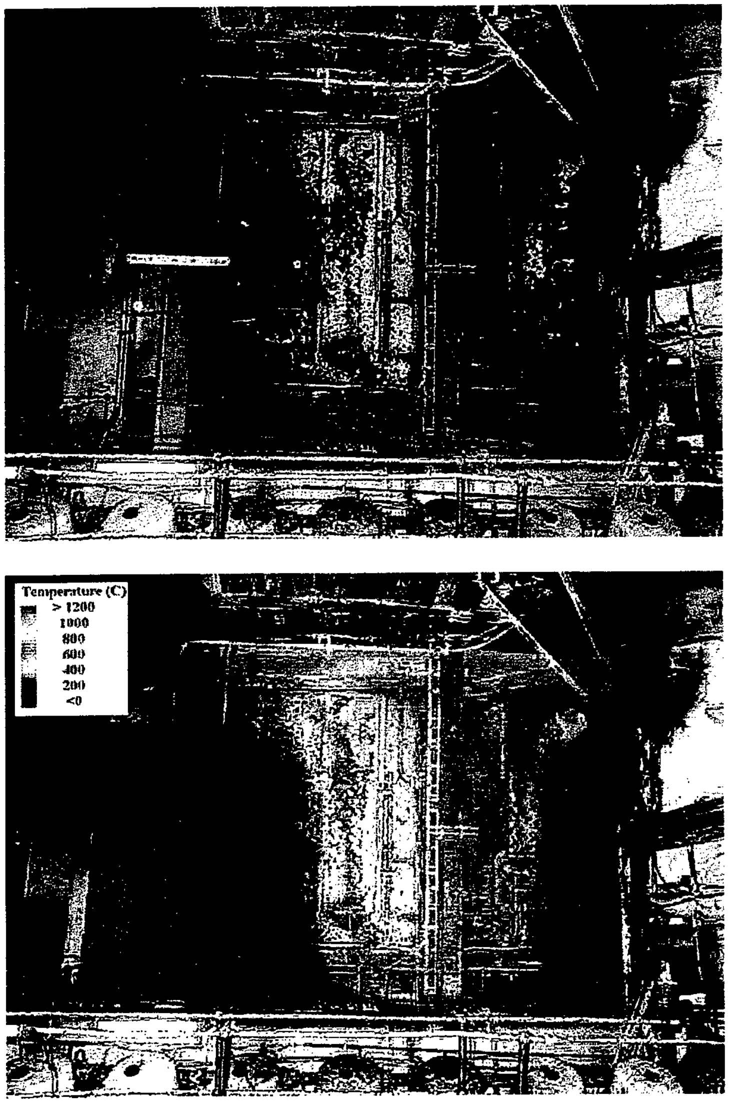

Figure 7. A comparison of the fire damage can be made with the maximum temperature distribution predicted by FLOW3D. The top picture shown the starboard wall adjacent to the fire source and the lower picture shows the FLOW3D temperature distribution predicted at the wall.

10.1.2 MCR deck

The temperature distribution under the MCR is of interest since this is where significant damage was done to the cabelling and the 3 tonne lifting rail directly above the fire source. Very high temperatures are indicated in the region of the cables (>1200°C) and in the area above the cargo pumps. The temperature distribution predicted for a horizontal plane 0.5 m below the MCR floor is shown in Figure 8. The hot gases are predicted to flow under the MCR. The gases flow away from the fire plume radially. The hot gases flowing to aft are boyant and rapidly flow up the stack at the aft end of the MCR. Those hot gases flowing across the compartment provide entrapment to hot gases flowing forward. In the forward direction hot gases are trapped and forced into an eddy over the top of the cargo pumps. The predicted flow pattern for a forward to aft vertical section through the fire source is shown in figure 9. The eddy above the cargo pumps is clearly evident.

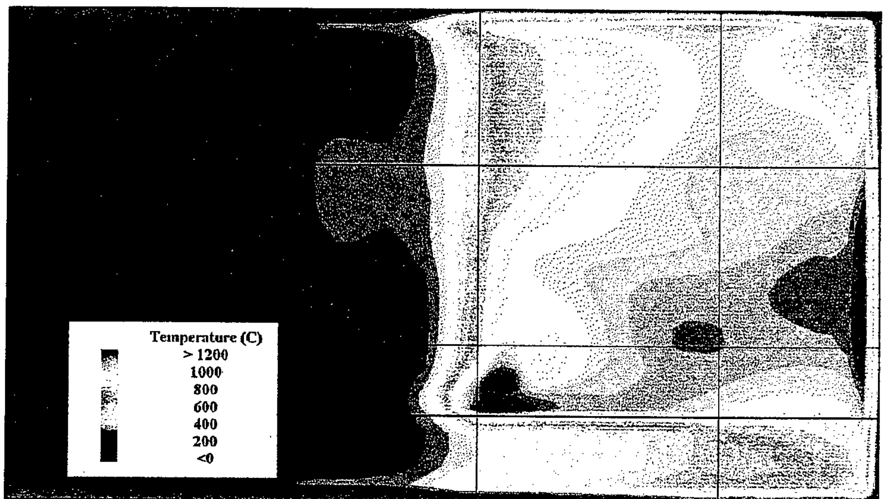

Figure 8. The temperature distribution is shown, viewed from above, 0.5 metres below the MCR 1 minute into the event. A fireball is predicted to have spread across the whole of the underside of the MCR. The hottest spot is directly above the fire source. The wall adjacent to the starboard engine can be seen to effectively to block the heat getting to the machinery behind it.

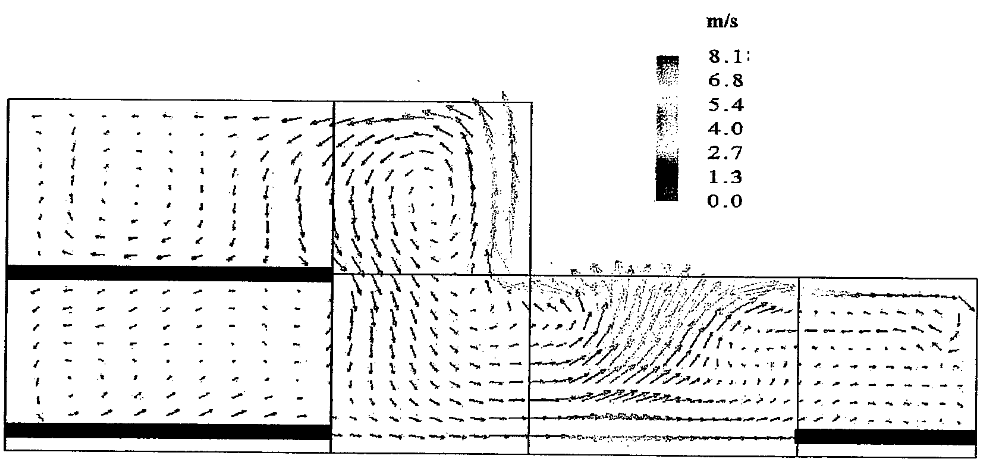

Figure 9. The bulk airflow of the compartment is depicted 1 minute into the incident for a aft-forward vertical section through the fire source. The main area of concern is the flow above the cargo pumps where hot gases are directed down onto the top of the motors.

10.1.3 Cargo pumps

The exposure of the cargo pumps to high temperatures is of concern to the cost of repairs to the vessel. The predicted temperature contours is shown in Figure 10 for a section across the compartment through the location of the cargo pumps.

The 150 C isotherm is labeled and is significant as at this height the adhesive label was obtained from cargo pump number 3. A contour interval of 50°C was used in drawing the figure.

The flow of heat to the diesel generators is also of some concern. Figure 11 shows the predicted temperature distribution of the fire incident after 1 minute. The figure shows an aft to forward section through the origin of the fire. The bottom of the picture corresponds to the top of the starboard engine. The temperatures in the area of the diesel generators remain near ambient. However the area near the cargo pumps at the forward bulkhead are subjected to significant heat loading at levels corresponding to the top of the pumps.

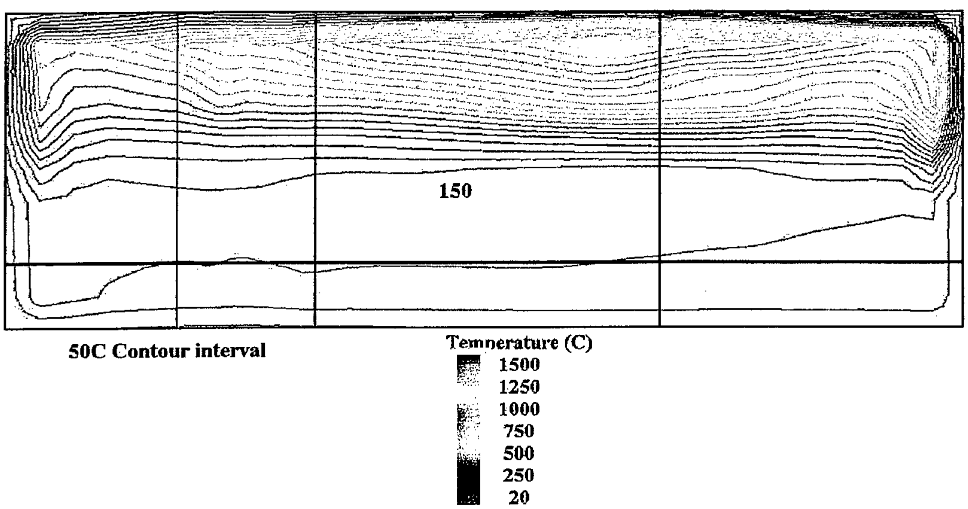

Figure 10. The isotherm predictions are shown, 1 minute into the incident, for a section through the cargo pumps area. The view is toward aft. Temperatures as high as 500C are predicted of the air at the tops of the pumps. The 150°C contour corresponds to the position of an adhesive label attached to the pump. An examination of a sample of this label suggests an exposure to a temperature of approximately 140°C.

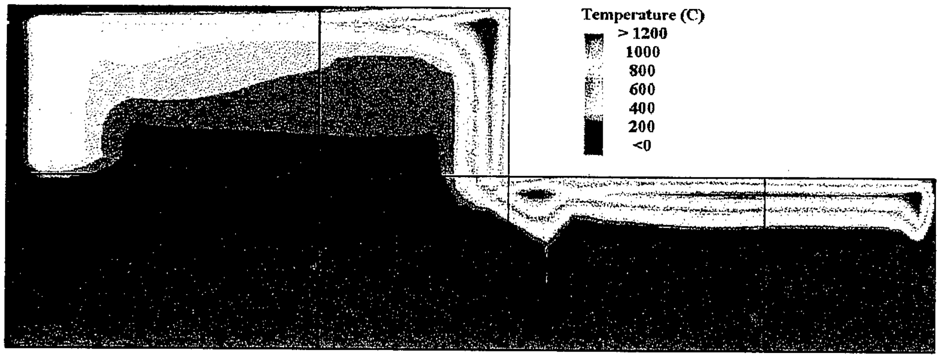

Figure 11 shows the predicted temperature distribution of the fire incident after 1 minute. The figure shows an aft to forward section through the origin of the fire. The bottom of the picture corresponds to the top of the starboard engine.

10.1.4 Aft End of the MCR

The model temperature predictions for the section just aft of the MCR looking aft are shown in Figure 12. The hot plume spilt from under the MCR can be seen to rise up the starboard side. Predicted temperatures of approximately 500 to 600°C would be experienced at the MCR level near the starboard escape ladder (marked with an X). This is consistent with the damage to the aluminium walkway, which softened and buckled during the incident. The top of the port escape ladder (marked with an X) also was predicted to be exposed to temperatures of 300 to 400°C, again consistent with the damage observed (paint blistered and burnt, light fitting difusers melted and signs damaged).

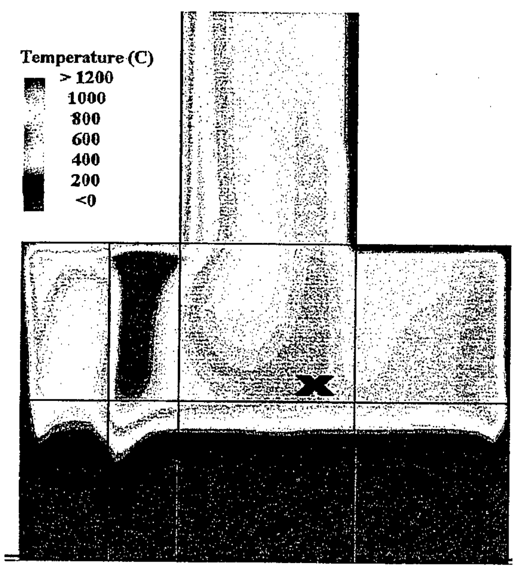

Figure 12. Temperature distribution 1 minute into the event for a cut across the compartment aft of the MCR looking aft. High temperatures of the order of 400°C are predicted to exist at the top of the port ladder (marked with an X).

10.1.5 Fridge Flat

The firefighting team, from the level of the fridge flat, attempted re-entry into the engine compartment. This level refers to the top platform at the aft end of the compartment. The platform can be seen in Figure 2 just above the boiler. The predicted temperatures on the fridge flat level, depicted in Figure 13, one minute into the incident indicate that there is significant heating across the whole of this area. Temperatures are predicted to be near 350°C. The predicted temperature four minutes into the event is shown in Figure 14. Temperatures are predicted to have fallen to 100°C. At four minutes, this is still too hot for an attempted reentry [9]. The observed damage at the fridge flat level is again consistent with the predicted temperature history (light fittings melted and little damage to paint work)

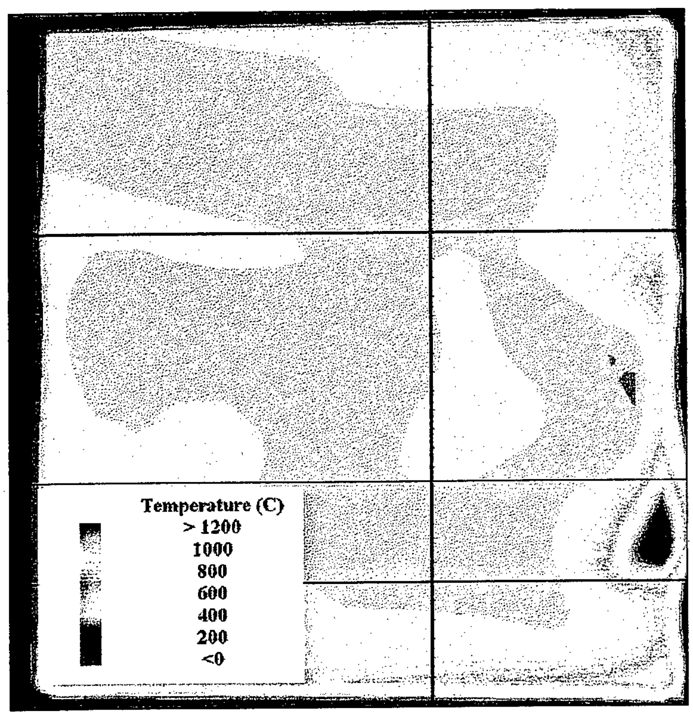

Figure 13. The temperature distribution one-minute into the fire incident at the level of the fridge flat.

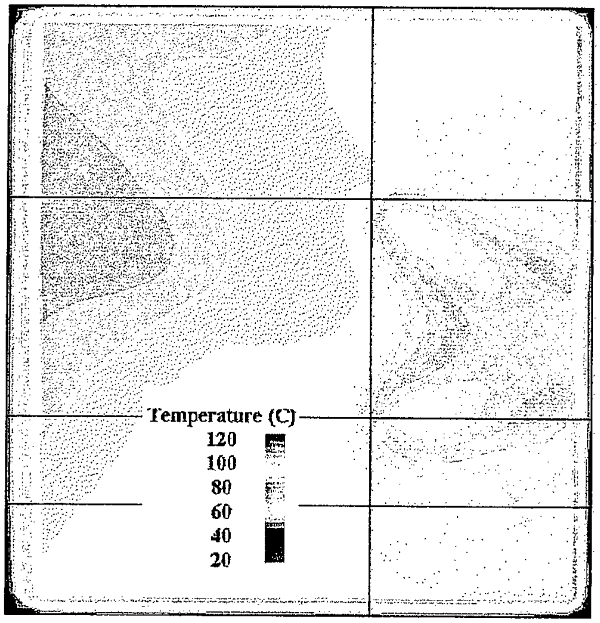

Figure 14. The temperature distribution is depicted 4 minutes into the fire incident at the level of the fridge flat. The residual temperatures at the aft end of the compartment, where the fire fighters attempted to re-enter the compartment, is still near 100°C and too hot for a reentry.

10.1.6 Oxygen and CO_2 content

The oxygen content of the compartment is shown in Figure 15 for a section across the compartment just aft of the MCR looking aft at 30 and 60 seconds into the fire. The starboard side shows the depleted air associated with the fire plume rising rapidly up the starboard side of the stack. The port side shows a depleted oxygen level within a minute as smoke fills the whole compartment. The carbon dioxide level in the model, shown in Figure 16, has filled the compartment with levels of up to 10% CO_2 down below the MCR within a minute. The CO_2 distribution matches the oxygen loss distribution well indicating that in the model fire the fire was well ventilated.

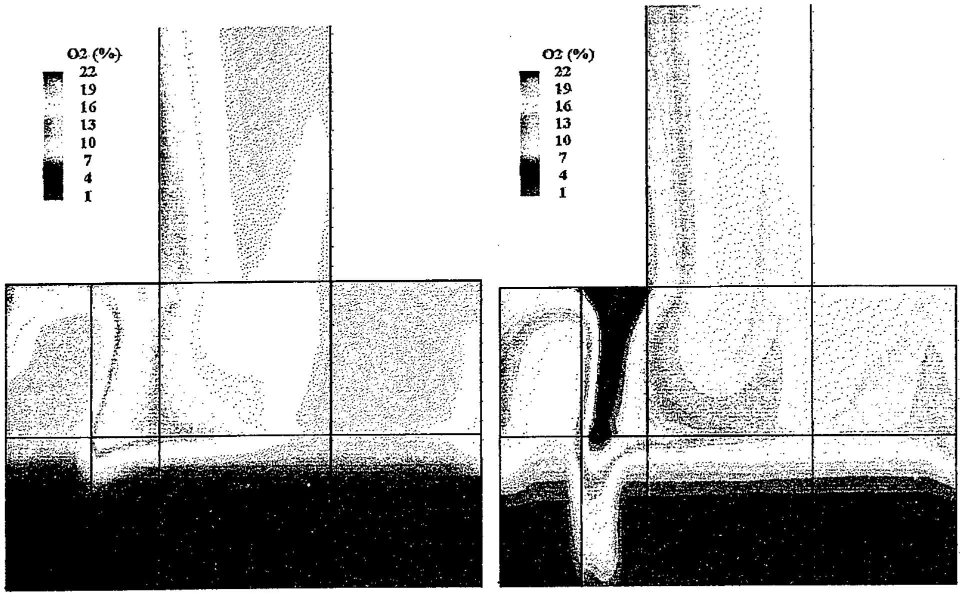

Figure 15. Calculated oxygen content 0.5minute and 1 minute into the fire incident. A cut across the compartment aft of the MCR is shown looking aft. The bottom of the picture corresponds to the level at the top of the engines. The horizontal line in the middle of the picture is at the level of the MCR. Low concentrations of oxygen are predicted at the top of the escape ladder

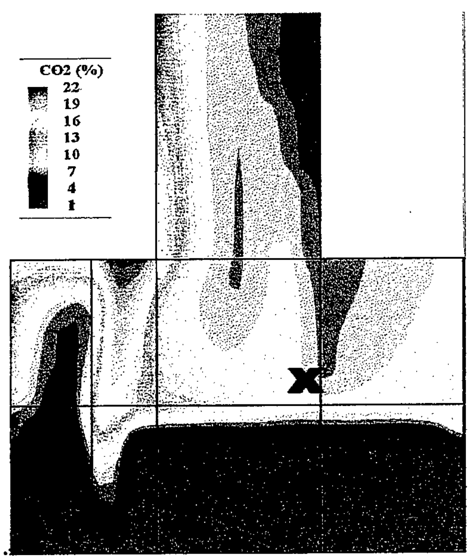

Figure 16 Calculated carbon dioxide levels 1 minute into the fire incident. A cut across the compartment aft of the MCR is shown looking aft with the same geometry as in Figure 15. High concentrations of CO_2 are predicted at the top of the port escape ladder at the level of the MCR, (marked with an X).

10.2 Temperature Distributions 4 minutes into the incident.

In the modelled scenario the fuel source is removed 1 minute into the event and the compartment is allowed to cool. A longitudinal compartment section through the origin of the fire is shown, in Figure 17, four minutes into the event. The temperature in the region of of the cargo pumps and the diesel generators on the lower platform has reduced significantly over the temperature after one minute and become evenly heated at about 100°C. Cool air can be seen to be flowing down from the stack just aft of the MCR.

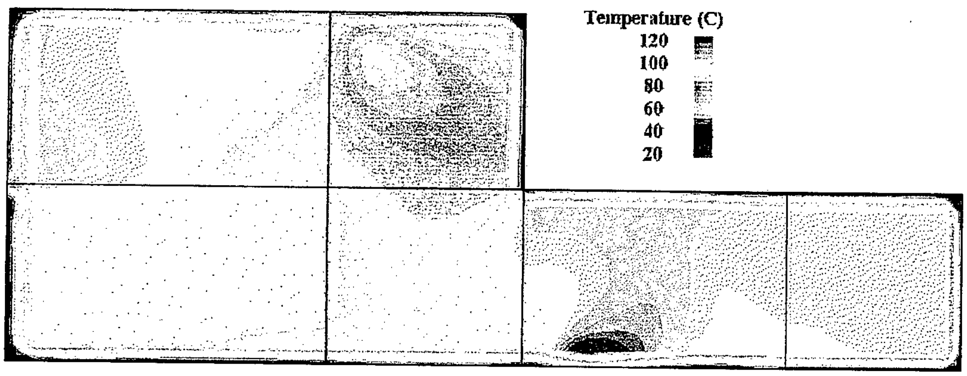

Figure 17. The predicted temperature distribution is shown for a section through the origin of the fire three minutes after the fuel supply is cut to the fire.

The predicted flow pattern depicted in Figure 18, shows a series of slowly swirling eddies supported by convective gas flows caused by heat losses to the compartment walls and to the atmosphere throught the opening at the top of the stack.

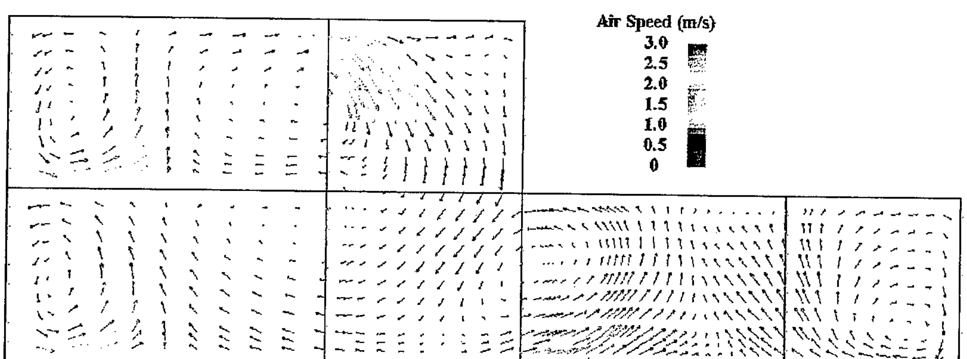

Figure 18. The residual airflow for the simulated incident is shown for a section through the origin of the fire. The downward flow of cool air from the open stack and the associated circulations are clearly visible.

The stack provides the main flow of heat out of the compartment. The large surface area of the stack allows conduction to cool the air and the opening at the top of the stack allows warm air to leave compartment, which is replaced by a down flow of cool air into the compartment. Figure 19 shows the predicted temperature distribution for a cut just aft of the MCR four minutes into the event. Temperatures in the compartment at the level of the MCR and below remain at levels considered too high for firefighting above 80°C [9]. Cool air from the stack has penetrated to the region of the top of the port escape ladder, marke with an X in Figure 19.

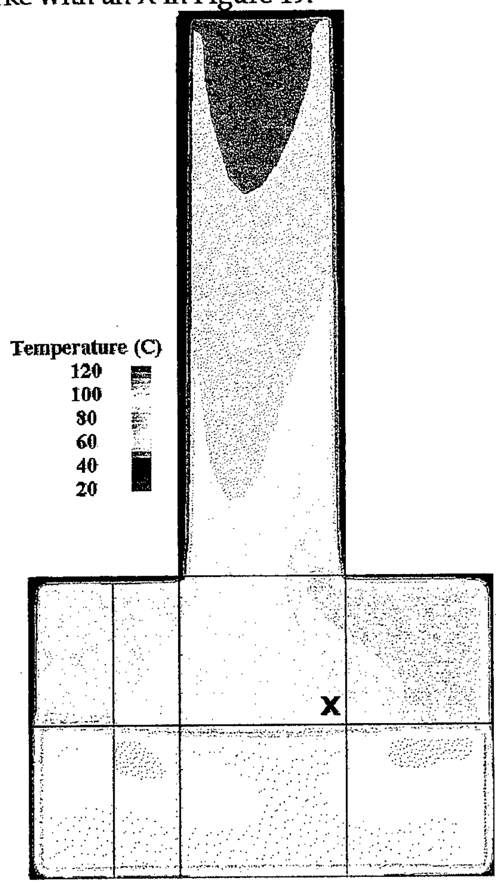

Figure 19. The predicted temperature distribution is depicted for a section just aft of the MCR, facing aft, four minutes into the modelled incident. The blue area corresponds to a downdraft of cooler air flowing back down the stack. The x marks the location of the top of the port escape ladder.

Four minutes into the event the airflow in the lower sections of the compartment is no longer driven by the heat of the spray fire but is driven by convective eddies created by the cool hull locally cooling the air. The upper section of the compartment is still subjected to convective cooling as warm air escapes up the stack. Figure 20 shows the predicted airflow at 4 minutes for a section just aft of the MCR looking aft. The flow up the stack is linear in this section and upward. However sections further aft reveal a complex flow of warm air rising and cool down drafts.

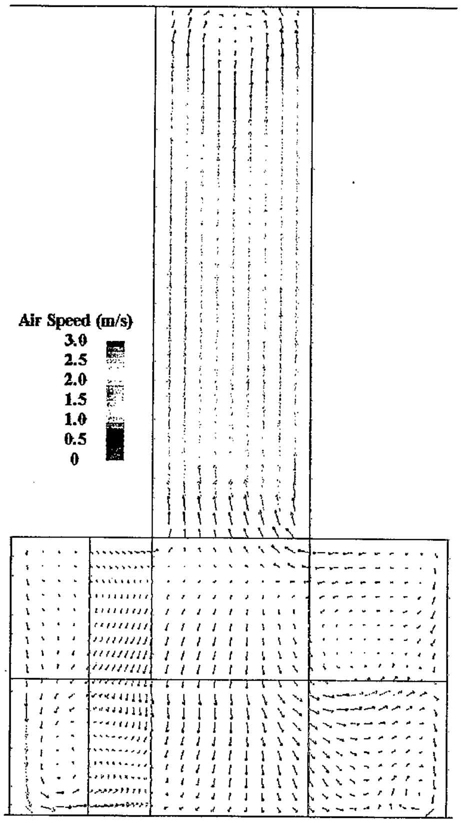

Figure 20. The air speed is show to the same section as in previous figure. The velocities are generally low less that 1.0 m/s except in the region of the stack. Convective eddies driven by the cool hull provide the main flow in the compartment below the level of the MCR.

The oxygen level in the compartment four minutes into the modelled event show the levels to be only 10% less than normal. The levels being most depressed near the fire origin and at the fridge flat. Figure 21 shows the predicted oxygen levels at four minutes for a section though the fire origin.

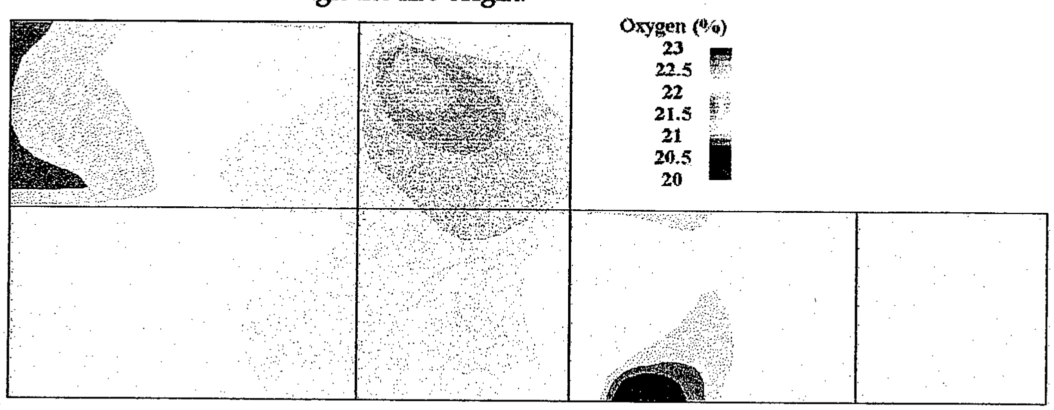

Figure 21. The predicted oxygen levels for a section through the fire origin is shown.

Figure 22 shows the oxygen content in the compartment for a section across the compartment just aft of the MCR looking aft. Clean air is seen to be flowing back into the compartment through the opening at the top. The overall oxygen level is near normal level throughout the compartment.

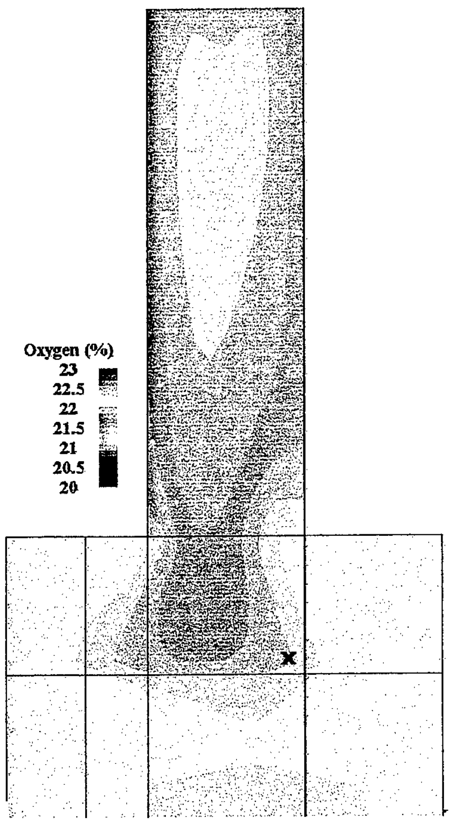

Figure 22. The predicted oxygen levels four minutes into the event for a section through the compartment just aft of the MCR, looking aft. The opening at the top of the stack has allowed the inflow of fresh air.

The level of CO_2 throughout the compartment is still high indicating mixing of the combustion products with the inflowing air. The levels are highest near the origin of the fire and at the fridge flat, see Figure 23. The effect of the down flow of fresh air from the stack can be seen in the area aft of the MCR as a reduced concentration of CO_2.

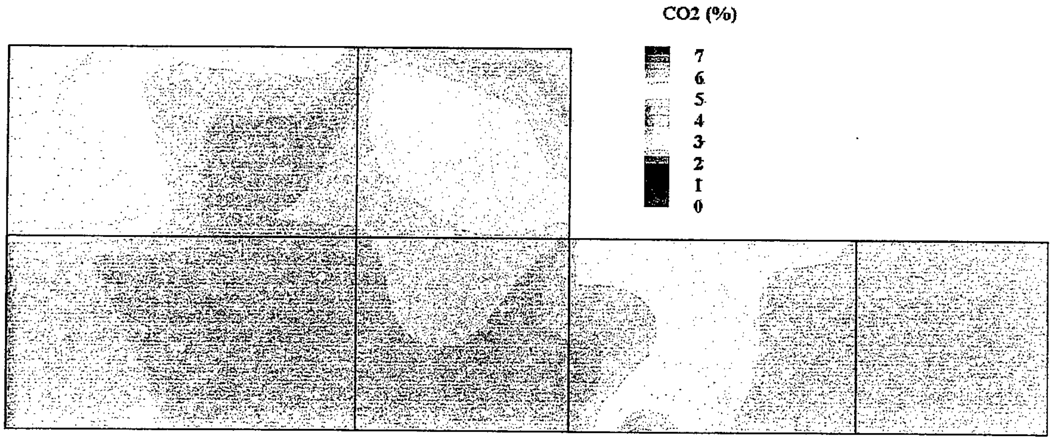

Figure 23. The levels of CO_2 are shown for a forward-aft section through the fire origin. The effects of residual fuel can still be seen near the fire origin. The rest of the compartment shows an even level of CO_2 at about 4%. The effect of the inflow of clean air down the stack is evident.

11. Conclusions and recommendations.

The calculations presented in this report have shown that relatively small quantities of fuel, when burnt in an enclosed environment, create a potentially lethal cocktail of hot thick smoke and high concentrations of carbon monoxide in a very short time even in large volumes.

This report has show that the Westralia fire of 5 May 1998 can be modelled sucessfully by the combustion of about 30 litres of diesel fuel in approximately 1 minute. The levels of damage observed are consistent with the model. The continuation of the modelling beyond four minutes becomes increasingly uncertain as the new events occurred. The fire flaps were shut at about this time.

RAN fire-fighting procedures on the reporting of a fire incident are to imediately shut down the ventilation system to restrict the flow of fresh air into the compartment. The procedure is then to switch on the exhaust fans and establish a smoke path inorder to extract smoke and heat from the vessel. In the Westralia fire incident, the ventilation system was shut down, however, the exhaust fans and flaps were not used with the consequence that heat and smoke was retained for a substantial period after the fire had been extinguished. The mechanism for heat loss was restricted to conduction as the convective mechanism normally dominant is denied.

The attempted fire fighting from the fridge flat was not ideal, even for the modelled fire, as the heat and combustion products were retained in this area.

The current practice of attempting to provide firstaid fighting to fires in these poorly ventilated spaces without the use of breathing apparatus is not recommended.

12. Acknowledgements

The authors would like to acknowledge the valuable help and assistance offered by the crew of HMAS Westralia during their visit to the ship after the incident. The authors would also like to acknowledge the assistance of the board of inquiry in allowing access to the ship and information on the fire as well as their comments on drafts of this paper.

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14. Appendix 1

Estimated Fuel Consumption and Booster Pump Capacity for SEMT Pielstick PC2.2V14 Engines

Information provided by Dr Geoff Goodwin, Maritime Platforms Division, Aeronautical and Martime Research Laboratory.

PC2.5 and 2.6 engines are rated at 550 kW/cyl @ 520 rev/min. (Pounder's Marine Diesels, 6th ed., ch. 14 & MER Directory of Marine Diesel Engines 1998)

For a 14 cylinder engine, this represents 7.7 MW per engine.

Westralia's engines, according to Jane's Fighting Ships, are rated at 10.3 MW.
The implication is that Westralia's engines are rated at less than the maximum for the type, at about 5.2 MW. This is reasonable, as they are an earlier PC2.2 engine. (I assume Jane's quotes total propulsion power, rather than power per engine.)

Assuming an overall BSFC of about 230 g/kWhr, at rated load of 5.2 MW, the fuel required is:

$$0.23 \times 5200 \text{ kg/hr} = 1196 \text{ kg/hr}.$$

This figure is likely to be high rather than low – I would expect a BSFC between 210 and 230 g/kWhr for engines of this class and age. This is something of an "informed guess".

The engine runs at up to 520 rev/min (Pounder's, ch.14), or 8.67 rev/s, and requires 14 injections every 2 revolutions, therefore 7 per revolution, or 60.67 injections/s.

This is 218400 injections/hr, or 1196kg/218400injections, which represents
5.47×10^{-3} kilograms per injection, or 5.46 g/injection.

If it is assumed that the total flow is about 3 × that required for consumption, to provide fuel pump cooling, then the booster pump would require a capacity of about 3600 kg/hr.

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19. ABSTRACT

The HMAS Westralia fire incident of 5 May 1998, involved the combustion of a quantity of diesel fuel in the engine compartment. Four sailors were killed and the ship disabled.

This paper presents the results of a series of fire engineering calculations, material measurements together with a computer based simulation of the HMAS Westralia fire. The modelling is used to give an insight into the behaviour of the fire and physical phenomena observed.

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