STUDY OF WATER MIST SUPPRESSION OF ELECTRICAL FIRES FOR SPACECRAFT APPLICATIONS: NORMAL-GRAVITY RESULTS

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ABSTRACT

A preliminary investigation on the effectiveness of water mist as a suppressant in electrical fires under normal-gravity conditions for spacecraft applications is presented. Water-mist suppression experiments of a fire involving an overheated wire are conducted inside a container similar to the Space Shuttle mid-deck locker. Direct and indirect water-mist injection is used with various droplet-size distributions and flow rates. Water mist quickly extinguishes a fire that is directly impacted by the droplets, while much longer spraying times and larger amounts of water are required to suppress fires burning behind a baffle. Smaller droplet size distributions appear to be the most effective. A numerical model enables the simulation of a polydispersed spray, while still providing enough droplet scale resolution for the high-gradient fire suppression scenarios. The preliminary numerical results accurately predict droplet penetration, evaporation, and dispersion into the container as observed in the normal-gravity tests. These qualitative comparisons contribute to the on-going validation process of the model.

INTRODUCTION

The renewed emphasis on the human exploration of space is focusing on the development of new spacecraft like the Crew Exploration Vehicle (CEV) and on future planetary habitats for the long-term settlement of the Moon and Mars. The development of these new programs has consequently prompted a reevaluation of current fire suppression systems on spacecraft and it has motivated a feasibility study for possible replacement technologies. The challenges to the designer of a new fire suppression system for space applications are many and sometimes unique to the type of environment encountered outside the Earth's atmosphere and in other planets. The use of a light, non-toxic, and efficient suppressant capable of rapidly extinguishing a fire in a confined space with minimum generation of toxic byproducts and with fast and easy cleaning and recovery procedures are among these challenges. For long duration missions, the ability to refill the extinguisher with an agent easily available in the spacecraft is also of primary concern. In selecting such a suppressant agent it is necessary not only to look at its extinction efficiency as compared to other options, but it is also important to study the dispersion properties of the agent in partial gravity environments and in the presence of complicated geometries with a variety of obstacles, ventilation sources, and fire scenarios.

In a preliminary evaluation of the various suppressant agents available, it appears that water mist may be a good candidate to address most of the above challenges. On a per unit-mass basis, water is as effective as Halon 1301, the agent currently used in the Space Shuttle, while water is more effective than carbon dioxide (CO_2), the agent onboard the International Space Station. Water is also non-toxic, non-corrosive, readily available in spacecraft for multiple uses, and water in the form of ultra-fine mist may act as a total flooding agent in reduced gravity. In addition, advantage may be taken of the rapid evaporation of ultra-fine mist for its use in fighting electrical fires. Finally, agent cleanup operations may be achieved with dehumidifiers in the ventilation system. Consequently, the suppression properties of water mist are currently being investigated in the search for new fire extinguisher systems for the next generation of spacecraft.

As a result of the motivating factors mentioned above, a comprehensive study of the fire suppression properties of water mist in spacecraft and extraterrestrial habitats is being conducted at the Center for Commercial Applications of Combustion in Space at the Colorado School of Mines. The purpose of this project is to investigate the effectiveness of water mist in single or mixed-agent configurations on different fire scenarios, geometries, and low-gravity conditions evaluated numerically and experimentally and compared to other fire-fighting agents currently used in spacecraft fire-safety systems. The modeling effort consists of developing detailed sub-models of the fire source, the suppression agent generation and distribution, and the radiative shielding of the suppression agent. These sub-models will then be integrated into a high-fidelity, fire-suppression model. Finally, a reduced order model will be developed to minimize the computational requirements, yet retain the simulation capabilities of the original formulation. This paper captures the experimental and numerical modeling work done to date, which has focused on the preliminary evaluation of the effectiveness of water mist as a suppressant agent in electrical fires under normal-gravity conditions. The experimental work concentrates on evaluating the suppression effects of droplet size distribution and the behavior of water mist in a constrained geometry. In a parallel effort, the numerical work focuses on the simulation of the generation, evaporation, and distribution of the mist as it moves through the container and as it interacts with the fire source.

EXPERIMENTAL SETUP

The first set of experiments conducted under this program has been performed in a 44-cm wide, 25-cm high, and 51-cm deep container with similar characteristics to the Space Shuttle mid-deck locker, as described in a previous publication [1] and as shown in Fig. 1. Since an overheated-wire failure has been identified as one of the most probable fire scenarios to occur in a spacecraft, suppression experiments are conducted with a 15-cm long, polyethylene-insulated #20 wire with a high current flowing through it. Burning behavior is observed and flame-spread and heat-release rates under a downward propagation configuration are measured. Although these tests are conducted in normal gravity with a buoyancy dominated flow field, these downwardly propagating flames exhibit a well-behaved flame front reminiscing of propagation under low-gravity conditions. In contrast, flames propagating in the horizontal and upward direction are plagued with instabilities and turbulence generated by buoyancy. A measure of the time from ignition to extinction of the flame, the mass of insulation burned, and the heat of combustion of polyethylene gives an average fire size of 72 W. The electrically heated wire raises the surface temperature of the wire insulation to over 100C with a current of 35 amps without leading to ignition. Raising the current level above 35 amps only causes the wire to distort and melt away the insulation without a transition to flaming. Thus, an external ignition source is needed to initiate a flame that can only be sustained by constantly heating the wire with electrical current.

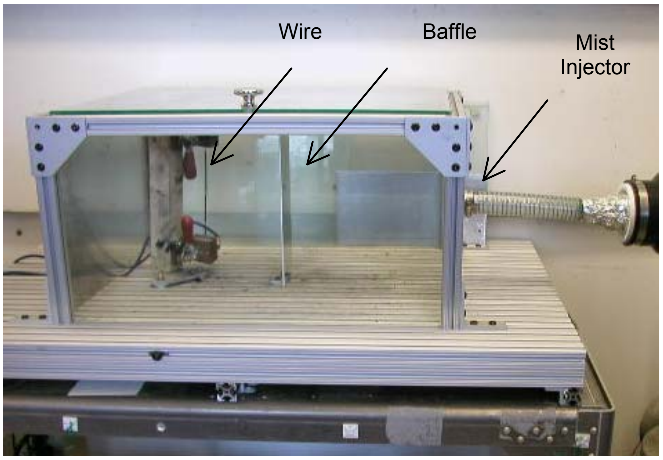
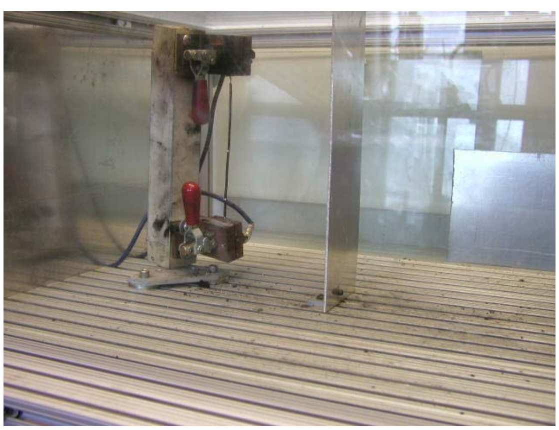


Figure 1. Experimental apparatus for electrical fire suppression tests based on the Space Shuttle mid-deck locker.



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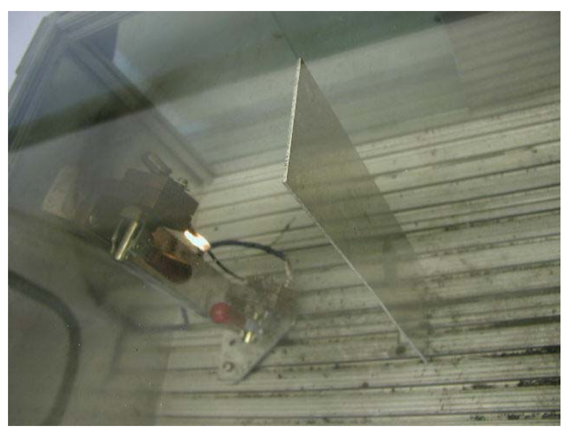


(b)

Figure 2. (a) Side view of the experimental setup showing the vertical test wire and the baffle in front of it, and (b) overhead view at the start of a test with a flame at the top of the wire.

In a typical test, the sample wire is held vertically between two large copper clamps. A current of 35 amps is applied and the wire is allowed to heat for 30 seconds before it is ignited near the top clamp with a propane lighter. After propagating for 2.5 cm, the burning time is measured for the next 5 cm to calculate the flame speed. The average downward flame speed is 0.06 cm/sec. Images of the experimental setup and the burning wire are shown in Fig. 2.

For the suppression tests, direct and indirect water-mist injection methods with a high-momentum jet are used. As shown in Fig. 1, the wire is located 40 cm from the water mist injector and for the indirect-injection tests a 13-cm wide, 25-cm high baffle is placed at 26 cm from the nozzle, in front of the burning wire. This last configuration is used to provide an extremely difficult path for the water mist to reach the burning wire. Interestingly, varying the width of the baffle from 5 to 13 cm had only a minor effect on the suppression efficacy of the high-momentum jet. Different droplet-size distributions and flow rates are possible by varying the water pressure on a water-mist injector with a 0.2-mm diameter orifice. Droplet size distributions with a Sauter mean diameter (SMD) of 40 to 27 μm are achieved with pressures varying from 100 to 1000 psi, respectively.

NUMERICAL MODEL

The mist dispersion and evaporation model used in this paper has been described previously [1] and is only outlined here for completeness. The mist is discretized using a Monte Carlo approach [2] that requires as inputs four parameters: diameter, speed and two angles of injection. The method assumes a log-normal drop size distribution, Gaussian droplet speed distribution, and uniformly distributed angles of injection. The droplets have the same temperature at injection (300K). The history of each representative droplet thus defined is then calculated as described below. Finally, overall mist behavior is reconstructed by integrating droplet histories in the Eulerian frame. This approach is somewhat similar to that proposed by Schmehl and co-workers [3]. More details regarding this approach are provided in [2].

Evaluation of the mist behavior requires a thorough understanding of in-flight droplet motion. The droplet-gas relative velocity significantly influences the vaporization rate of the droplet in-flight, as well as its trajectory and, therefore, mist penetration. To represent this phenomenon, a simplified version of the particle equation of motion is employed to track the droplets in a Lagrangian manner [4],

$$m_d \frac{d\vec{V}_d}{dt} = F_D + F_T \tag{1}$$

where m_d is the droplet mass, V_d is the droplet velocity, F_D is the drag force, and F_T is the thermophoretic force based on the temperature gradient in the continuous phase.

Depending upon the resolution required by the configuration considered, droplet thermal energy conservation may be evaluated using a lumped parameter approach or using the spherically symmetric transient conduction equation,

$$\frac{\partial T}{\partial t} = \alpha_{\text{eff}} \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) \tag{2}$$

where T is the droplet temperature, α_{eff} is the effective diffusivity, a symmetry condition is enforced at the droplet center, and convective heat transfer is applied at the droplet surface. While it is more computationally intensive than the lumped parameter approach, the resolution of the temperature distribution in the droplet more accurately portrays the evaporation process, especially in situations where the droplet is exposed to large temperature gradients, as is the case here.

As the droplet evaporates, the interface recedes and latent heat is absorbed [5]. The balance between the heat conducted in the droplet, the heat convected from the carrier gas and the enthalpy of vaporization provides the boundary condition at the droplet surface. The evaporation of the droplet is evaluated using Abramzon and Sirignano's extended film model [6],

$$\dot{m} = 2\pi \widehat{\rho_g \mathcal{D}_g} R \, \mathrm{Sh}^{\star} \, \ln(1 + B_M) \tag{3}$$

where ρ_g is the droplet density, D_g is the diffusion coefficient of the continuous phase, B_M is the transfer number, and Sh^* is the modified Sherwood number which, in addition to the convective effects, accounts for the effect of Stefan flow on the mass transfer. The droplet surface temperature is an eigenvalue of the problem obtained from the film model and it is used to calculate the partial pressure of water vapor at the droplet surface using the Clausius-Clapeyron equation [7]. The droplet surface regression rate is then given by:

$$\frac{dR}{dT} = \frac{-\dot{m}}{4/3\pi \rho_{\ell} R^2} \tag{4}$$

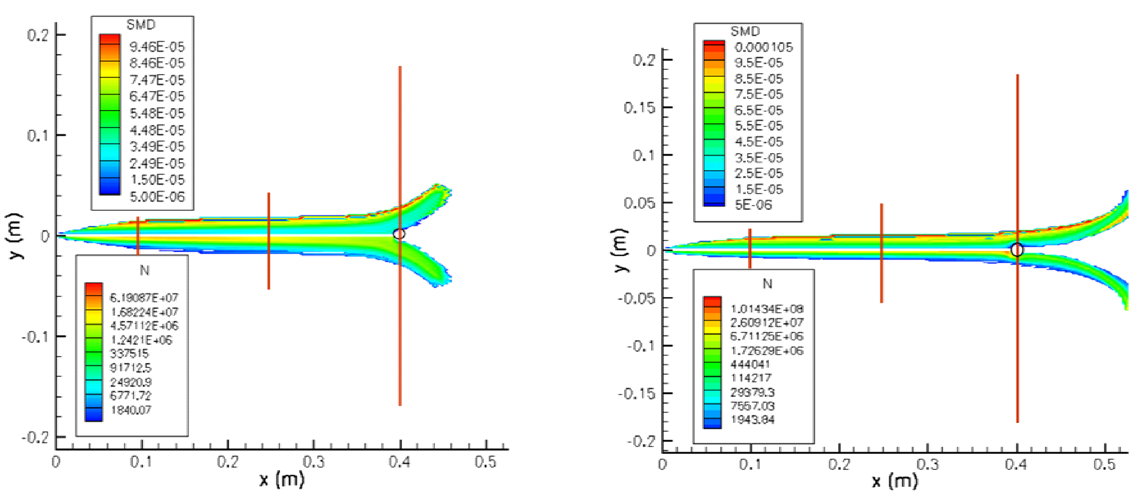
The local gas conditions needed at each location to solve for the droplet equations are obtained by interpolation in a pre-computed background flowfield using the CFD-ACE software code developed by the CFD Research Corporation.

RESULTS AND DISCUSSION

The preliminary tests show that water mist quickly extinguishes a fire that is directly impacted by the droplets, while much longer spraying times and larger amounts of water are required to have an effect on the fires burning behind a baffle. For a water pressure of 300 psi producing a spray with a Sauter mean diameter of 35 μm and a droplet velocity of 5 m/sec, the average extinguishment times for the direct and indirect injection cases were 10 seconds and 95 seconds, respectively. Similarly, the average amount of water used for extinction was 10 ml and 95 ml for the respective cases. For the latter, a gravimetric measurement of the water reaching the wire showed only a 1.5% of the total amount of water injected during the test, indicating that most of the droplets are captured by the baffle and the walls of the container. For larger droplet sizes at the lowest water pressures with the baffle present, the flames were only slightly slowed down, but never extinguished. While the direct injection method is much more effective in extinguishing a flame than the indirect injection method, both cases exhibit similar extinction behavior where the flame shows a brief oscillation between small and large size flames until extinction occurs. This type of pulsating extinction phenomena has been observed before in suppression experiments with water mist [8].

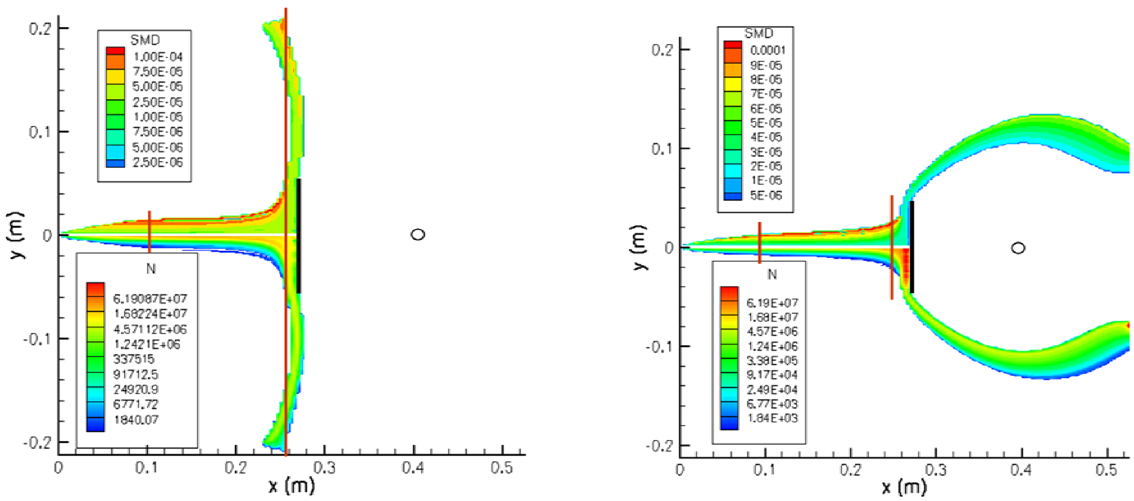
Using the numerical model described in the previous section and using the same mist characteristics as in the experimental tests, a limited parametric study of fire suppression by water mist was conducted. The numerical results show the dispersion and evaporation of droplets as they move towards the fire source in the container used in the normal-gravity tests. The numerical simulations occur in a 2-D configuration coinciding with the experimental locker setup to predict the fire suppression ability of the mist. The four relevant configurations are constructed by varying two parameters: the presence of an obstacle, and a coflow in the locker. The four spray development plots in Figs. 3 and 4 show the resulting spray conditions present in each of the four cases. The presence of the coflow greatly influences the temperature field seen by the mist. In the two cases with the coflow the locker temperature is lower, because the residence time in the chamber is affected by the coflow. The presence of the baffle also creates two circulation zones, divided by the baffle. These zones greatly affect the ability of the droplets to interact with the burning wire and are highly dependent on the position of the two outlets on the wall behind the burning wire. The circulation zones also will affect the temperature field seen by the droplets.

The fire suppression ability is exhibited by the Sauter mean diameter (SMD) and number density (N) profiles produced by the numerical simulations. The two cases evolving in the field without the obstacle, exhibit similar flow patterns, and both have direct spray interaction, where the high latent heat of vaporization of water can be utilized. The direct interaction scenario is ideal for fire suppression. The coflow also influences the suppression ability. In the specific burning wire case, the coflow assists in focusing the spray at the target as seen in Fig. 3b. This is evident in the comparison of the two cases. The number density in the coflow assisted case is two orders of magnitude higher, thereby increasing the enthalpy removal from the flame.



(a) (b)

Figure 3. Predicted water-mist Sauter mean diameter (SMD) and number density (N) profiles with (a) no coflow and (b) a 5 m/s coflow.

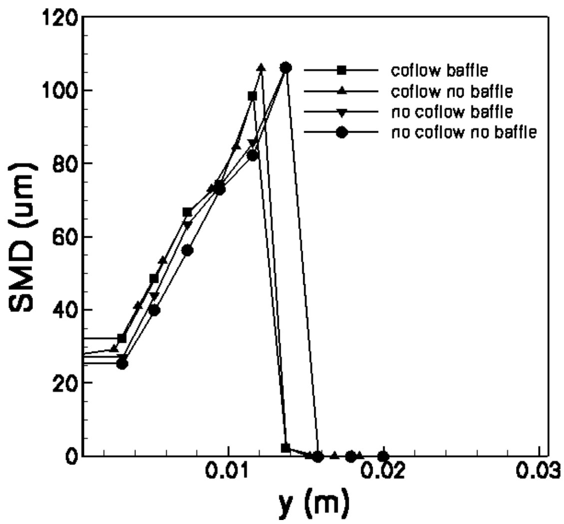


(a) (b)

Figure 4. Predicted water-mist Sauter mean diameter (SMD) and number density (N) profiles evolving around an obstacle with (a) no coflow and (b) a 5 m/s coflow.

The two direct spray scenarios are in stark contrast to the scenarios involving the baffles. In the latter, the obstacle provides a limitation to the effectiveness of the high-momentum mist injectors used. Figure 4 shows how the baffles serve to deflect the flow, causing the predicted Sauter mean diameter maps. The predicted behavior shows no direct interaction between the mist and the burning wire. In the case without the coflow, the droplets do not have significant inertia to move around the obstacle and instead a large recirculation region is generated, where the mist will eventually impinge on the chamber walls. In the case with the coflow however, the droplets get diverted and move around the obstacle. The reattachment length for the spray occurs past the chamber wall, making it impossible to have direct interaction with the wire. The experimental results show that the wire will interact with only about 1.5% of the mist by mass. The discretization process associated with the numerical model is not accurate to that low percentage level. Increasing the number of representative droplets would increase the model accuracy and might allow the description of this interaction. In the current scenarios, the lack of interaction would suggest, as confirmed by experiments, that fire suppression effects would be minimal, and they would mainly be due to mechanisms other than enthalpy extraction.

The radial SMD profiles elucidate the interaction conditions. Figure 5a shows the difference in the radial spread of the mist, at 10 cm away from the injector, in which the 5 m/s coflow concentrates the mist flow into the center, where the spray/wire interaction will be increased, effectively enhancing the suppression effect. Fig. 5b shows the divergence of the mist around the obstacles at a point 25 cm away from the injector and the eventual recirculation region of the mist without the coflow. The direct interaction seen in Fig. 5c at the wire location, 40 cm away from the injector, predicts a larger SMD in the case with the coflow. The number density plots in Fig. 3 would suggest that the total mass flow rate required for suppression would be less than the situation without the coflow.



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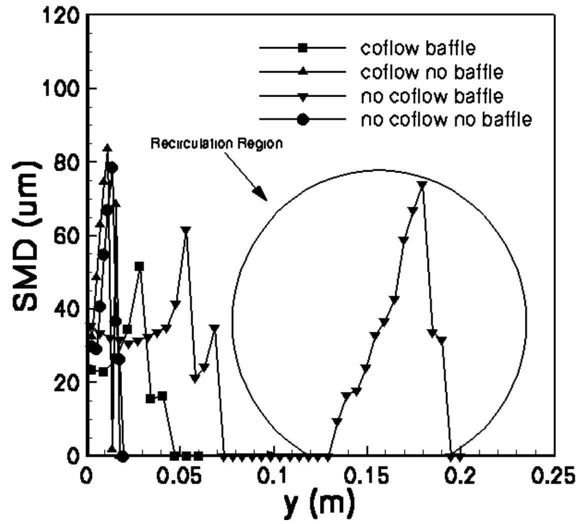

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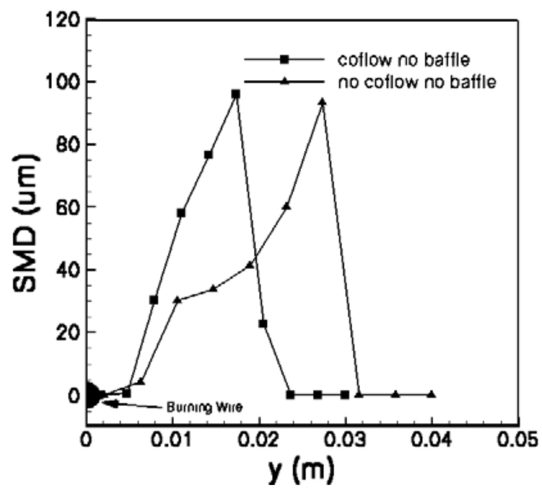

(c)

Figure 5. Radial SMD profiles at various axial locations: (a) 10 cm, (b) 25 cm, and (c) 40 cm, with the latter showing the interaction of the mist with the burning wire.

Based on the results obtained with the high-momentum, large-droplet-size jets, we have recently started a series of tests with low-momentum, ultra-fine mist for comparison purposes. For these tests, the high-pressure nozzles were replaced by an ultrasonic mist generator developed by NanoMist Systems, which generates a droplet size distribution with a SMD lower than 10 μm at flow speeds in the vicinity of 0.5 m/s. From the few cases run to date, it is clear to see that ultra-fine mist can easily go around the baffle and rapidly flood the entire container in a gas-like manner. For the same experimental conditions described in previous sections for the indirect-injection case with a baffle, the flame propagating down the insulated wire was extinguished by the ultra-fine mist with an average of 4 ml of water in approximately 10 seconds, an order of magnitude lower, in both extinction time and water amount, than the high-momentum, large-droplet-size spray jet.

CONCLUSIONS

A preliminary experimental and numerical investigation on the effectiveness of water mist as a suppressant in electrical fires under normal-gravity conditions for spacecraft applications has been conducted. Direct and indirect water-mist injection is used with various droplet-size distributions and flow rates to extinguish a burning wire inside a container similar to the Space Shuttle mid-deck locker. Water mist quickly extinguishes a fire that is directly impacted by the droplets. However, much longer spraying times and larger amounts of water are required to suppress fires burning behind a baffle. Extinction times and water amounts are reduced as the droplet size distribution is lowered. A numerical model simulating the generation, evaporation, and distribution of a polydispersed spray accurately captures the phenomena observed experimentally. This experimental-numerical comparison has provided valuable information in the on-going validation of the mist dispersion sub-model, which is part of a three sub-model suite (along with the fire and radiation sub-models) required for the final development of a reduced order model to describe the complete fire suppression process.

As a result of the ineffectiveness of high-momentum, large-droplet-size spray jets to maneuver around obstacles and extinguish obstructed fires, the research effort is now shifting to the study of low-momentum, ultra-fine mist as a technique to produce total flooding of the confined space and effective suppression even in complicated geometries with fires hidden by multiple obstacles. The preliminary results obtained on the suppression of a burning wire with ultra-fine mist show an order of magnitude reduction in the time and the amount of water needed to extinguish the fire. These promising results have prompted an evaluation of ultra-fine water mist as a potential agent for the suppression of the fire types most likely to be encountered in spacecraft applications. An experimental and numerical feasibility study of the fire suppression properties of ultra-fine water mist will constitute the next phase of the project.

ACKNOWLEDGMENTS

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WATER MIST FIRE PROTECTION SYSTEMS FOR TELECOMMUNICATION SWITCH GEAR AND OTHER ELECTRONIC FACILITIES

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SUMMARY

Although water is known to be an effective Class A and B fire suppressant, scepticism remains over its use in Class C applications due to its conductivity. Therefore, a joint Kidde-Fenwal/GTE/FSI Research feasibility study into water mist fire protection in live telecommunication switch gear was carried out.

The switch gear bays, which were composed of vertically mounted, parallel printed circuit boards (PCBs), were found to be a considerable fire threat. A localised 'in cabinet' fire suppression system comprising single fluid spray nozzles operating at high pressure was used. Test fires were extinguished in 1-2 seconds using less than 1 L (0.26 US gal) of water. In addition, the current trips contained in the switch were activated when water was incident and this result, coupled with the low volume of water used, reduces the electric shock hazard considerably.

Therefore, water was found to be an efficient and safe fire suppressant in switch gear. Since these initial experiments, further tests have been carried out on alternative equipment supplied by Mercury Communications, for which findings are briefly presented.

1. INTRODUCTION

The FSI Research Department is a group of about 20 scientists and engineers which undertakes projects on behalf of the companies within the FSI Group (Kidde-Graviner and Kidde-Hartnell in Great Britain, Kidde-Fenwal, Walter Kidde Portables, Walter Kidde Aerospace, Fenwal Safety Systems and Detector Electronics in the USA, Deugra in Germany, Kidde-Dexaero in France and Pyron in Australia). FSI Research's extensive experience in water mist technology, including its computer cabinet fire protection studies, prompted Kidde-Fenwal, in conjunction with GTE, to initiate a feasibility study into water mist fire protection in telecommunication facilities.

Gas-flooding systems are commonly employed in computer installations whereby a gaseous fire extinguishing agent is introduced into an enclosed space via either a fixed pipe system from a large storage vessel or by a number of in situ pressurised bottles. The conventional agents used in these applications are the Halons 1211 and 1301 and CO_2. The advantages of these extinguishants when used as a means of protecting sensitive electronic equipment are that they are non-conductive and able to permeate to obscured fires.

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Problems arise when using CO_2 because the concentration required to suppress fires (around 30%) will be lethal to humans. Measures must be taken, therefore, to ensure that all staff are evacuated from the room prior to discharge, and that re-entry is delayed until the area is fully ventilated. Other problems encountered include damage to equipment caused when objects are dislodged by the fast discharge of a large volume of gas, and thermal shock resulting from the rapid cooling of the air during this process.

Halon 1211 has a suppression design concentration of 5 to 8%. This gas is toxic at these concentrations, however, resulting in dizziness and impaired co-ordination as well as some risk of cardiac arrhythmias. In common with CO_2, therefore, persons should not be present in the protected space during or directly following discharge. Halon 1301 is less toxic than 1211; a concentration of up to 7% does not cause undue effects in humans. Since it is inherently safer than 1211 or CO_2 at effective fire fighting concentrations, Halon 1301 used to be the preferred option for gas flooding.

Halons, however, have been shown to be responsible for a considerable part of the damage to the ozone layer observed since 1978. As a result, they were included in the list of compounds whose production is to be controlled and ultimately phased out under the Montreal Protocol [1]. This legislation sought to control the production of Halons at 1986 levels and subsequently reduce them. These control measures were further tightened in 1990 at the London Review Meeting of the Montreal Protocol [2]. A further review took place in Copenhagen in November 1992 and as a result, a total ban on Halon production is now being implemented as early as January 1994.

Clearly there is an urgent need to find a suitable replacement fire suppression system, with water mist being one possible candidate as it has been found to be an efficient Class A and B fire suppressant and is also non-toxic, cheap and environmentally friendly.

1.1 Water as a Fire Suppressant

Water's favourable physical properties are utilised when it is employed as a fire suppressant. Its high heat capacity (4.2 $J\ g^{-1}\ K^{-1}$) and latent heat of vaporisation (2442 $J\ g^{-1}$) result in the abstraction of heat from flames and fuel, leading to extinguishment. In addition, the steam produced upon evaporation aids extinguishment by diluting the vapour phase concentration of fuel and oxygen (water expands 1700 times upon evaporation to steam) [3].

To achieve its full thermodynamic potential, water is produced in the form of a spray thus maximising the surface area for heat absorption and evaporation. It follows that finer sprays are more efficient at heat absorption relative to more coarse sprays.

To extinguish Class A and B fires rapidly, direct impingement is essential. Also, for Class B fires, complete surface coverage of the fuel is important. For direct impingement to be efficient, the downward momentum of the spray must overcome the upward thrust of the flames and fire gases in order to penetrate to the combustion zone. Furthermore, droplet size must have a lower limiting value because droplets must be large enough to penetrate to the core of the fire [4].

In some environments, direct impingement of spray onto a fire is not possible. However, water fog can be used as a 'total flood' agent in these cases. Again small droplets facilitate extinguishment, the droplets being entrained into the flames. Extinguishment is brought about by the gradual cooling of the flames and the inerting effect of localised steam production.

Scepticism remains over the use of water in Class C environments as it conducts electricity which could lead to equipment damage and shock hazard to personnel. Recent research suggests it is possible to use water spray in Class C facilities safely and without causing damage [5]. The aim of this project, therefore, was to establish the feasibility of using water spray/mist in telecommunication installations. To this end, GTE donated 34 2EAS telecommunication switch gear bays plus power supplies to Kidde-Fenwal for trials work, the testing taking place at Fenwal Safety Systems Inc., Combustion Research Centre in Holliston, Massachusetts.

Fire suppression studies in telecommunication facilities have so far been limited to cable fires, where it is agreed the main fire threat lies, and it has been shown that water spray is effective against such fire challenges [5], [6]. We believe that this is the first study into fire suppression in telecommunication switch gear and intend to prove that there was indeed a fire threat associated with this equipment and that water fog can be an efficient, safe and non-destructive extinguishant.

It was made clear at the outset of this project that GTE did not want a total room flooding water mist system because of the potential disruption this may cause to non-affected switch gear bays contained in the suite; GTE stipulated that all switch gear bays not affected by fire must remain live.. Tests were largely confined, therefore, to systems deploying water spray within the switch gear bays themselves.

2. EXPERIMENTAL CONSIDERATIONS

2.1 GTE 2EAS Switch Gear

The switch gear bays contained several types of PCBs separated at different intervals depending on the function of the bay. The PCBs contained in the switch were either relay boards, Complementary Metal Oxide Semiconductor (CMOS) control boards or power supply units. The dimensions of a typical switch are shown in Figure 1.

The switch gear bays chosen for all the fire tests had the densest array of printed circuit boards possible, with the boards being positioned such that void channels ran vertically through the bay, allowing direct impingement of top-mounted sprays onto the test fire. These bays had PCBs with separations of 0.01 m.

The switch gear bays were powered-up using a 50 V/10 A DC battery charger.

2.2 Ignition Method

Nichrome ribbon (0.5 m x 0.005 m) was weaved into four slits (0.10 m) cut into a reed relay board stripped of all its components (Figure 2). The wire was connected via spring loaded clamps to a 20 A variable transformer. The Nichrome ribbon glowed red and caused ignition within 30 seconds when approximately 30 V AC was supplied.

2.3 Instrumentation and Measurements

2.3.1 Temperature Measurement

A total of 12 mineral insulated bare tip type K (nickel chromium alloy/nickel aluminium alloy) thermocouples were deployed in most experiments. The positions of the thermocouples used during the test programme are given in Figure 3.

2.3.2 Smoke Measurement

The obscuration equipment was a two part system comprising a remote optical head unit linked to an amplifier/driver unit, the former being mounted above the switch (Figure 4). A 4 Hz light signal generated from a 2 V, 340 mA filament lamp was passed through a collimating lens and directed across a 30 cm path length to a collecting lens. The light was focused onto a BPW 21 photodiode and the resulting signal amplified and passed to the amplifier driver unit via a 20 m cable. Signals to the 4 Hz lamp and from the amplifier photodiode were fed into an AD630 phase detector integrated circuit in order to enhance the smoke obscuration signal, thereby enabling the unit to operate in high and variable ambient light conditions. The analogue voltage produced was then passed to an Orion data acquisition system (see section 2.3.7).

2.3.3 Radiation Measurement

An infrared (IR) flame detector was positioned at a height and distance of 0.5 m and 1.2 m respectively. The detector comprised a thermopile fitted with a 4.4 μm filter, with the signal produced being amplified and recorded by the data acquisition system. A flame flicker signal was also recorded by AC coupling the amplified signal.

2.3.4 Hydrogen Chloride Concentration Measurement

A Servomex 1490 IR analyser was used to monitor constantly the concentration of hydrogen chloride (HCl). The inlet tube for the analyser was positioned above the switch (Figure 4), the gas reaching the analyser by means of a small air pump.

2.3.5 High Sensitivity Smoke Detection

A Kidde-Fenwal high sensitivity smoke detector (Analaser) was used in some experiments. The inlet tube for the Analaser was placed above the switch gear bay (Figure 4).

2.5.2 Suppression Tests

For each nozzle manifold position, the fire challenge was the same in terms of relative position and intensity. The distance between the nozzles and fires was as large as possible and the densest array of PCBs was chosen to maximise the degree of obstruction to the spray.

Pre-burn was measured from the commencement of flaming combustion and was judged visually. The water fog was activated after flaming combustion was sustained on the level above the ignition source; the time for this to be achieved was usually between 90-180 seconds.

3. RESULTS

3.1 Unsuppressed Fire Test

Ignition was by the Nichrome ribbon method (see section 2.2) and the ignition board was placed in a central position at the base of the bay. Dense red smoke was produced upon ignition, the smoke obscuration above the bay reaching 100% in seconds. Upon the commencement of flaming combustion, the smoke lost its red coloration.

After ignition the fire was found to propagate vertically up the switch, with temperatures reaching 600-800 °C. As the intensity of the fire increased, more lateral spread was apparent and at its peak, temperatures were in excess of 1000 °C with flames rising 2-4 m above the bay.

Smoke obscuration inside the building reached 100% within 20 minutes. IR flame flicker measurements revealed combustion ceased after 30 minutes. No hydrogen chloride was detected in the course of this experiment.

3.2 Fire Suppression Tests

3.2.1 General Comments on Instrumentation Results

In general, maximum temperatures at the ignition source were between 350-500 °C, with the rate of temperature rise being in the order of 100-200 °C/min. Thermocouples placed at the top of the switch did not show consistent temperature rises, if any temperature rise was recorded at all.

3.2.2 Smoke Obscuration and High Sensitivity Smoke Detector Results

Smoke obscuration above the switch gear bay reached 100% within seconds of the activation of the Nichrome ribbon. The Analaser, when used, went into alarm immediately after the Nichrome ribbon was switched on. When the nozzles were placed at the top of the bay, the smoke obscuration fell markedly upon activation of the spray.

3.2.3 Hydrogen Chloride Analysis

The concentration of hydrogen chloride never rose above 10 ppm in any of the experiments conducted, with no HCl detected in the majority of tests.

3.2.4 Pressure Measurement

Pressure measurement at the nozzle manifold enabled the pressure drop between the bottle and nozzles to be determined and hence allowed the accurate calculation of flow rates based on manufacturer's data.

3.3 Suppression Results

Fire tests conducted with nozzle manifolds mounted at the top of the switch revealed that single fluid, full cone and narrow discharge angle nozzles operating at high pressures were the most efficient types. The high velocity fogs produced by these nozzles could repeatedly extinguish a test fire within 2 seconds using less than 1 L of water.

High water flow rate, low pressure, coarse (sprinkler like) sprays used more water and gave longer extinguishment times than the high velocity fogs. In addition, low water flow rate, low pressure, fine sprays used in recent studies [5] consumed more water and gave longer extinguishment times than the high velocity fog.

Air atomising nozzles gave good results for small scale test fires. However, if a fire was of greater intensity, these nozzles resulted in longer extinguishing times and used more water than the high pressure single fluid nozzle combination.

The high pressure single fluid nozzle combination was also found to give the best results when mounted at the bottom of the switch, although their performance was not as good as when they were placed at the top of the bay.

Wide cone angle single fluid nozzles operating at high pressures gave good results when mounted at the front of the switch.

Remote room fogging experiments proved to be far less effective than the in-cabinet arrays.

3.4 Discharge Tests on Live Switch Gear

The different types of switch gear were all powered using a 50 V (DC) battery charger. Tap or distilled water was discharged onto the switch using a frontal nozzle array. As soon as water was in direct contact with the PCBs, the trips contained were activated, cutting off power to the switch. All the switch gear bays became fully operational when dry.

Some PCBs were connected to the mains 110 V supply. Circuit breaks were activated upon the application of water. Again, the boards became fully operational when dry.

3.5 Suppression Tests in Live Switch Gear

Fire suppression tests were conducted on live switch gear. The trips contained in the switch gear bay were activated when water fog was incident. Occasionally, smoke from the fire activated trips prior to suppressant discharge.

Fire characteristics were not different from those in unpowered switch gear. The fires were extinguished in under 2 seconds using the optimum top-mounted, single fluid nozzle, high pressure array.

The switch became fully operational when dry (except for the fire damaged cards). The long term effect of the exposure of PCBs to smoke, fire and water is being examined by GTE.

3.6 Leakage Current Measurement

Leakage currents between two parallel tracks on a PCB surface were measured using the apparatus described in Section 2.3.8. The leakage currents for distilled water, tap water and the condensed material from smoke were 18, 45 and 56 μA respectively with resistances of 1.80, 0.21 and 0.20 MOhm respectively.

4. DISCUSSION

4.1 Unsuppressed Fire Test

The damage caused by a fire in a switch gear bay is extensive. The PCBs directly affected by the fire are rendered completely unusable. The IR output and thermocouple measurements of the fire reach maximum values in about 10-12 minutes with temperatures high enough at the peak of combustion to melt some of the solder and aluminium components contained on the PCBs. The combustible-rich smoke plume leads to flames reaching 2-4 m above the switch gear bay.

The lateral spread of the fire, coupled with the flames in the smoke plume and high temperatures, means that the chances of the fire remaining contained in a single switch gear bay if unchecked are minimal. The cables usually present above the bay would be easily ignited by flames in the smoke plume, and the proximity to other switch gear bays in normal operation means neighbouring bays are also likely to burn.

4.2 Suppression Tests

The high velocity fogs produced by single fluid nozzles at high pressures proved to be the most efficient fire suppressing combination when placed either at the top, bottom or front of the switch. In addition to the other benefits of fine sprays, the high velocity fog is able to negotiate obstacles and penetrate to the seat of a fire.

When placed at the top or bottom of the switch, narrow cone angled sprays concentrate the water inside the bay, leading to rapid extinguishment. Figure 7 shows the temperature profile at the core of the test fire and shows a dramatic reduction in temperature after the activation of the water fog.

Although air atomising nozzles produce high velocity fogs, the amounts of water used were too low to extinguish efficiently a test fire.

Coarse sprays in common with those used in a recent telecommunication fire suppression study [8] and 'sprinkler like' sprays were not effective against this fire challenge. These large droplet size, low thrust sprays were unable to negotiate obstacles and penetrate to the seat of the fire.

Room fogging experiments were less successful than the 'in-cabinet' tests as the concentration of water around the core of the fire was not high enough to bring about rapid extinguishment. Total flood water fog or sprinkler systems were not favoured by GTE in any case (vide supra).

Frontal nozzle arrays were effective as there was less obstruction to the spray. However, it is difficult to envisage the unobtrusive installation of such a manifold.

Experiments conducted on live switch gear showed that water fog did not damage the electrical equipment contained in the bay. The shock hazard associated with such equipment is low as the power was cut-off to the switch gear bays upon the activation of the fog. The switch gear bays became fully operational when dry. In addition, there was no reduction in performance of the optimum single fluid, high pressure nozzle array when suppressing a fire in a live switch relative to an unpowered bay.

The simple conductivity measurements revealed that the smoke produced by the burning circuit boards was more conductive than tap water, explaining why, in some experiments, trips were activated before the actuation of the water spray.

5. CONCLUSIONS

This study shows that the PCBs contained in the 2EAS switch gear were a substantial fire threat and if a fire occurred, the loss of revenue due to down time and salvage could be enormous.

As a potential candidate for fire suppression in these situations, 'in-cabinet' water fog has been found to be extremely effective, safe and non-destructive. Coupled with this, water is non-toxic, environmentally friendly and cheap.

There is no foreseeable problem in designing a fully integrated 'in-cabinet' system including 'double knock' (dual) activation of a clean, initially dry spray manifold. Therefore, the drawbacks of conventional water systems (large volumes of water, accidental discharge, leaks and impure water) have been addressed and negated.

6. CURRENT TEST WORK

It is recognised that these trials are confined to one particular type of telecommunication cabinet and that more work is required on different types of electronic equipment before a 'universal' protection system is available.

A recent visit to Mercury Communications premises in central London showed there to be a variety of systems hardware of differing function and geometry where direct impingement of water fog was not possible. In addition, the fire threat associated with bundles of coaxial cables laid in metal trays positioned above the cabinets would have to be addressed.

Links have been forged between Mercury Communications with a view to further testing of 'in cabinet' water spray. An on-going project using Mercury Communications electronic cabinets has shown water fog to be versatile. Mercury's fully-enclosed cabinets usually contained PCBs; however, many different types of equipment are also contained, making direct impingement of water fog from either the top or bottom impossible.

Figures 8 and 9 show diagrams of Mercury equipment and the fire challenge tackled in the current test program. Results so far show that obscured fires can be extinguished by water fog produced by nozzles placed inside the cabinet using less than 1 L of water. These test fires are believed to be extinguished by the cooling effect of entrained water fog and the inerting effect of water vapour. Although this testing is in its early stages, it is envisaged that the 'in cabinet fogging' system may be successfully applied to a wide variety of telecommunication and other electronic installations.

7. ACKNOWLEDGEMENT

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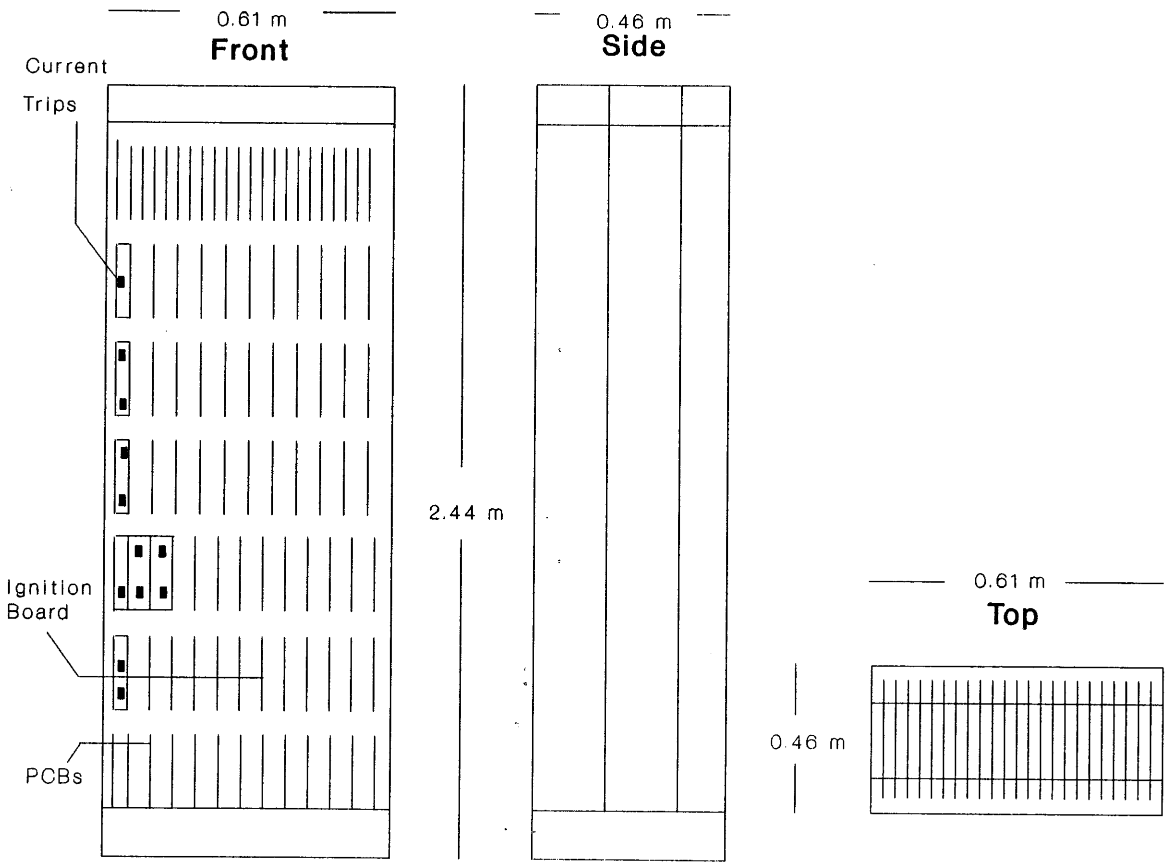

Figure 1: A Typical Switch Gear Bay and Position of the Ignition Board

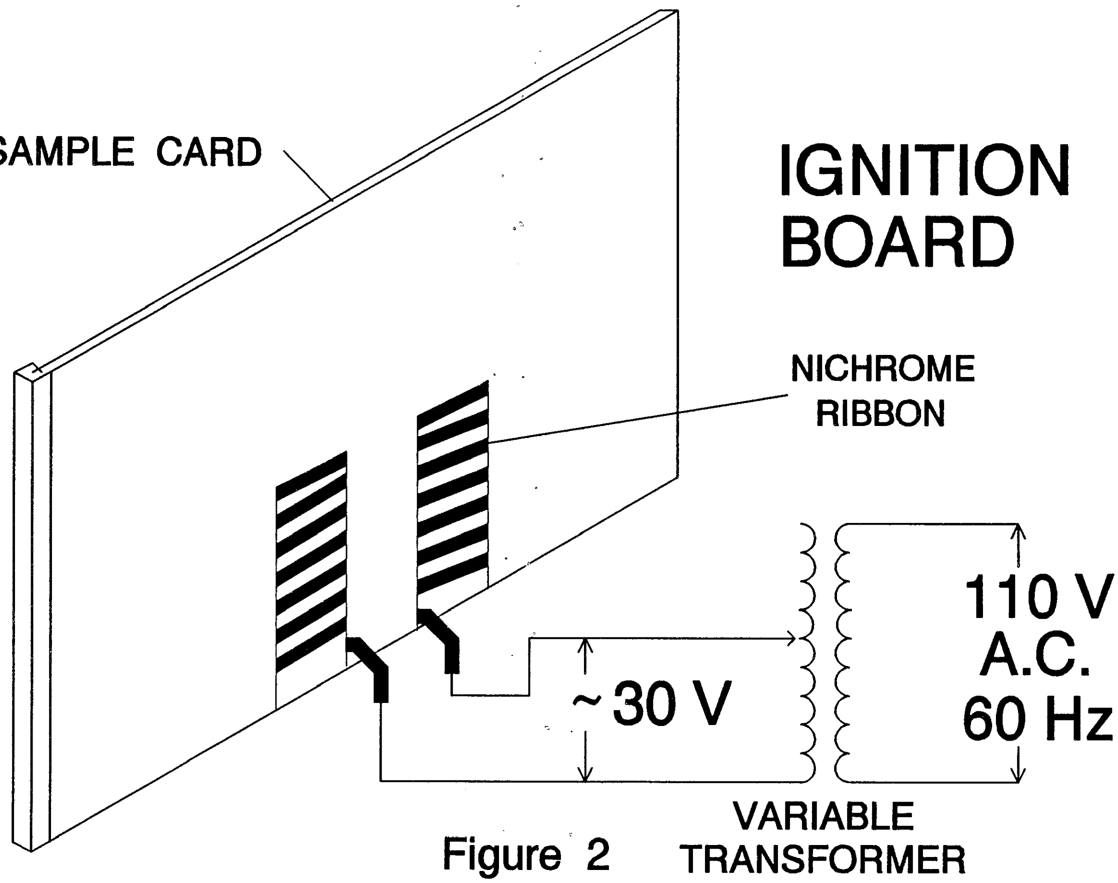
SAMPLE CARD
IGNITION BOARD
NICHROME RIBBON
~30 V
110 V A.C. 60 Hz
VARIABLE TRANSFORMER

Figure 2

THERMOCOUPLE POSITIONS

TESTS 2 - 18, 22, 28 - 34.

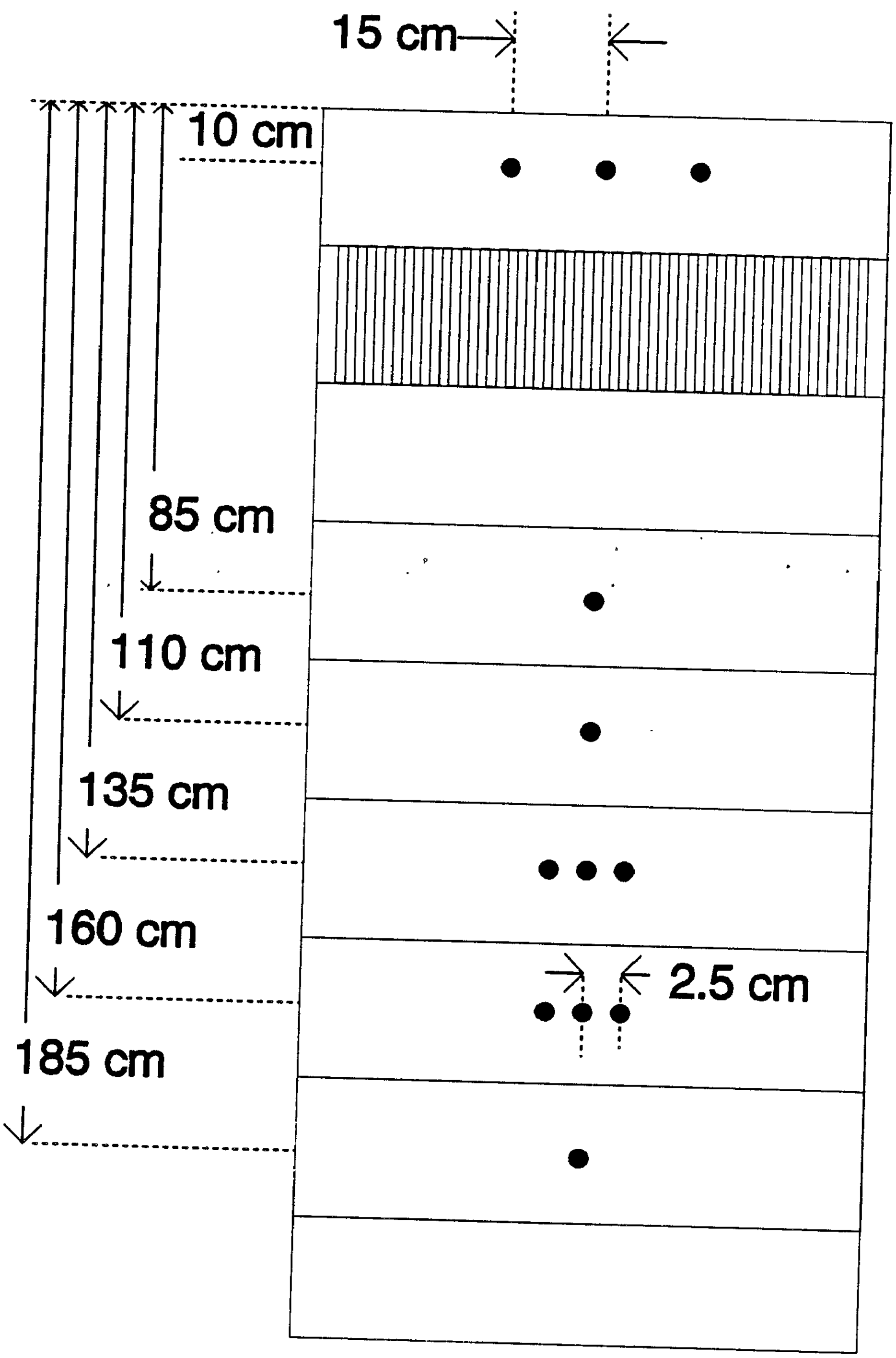

Figure 3

SENSOR POSITIONS

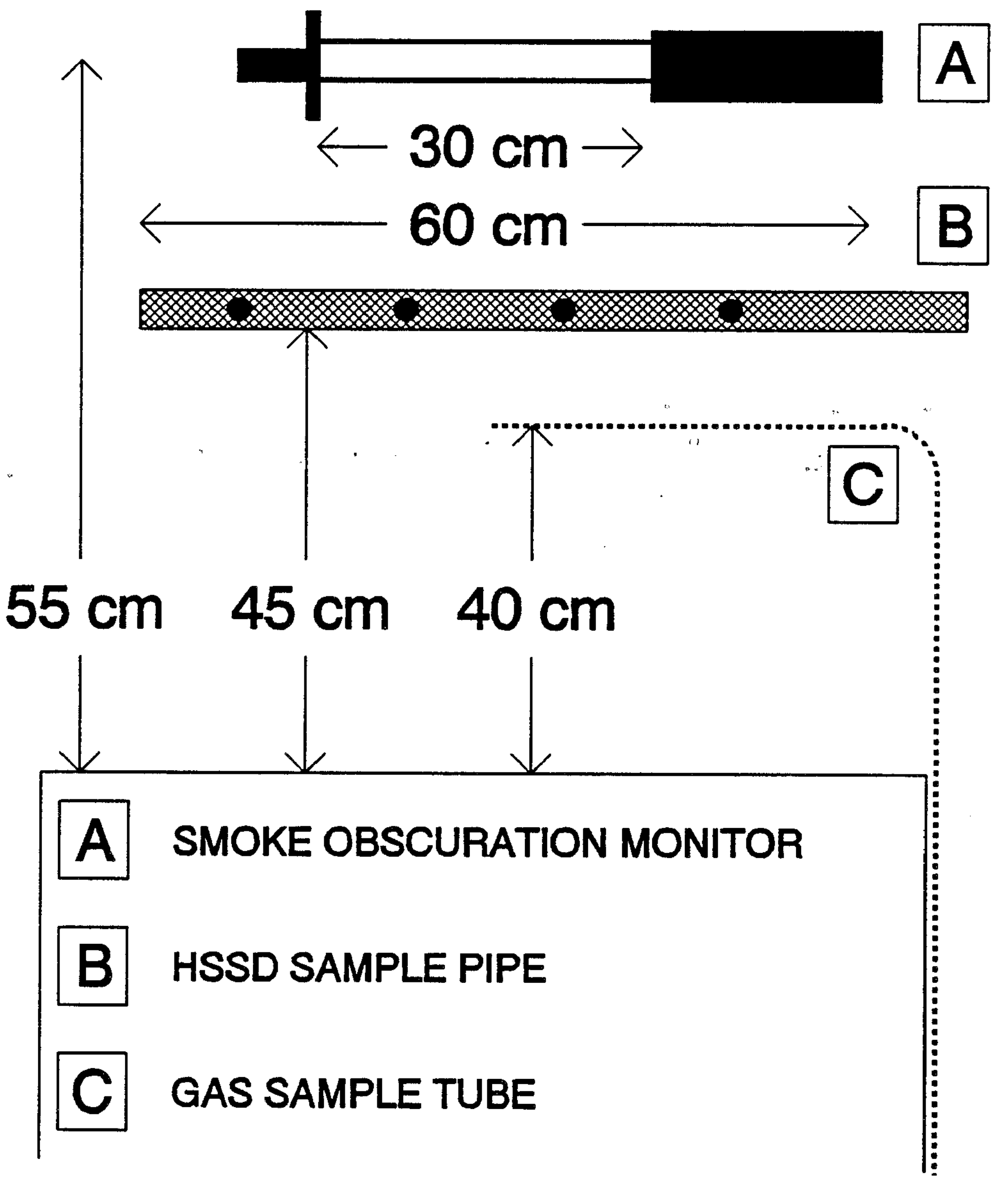

Figure 4

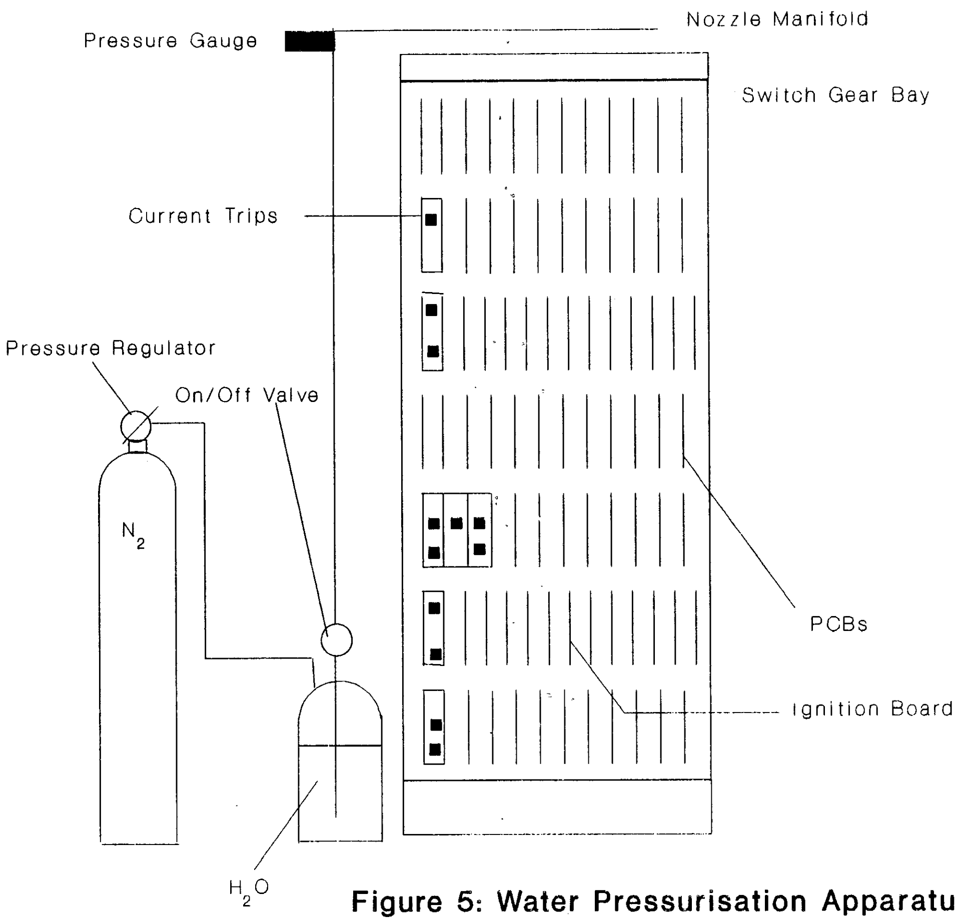

Figure 5: Water Pressurisation Apparatus

DATA LOGGER CONNECTIONS

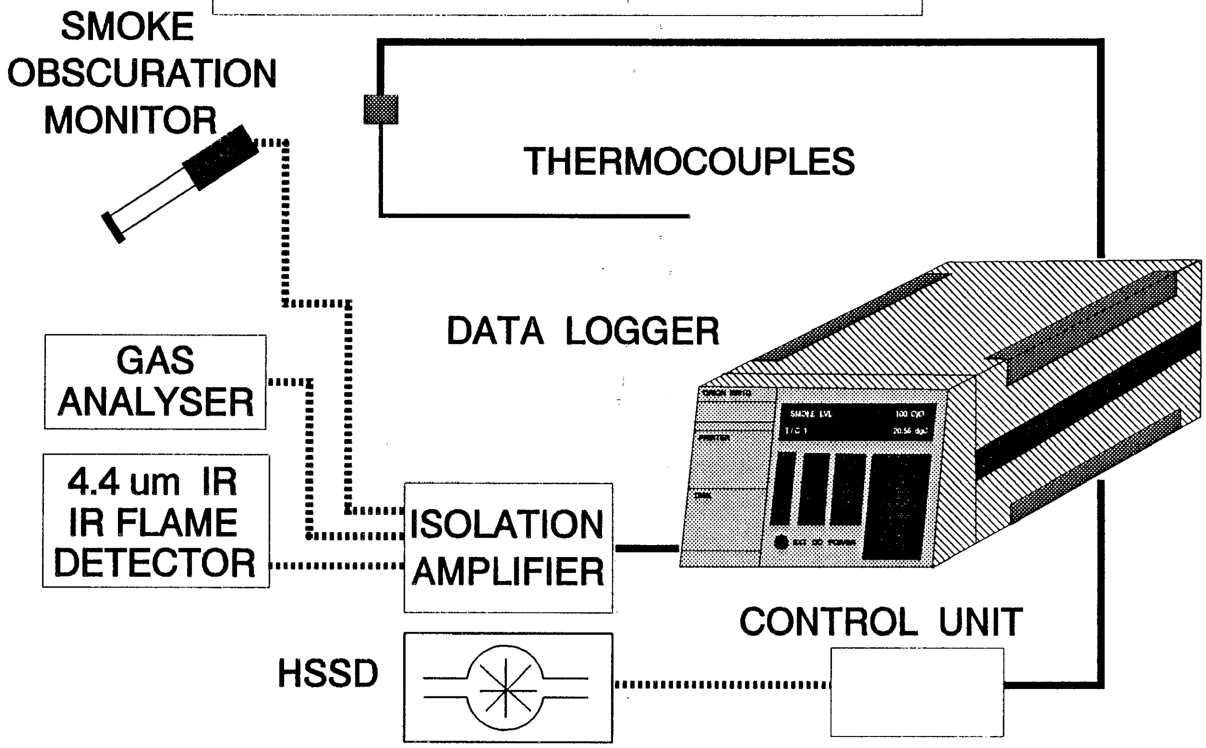

Figure 6

FIGURE 7

TEMPERATURE PROFILE FOR EXTINGUISHMENT BY HIGH VELOCITY FOG

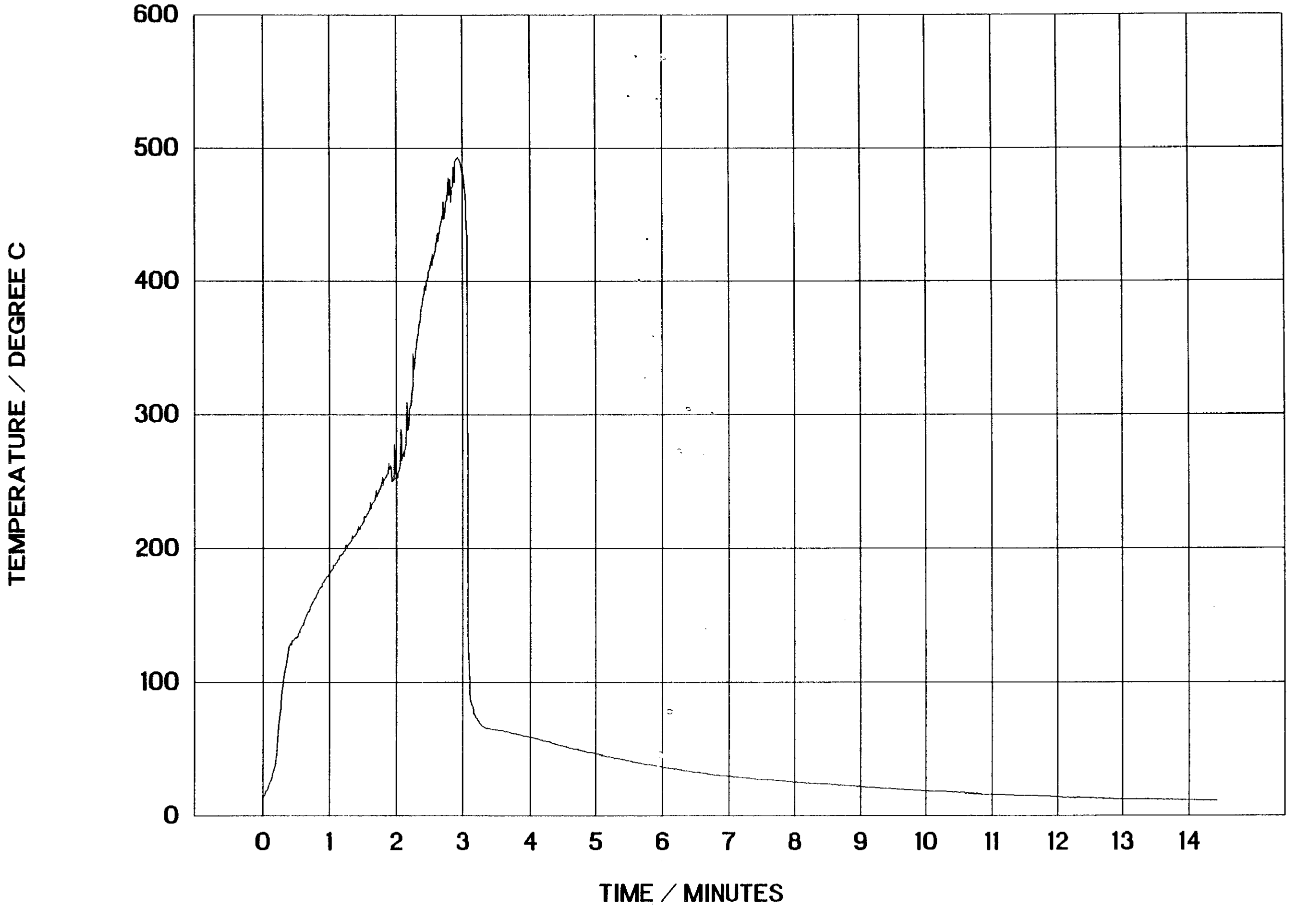

Figure 8: External features of an enclosed telecommunication cabinet

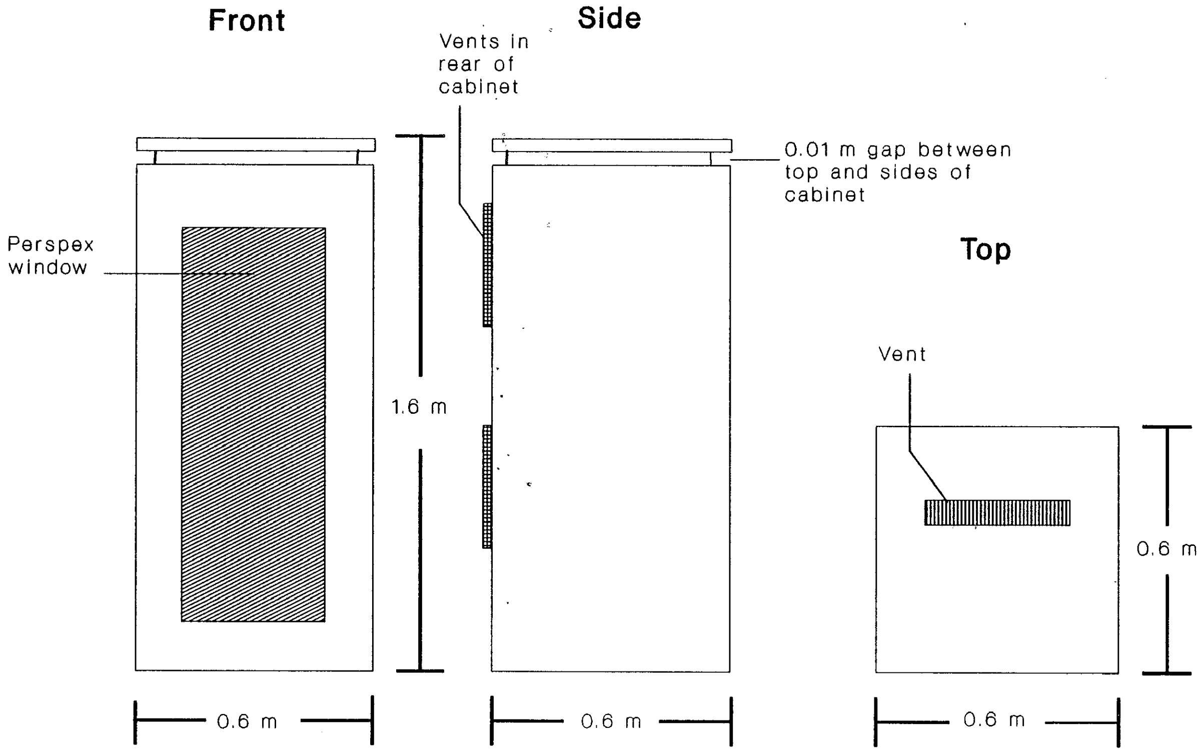

Figure 9: Fire challenge inside an enclosed telecommunication cabinet