PYROGENIC AEROSOL FIRE SUPPRESSANTS: ENGINEERING OF DELIVERY SYSTEMS AND CORROSION ANALYSIS.

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Abstract

The search for a halon replacement has yielded an effective substitute in the form of particle suspensions or aerosols. Aerosol suppressants have been shown to be six times more effective on a mass basis **than** Halon 1301. Aerosol suppressants are generated by deflagration of a combination of a solid precursor, oxidizer, reducer, and binder commercially known as SFE (Spectrex Eire Extinguishent). In this paper these aerosols are referred to as pyrogenic aerosols. The generation temperature has been measured to be about 2300°C. The uncooled aerosol stream, when released in enclosed areas, will freely convect to the top of the compartment. As the aerosol dissipates and stratifies it becomes a less effective fire suppressant due to the uneven distribution **and** lack of mixing. Delivery system designs **are** presented which achieve cooling of the aerosol stream to an average 55°C. The pyrogenic aerosol was also evaluated for corrosivity effects on metals as per ASTM Standards and Methods. Results indicate a marked difference in corrosivity between three formulations of the SFE aerosol generators. Corrosion rates are presented and results discussed.

Introduction

A new class of fires suppressants, known as ***Encapsulated Micron Aerosol Agents*** (EMAA), having superior volumetric efficiency, low initial and life cycle costs, low toxicity, no known global atmospheric environmental impact (ODP/GWP), and with the potential for a wide variety of applications, is being developed via a joint program between the private sector and the **US** Air Force. A thorough review of the mechanisms and fundamentals of aerosol fire suppression is given by Kibert and Dierdorf.

The pyrogenic generation of aerosol fire suppressant occurs at elevated temperature. The ignition and burn of the solid precursor, binder, and oxidizer liberates aerosol particles (order of 2 µm). In addition to the aerosol stream being liberated, other gases are generated simultaneously which are also exhibit fire suppressing properties. The high temperature nature of **the** generated aerosol and gases (~2000°K at the source) causes the stream to freely convect to high elevations within enclosed areas, thus diminishing fire suppression effectiveness in fires located at low elevations. In addition, the generated aerosols are mainly composed of highly basic compounds (KOH, among others) which in the presence of substantial humidity can cause significant corrosion in metals.

The present work evaluates the engineering development and design of delivery systems capable of producing aerosol and gaseous streams which are cooler and **thus** able to enter into thermodynamic equilibrium with ambient air at a much faster rate. In the case of high temperature discharges the speed at which equilibrium is reached is dependent primarily on the mixing attainable in an enclosed volume. If the temperature is lowered, mixing and thermodynamic equilibrium can be easily reached by normal free convection. Thus the primary objective in designing delivery systems is the lowering of the aerosol temperature. This can be accomplished by a number of heat exchange techniques, including radiative heat transfer, convection, and conduction. At high generating temperatures it would seem reasonable to exchange heat by means **of** radiative transfer. Although this might be the most effective method, it presents inherent hazards which may not be easily accommodated or resolved. A typical design would involve the use of windows which would allow for most of the infrared energy to be dissipated to lower temperature bodies in the surroundings. This might in turn be a source of high heat flux capable **of** starting secondary fires.

A more conventional approach is the use of convective mass transport as a means of stirring and removing heat from the stream of aerosol. This would involve the use of secondary air streams impinging on the aerosol generating device at a rate sufficient to remove heat by diluting and mixing the original aerosol stream. While this approach may seem reasonable it may be cumbersome to engineer.

A more effective approach to removing energy from the aerosol stream involves the use of heat absorbing materials in the path of the aerosol stream. Heat absorbing or heat exchange materials are optimized such.that the rate at which heat is conducted is comparable to the heat capacity of the material. This condition has allowed for the design of a delivery system composed of heat absorbing materials capable of cooling the aerosol stream to within ambient temperature range. This reduction in temperature allows for the aerosol to be dissipated and equilibrate to room temperature within reasonable settling times (seconds versus tens to hundreds **of** seconds at about 2200°C).

Analysis **of** the corrosion caused by the aerosol deposition on metals is **of** importance in determining the viability **of** using this aerosol technology in fire suppression scenarios. It has been found that the aerosol is composed mostly of potassium salts (KCI) and basics **(KOH).** The deposition of these aerosols on metal surfaces has been shown to cause significant corrosion. This paper discusses the results of an ASTM standard study **of** corrosion applied to the deposition of SFE formulations A,B, and C.

ENGINEERING DESIGN OVERVIEW

Testing Procedure

The tests were conducted in an enclosed area of dimensions **1.8** m x **1.8** m x 2.4 m **(7.8** m^3) and K type thermocouples were placed at a distance **of 5** cm away from the aerosol exhausting surface.

Air Discharge

A measurement of the aerosol temperature as released unabated into free air is shown in Figure **1.** The temperature stream peaks at **850** "C. The measurement was made by placing a thermocouple at a distance of 5 cm away from the burning surface.

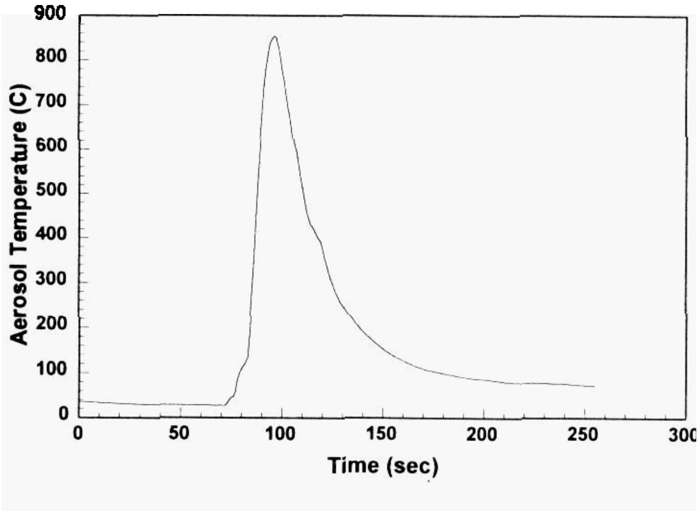


Figure 1. Temperature History of Aerosol Discharge into Open Air.

Water Cooling

As stated earlier the design of an adequately cooled delivery system involved the use of heat absorbing materials **or** fluids. Several trials using water as a coolant showed no significant improvement in the exhaust temperature. In this design, the aerosol stream impinges on a U-tube design heat exchanger which is surrounded by water. The heat exchange generated steam and it was vented along with the aerosol producing a steam aerosol mixture. The resulting aerosol stream temperature history is shown in Figure 1.

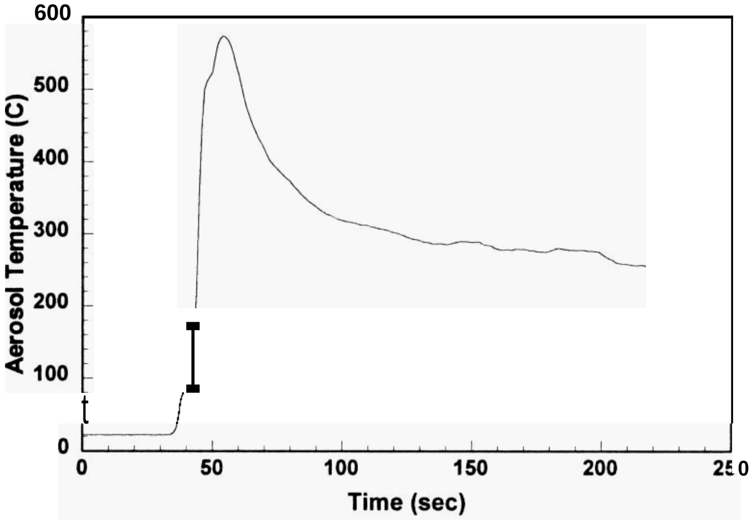


Figure 2. Temperature History of Aerosol Generator Discharge into Delivery System Composed of a Water Jacket.

The aerosol peak temperature reached 570 °C. Even though this represents a 33% reduction in peak temperature, it still represents a large enough temperature whereby settling times are still quite high due to the buoyancy of the hot aerosol. This large temperature is in part due to the comparatively low thermal conductivity of water and the fast heat generation rate of the aerosol precursors.

Solid Bed Cooling

The use of heat absorbing materials to remove thermal energy from the aerosol stream follows from the need to remove heat at a rate similar to that at which it was generated. Solids in general have better thermal conductivity than water, but not as good a thermal heat storage capacity. Another important property of some solids is their high melting point which helps to maintain structural integrity of the device. The principle of cooling is based on allowing the aerosol stream to flow through a packed pebble bed of these heat absorbing materials. The packing of the bed is critical as optimizing the surface area of the pebbles is key to effective heat transfer from the stream to the heat absorbing material. The surface area of the pebbles provides the basis for high convection and thus the heat transfer rates to the pebbles is largely dependent on their packing and available surface area. Using relatively large pebbles, besides adding weight to the device, allows for a less constricted flow thus increasing the total path required for a give amount of energy removal, i.e. it would require more pebbles per unit length. On the other hand, a pebble bed made up of smaller pebbles would present an even larger surface area exposure to the aerosol per unit path length. Thus smaller surface area pebbles would remove more energy per unit path length from the flow.

An additional concern is the adhesion of aerosol particles to the surface of the pebbles. Larger pebbles packed in a bed offer a smaller area to convective heat transfer to the aerosol stream and thus less adhesive area for the aerosol. In the case of smaller pebbles the effective convective area is larger and thus the effective area for adhesion of the aerosol is also large. Thus an optimization process whereby the surface area and overall total volume of the pebbles required to remove heat from the aerosol stream is required. Figure **3** shows the temperature history of an aerosol discharge using **a** bed **of** a mixture of refractory materials to include magnesium and aluminum oxide.

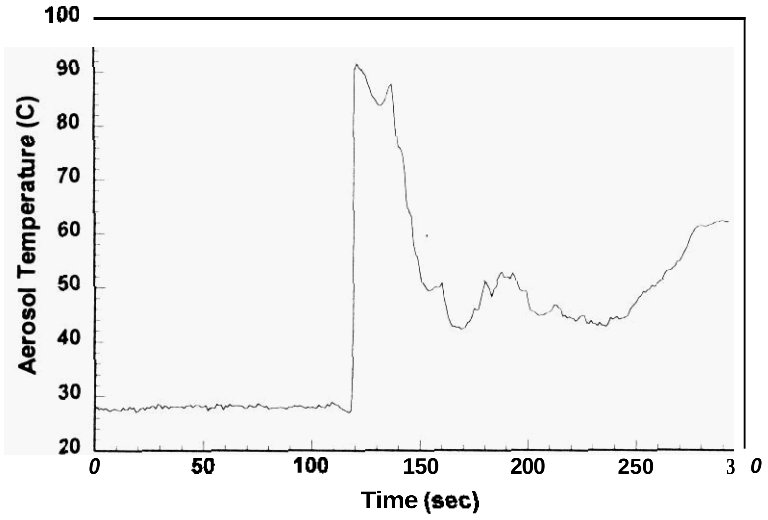


Figure 3. Temperature History of Aerosol Generator Discharge into Delivery System Composed of a Packed Bed of Refractory Materials (Magnesia and Alumina).

The peak aerosol temperature obtained in the refractory packed bed configuration was about 85°C. This allows for a settling time of a few seconds and therefore a more efficient fire suppression in enclosed areas. The achievement of smaller ambient range temperatures allows for the optimization of the design.

AEROSOL GENERATOR DESIGN

The EMAA aerosol generator design has three major components; the housing (including combustion chamber), refractory/insulation material, and ignition system. Given the problems concerning efficient thermal transfer and containment, many different coolant systems were considered. Aerosol cooling must be coupled with insulating the housing from the heat generated, therefore the possibility of a shapable refractory material coupled with **a** packed-bed of spherical refractory media evolved as the most feasible approach. Housing for the generator must allow for high resistance to heat and thermal shock, no pressure buildup of aerosol, and maximum surface area for contact with the aerosol without trapping excess aerosol particulate matter which could limit effectiveness of fire suppression. Finally, a dependable ignition system with a fail-safe device is needed.

The charge is located at the bottom and a bed of pebbles of heat absorbing materials is placed above at a given distance away from the charge. The charge is ignited by means of a magnesium firing squib activated by a 9 volt battery.

Materials

Several criteria were used to choose candidate materials. First, the materials must have a melting point higher than that of the pyrogenic precursor emissions at 10 cm away from the source. This limitation was imposed so **as** to avoid a meltdown of the cooling material and a total obstruction of the aerosol stream, thus causing the potential for overpressure and potential excursion resulting in an explosion. Second, the material should have as high a specific heat as possible. Third the material should be readily and commercially available. Two materials were found which fulfilled these three main requirements. The materials used were magnesium oxide and aluminum oxide. Properties of these materials **are** shown in Table 1. These materials are commonly used for high temperature insulation and water filtering applications.

	Specific Hea (KJ/Kg K) @ 600 K	**Melting** Point **(C)**	**Enthalpy** of **Fusio (KJ/mol)**
Aluminum Oxide	11.09	2054	78
Magnesium Oxide	1.17	2826	1111

Table 1. Thermodynamic properties of heat absorbing materials

Packed Refractory **Bed** Thermodynamics

The design and fabrication of the EMAA aerosol generator utilized refractories for thermal exchange and performance data of EMAA combustion. Ideally the goal for the generator is to cool the aerosol to approximately **80°C** at discharge. From previous tests, the heat generated upon combustion for EMAA formulation **A** is 4007 KJ/Kg, which provides **2003** KJ from a 0.5 Kg charge designed to provide coverage **for** a 10 m^3 volume.

If water alone were used as a coolant, the amount necessary would be the amount of heat (2003 KJ) divided by the latent heat of water (2274 KJ/Kg @ 1 atm @ 100 C) or 0.88 Kg of water. Unfortunately, because water vaporizes so quickly at these temperatures and has such a low thermal conductivity, it alone is not a suitable candidate.

As previously discussed, alumina (Al_2O_3) is an excellent refractory. The measure of alumina's ability to cool the aerosol is measured by its specific heat at constant pressure, c_p. This is defined as the quasi-static heat flux per mole required to produce unit increase in the temperature of a system maintained at constant pressure. Using the c_p of alumina (1.09 KJ/Kg K) and the overall system temperature change of 1300 K the heat transferred to the refractory is 1417 KJKg. If the total system heat is defined by Q, then the amount of alumina needed as refractory material is Q (2003 KJ) divided by the specific heat c_p (1.09 KJ/Kg K) times the change in temperature (1300 K). Thus the mass of pure alumina required is 1.4 Kg.

In the case of magnesium oxide the specific heat is 1.17 KJKg K and using **the** same data from above the amount of magnesium oxide required is 1.3 Kg.

Generator Housing Design

Primary considerations for the generator housing are heat resistance, and containment of the flame and potential **pressure** buildup produced from EMAA combustion. Steel provides the benefits of heat resistance, availability, strength, and recyclability or potential reuse. Steel tubing is also readily available in various-size diameters and thicknesses, is easily machined, and provides adequate long-term corrosion resistance.

The design for the 500 gram EMAA charge generator utilizes a 13 inch stainless steel tube with a 5 inch outside diameter, and 0.12 inches thickness. The sealed end of the housing uses 4 bolts, evenly spaced, and welded to the interior wall of the tube so as to secure a 0.125 inch thick plate. This plate has a machined lip to provide a uniform seal when bolted, and also has a central port with the necessary diameter **to** connect the ignitor squib at the EMAA charge to the ignition system. Beneath the plate is a 1.5 inch gap, which provides a buffer-zone between the top of the EMAA charge housing and the interior of the plate. This housing consists of a 2.25 inch section of 3.0 inch outside diameter stainless steel tubing centered within the generator. The housing rests on a 0.1 inch stainless steel mesh secured by two 0.125 inch stainless rods connected to the generator body. The space between the charge housing, the top plate, and the generator body is filled with high-temperature resistant alumina fiber blanket, which is easily contoured to fill these voids. This blanketing acts to reduce flame contact with the generator wall, and provides insulation and added thermal transfer.

Upon combustion, the aerosol flows through 9.0 inches of the packed-bed configuration of 0.25 inch alumina spheres, cooling it before it exits via an identical stainless steel mesh arrangement at the open end of the generator. Even with the large amount of void space in the packed-bed and relatively unrestricted flow from the charge housing to the outside space, possibility of pressure buildup from combustion should be taken into consideration.

Ignition System

Ignition of the EMAA charge within the combustion chamber is via a temperature specific thermocouple. This thermocouple uses two dissimilar metals that produce a current when heated. This current completes a circuit between a 9V battery and a magnesium ignitor squib which is inserted into the primer of the EMAA charge. In addition, a fail-safe ignitor should be considered, possibly a paraffin-coated woven cord running into the EMAA primer. In the case of a failed electrical ignition, this would provide fuse-type ignition of the EMAA charge.

CORROSION ANALYSIS

One of the concerns regarding the use of the pyrotechnically generated aerosol is how corrosive they may be due to prolonged contact with various metals and metal alloys. Depending upon the composition of the starting materials, the pyrotechnically produced aerosol can consist of potassium chloride (KCl), potassium hydroxide (KOH) , and/ or magnesium hydroxide(MgOH). Considering the many ways the aerosol may be utilized, it is possible for the potentially corrosive alkali salts produced upon combustion to come in contact with a variety of different metal surfaces. For this reason, this preliminary study provides an assessment of corrosion damage on samples of ten commonly used metals and metal alloys. This report provides data and results from a study lasting approximately **30** days. It should not be extrapolated to predict results for longer times of exposure, because corrosion does not always occur uniformly with respect to time. Some metals form passive films that indicate high initial corrosion rates, but after film formation, these rates fall dramatically. Prolonged testing of these types of metals and metal alloys allows for these films to be broken down, and more accurate corrosion assessment to occur. **A** suggested guideline for test duration from the American Society of Testing and Materials (ASTM) is: duration (hours) = 2000/(anticipated corrosion rate in mils per year). By using a test period of approximately **30** days for EMAA, a reasonably good assessment of corrosion damage may be predicted. It should also be noted that indoor environments, atmospheric conditions, airborne pollution, temperature, wind direction, and design features, all potentially affect corrosion types and rates. For this reason results should be considered indicative of potential corrosion rates and types.

POTENTIALLY CORROSIVE AGENTS IN EMAA FORMULATIONS

Magnesium Hydroxide

Magnesium hydroxide MgOH, is a white powder that is very slightly soluble in water. It decomposes at 350 C *(662* F). Magnesium hydroxide is formed by the reaction of sodium hydroxide and a soluble magnesium salt solution.

Potassium Chloride

Potassium chloride, KCl, also known as potassium muriate and sylvite, is a colorless crystalline solid with a salty taste that melts at 776 C (1420 F). It is soluble in water, but insoluble in alcohol. Potassium chloride is used in fertilizers, pharmaceuticals, and as a salt substitute.

Potassium Hydroxide

Potassium hydroxide, KOH also known as caustic potash, lye, and potassium hydrate, is a white crystalline solid that has a melting point of 360 C (680 F). It is soluble in water and alcohol. It is a powerful cleansing bath for scouring metals and when used in steel-quenching baths gives a higher quenching rate than water alone without attacking the steel as a salt solution would. Potassium hydroxide is slightly more aggressive in the corrosion of metals and nonmetals than sodium hydroxide.

Corrosion Analysis

Results are reported in the following three categories: corrosion rate (mils per year), mass loss percentage (grams per square meter), and pitting density (frequency per square millimeter). Both corrosion rate and mass loss percentage refer to relatively uniform, generalized attack, while pitting density refers to more localized, non-uniform attack.

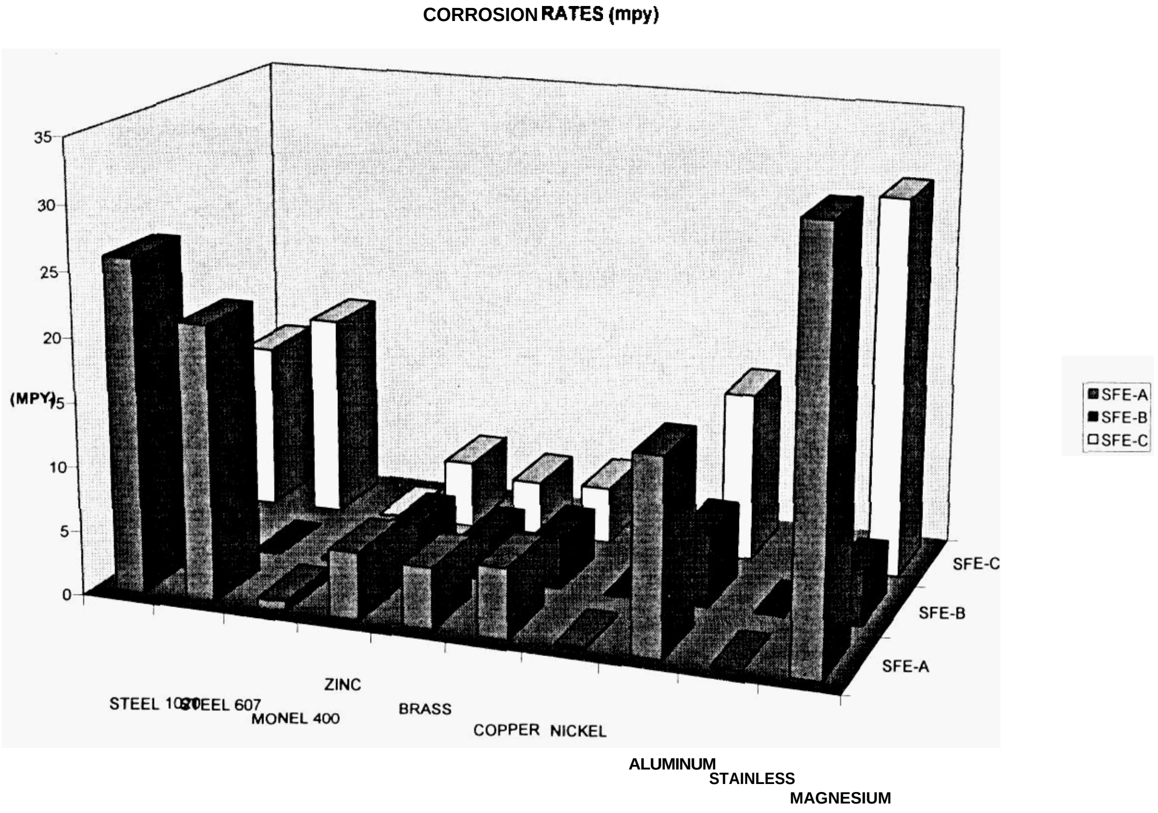


Figure 4. Corrosion Rate of SFE Formulations (mils/year)

Corrosion Rates, SFE Formulation A

Corrosion rates for coupons exposed to SFE-A formulation (Figure 4) vary from trace corrosion, < 1.0 mpy for monel 400, nickel, and stainless, to much heavier corrosion of carbon steels (1020 and 607), aluminum, and magnesium, (12.0 - 32.0 mpy). Zinc, brass, and copper sustained comparable corrosion rates in the 4.0 - 5.5 mpy range. Mass loss percentages (Figure 5) are comparable to the corrosion rates. Monel 400, nickel, and stainless had trace mass loss percentage, <0.01 %. Zinc, brass, and copper experienced similar losses, ≅ 0.02 %. Steel 607 and aluminum showed mass loss percentages ≅ 0.045%, steel 1020 0.08% and magnesium approaching 0.14%. Pitting density was uniform among all sample coupons (Figure 6), < 0.3 frequency per square millimeter, except aluminum which experienced severe localized attack, ≅ 2.7 frequency per square millimeter.

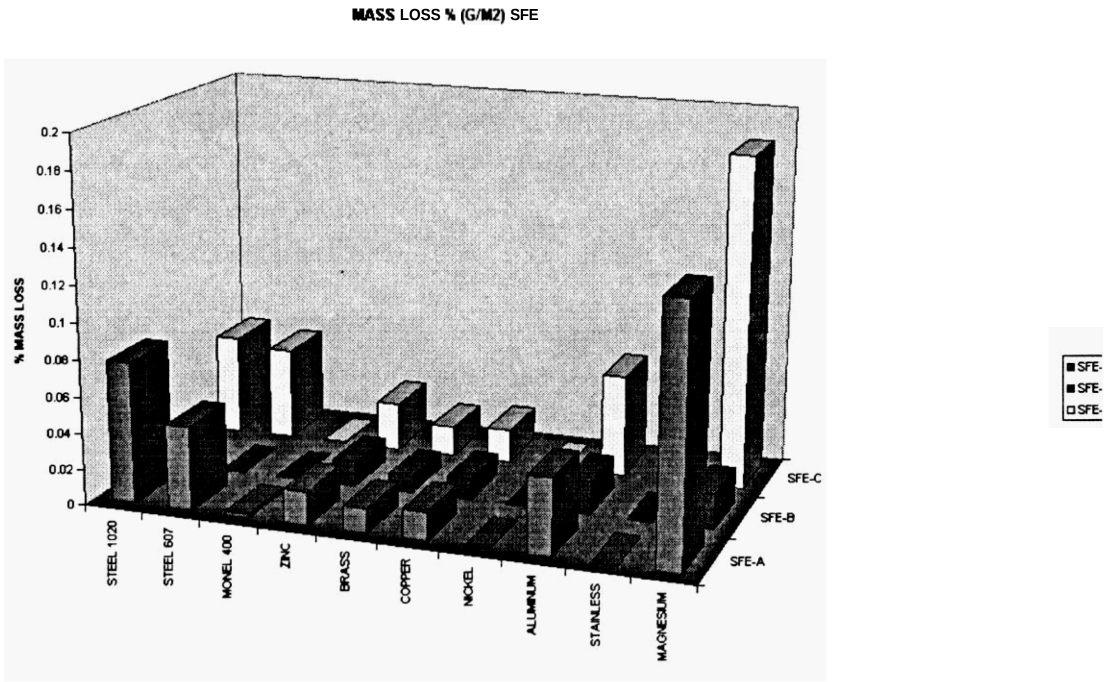


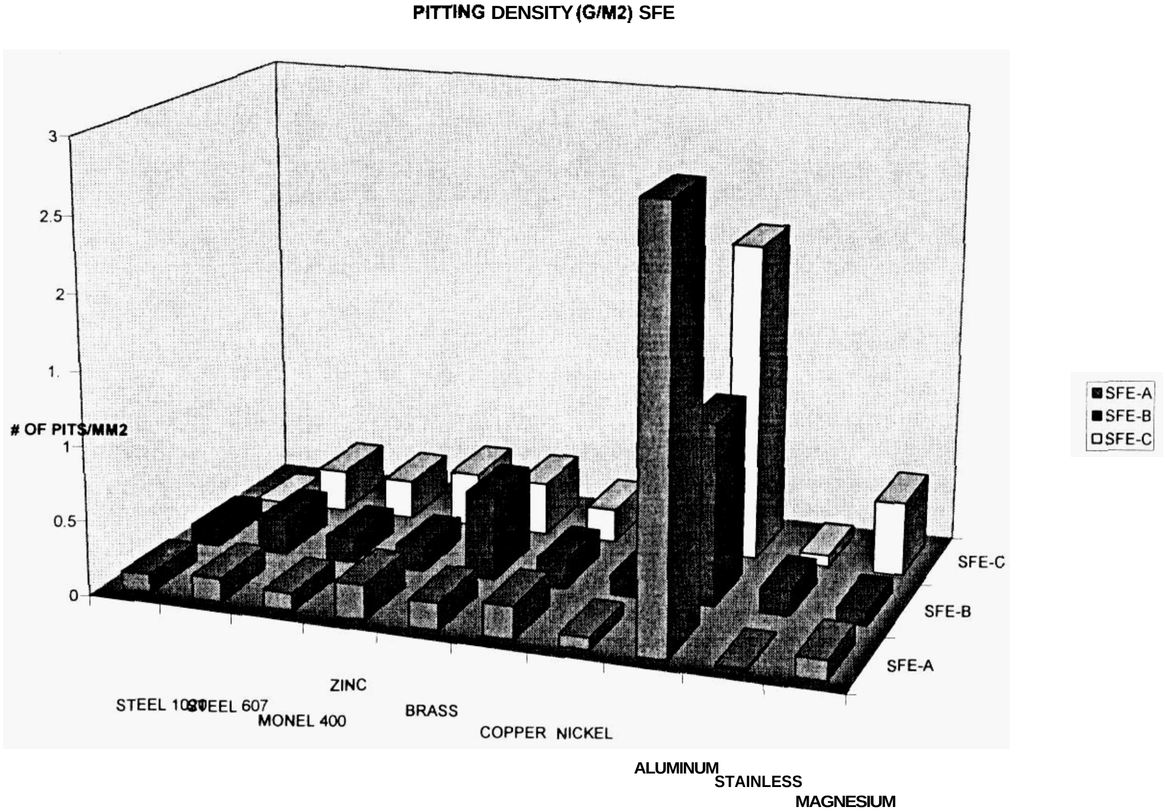
Figure 5. Corrosion Rate for SFE Formulations (Mass Loss)

Corrosion Rates, SFE Formulation B

Corrosion rates for coupons exposed to SFE-B formulation were far more uniform than those for SFE-A, and fall within acceptable levels for all samples. Monel 400, nickel, steel 607 and 1020, and stainless all had trace corrosion, <1.0 mpy. Zinc, brass, copper, aluminum, and magnesium had higher, but acceptable rates, 3.0 - 6.0 mpy.

Mass loss percentages were also more uniform than SFE-A, with no sample > .024 %.

Figure 6. Corrosion Rate for SFE Formulations (Pitting Density),



Eight of the ten samples experienced nominal pitting density. Brass and aluminum experienced some increased frequency of localized attack, although the severity and depth of the pitting was not as great as caused by **SFE-A.**

Corrosion Rates, SFE Formulation C

Corrosion rates for SFE-C were indicative of rates obtained from exposure to SFE-A. Monel 400, nickel, and stainless experienced nominal corrosion rates. Zinc, copper, and brass showed higher, but acceptable rates, and highest rates were again present in steel (607 and 1020), aluminum, and magnesium. Mass loss percentages were also indicative of rates obtained from exposure to SFE-A, as was pitting density.

RECOMMENDATIONS

The various SFE formulations are effective in fire suppression only when total flooding conditions are achieved. Initial estimates provide predict total-flooding to occur at 50 grams SFE in aerosol suspension per cubic meter of coverage area. Results from testing indicate that approximately 20 percent of the SFE material does not form aerosol upon combustion, and an additional 15 to 20 percent is lost to deposition in the packed-bed of refractory material. Successful fire-suppression was only noted while testing the two-kilogram charge generator. Under ideal conditions **(100%** efficiency) in aerosol generation and unrestricted movement through the refractory material, the **500** gram charge should provide total-flooding for a 10 cubic meter area. Under initial testing conditions, 2000 grams were needed to provide successful fire suppression. This must be considered when determining size, weight, and cost benefits of this type of halon replacement. Additionally, pressure increases due to restrictions placed on rapidly generated aerosol within the generator housing provide a potential for device failure.

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