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AN EVALUATION OF AEROSOL EXTINGUISHING SYSTEMS FOR MACHINERY SPACE APPLICATIONS

FINAL REPORT
February 2006

Prepared for:

U.S. Department of Homeland Security
United States Coast Guard
Assistant Commandant for Prevention (G-P)
Washington, DC 20593-0001

N O T I C E

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16. Abstract (MAXIMUM 200 WORDS)

Full-scale fire tests were conducted to identify the fire extinguishing capabilities and limitations of Aerosol Extinguishing Systems (AES) in shipboard machinery space applications. A total of 18 tests were conducted in this evaluation utilizing the equipment from three AES manufacturers (Ansul, FirePro and Flame Guard). The systems were tested against the current International Maritime Organization's (IMO) test protocol Maritime Safety Committee/Circular (MSC/Circ. 1007) for approving AES for machinery space applications.

The conditions produced by the discharge of the AES were quantified during these tests. With respect to the extinguishment capabilities of these systems, all three systems exhibited good capabilities against Class B fires but had difficulty extinguishing the Class A fires. As a result of these limited capabilities against Class A fires, none of the three systems successfully met the requirements of the IMO test protocol (as currently written). Based on the results of these tests, a number of modifications in the procedures, instrumentation, and fire scenarios in the test protocol are recommended.

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EXECUTIVE SUMMARY

The United States Coast Guard (CG) is currently considering the use of Aerosol Extinguishing Systems (AES) for protecting shipboard machinery spaces. These systems discharge a fire extinguishing powder/chemical (dust-like particles) that looks similar to a thick white smoke. The International Maritime Organization (IMO) has developed a test protocol for approving these systems. The test protocol, the Maritime Safety Committee/Circular (MSC/Cir. 1007) "Guidelines for the Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing Systems" (International Maritime Organization, 2001), is a modified version of a gaseous agent system test protocol and has never actually been used to test AES.

During this investigation, the CG conducted eighteen full-scale fire tests to identify the fire extinguishing capabilities and limitations of AES in shipboard machinery space applications and to assess the adequacy of the IMO test protocol. Three AES (Ansul, FirePro and Flame Guard/Zero Combustion) were included in this evaluation. Each manufacturer was responsible for the design of their respective system.

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the CG Fire and Safety Test Detachment located at Little Sand Island, Mobile, AL. The compartment is constructed to meet the dimensional requirements of the MSC/Circ. 1007, as well as other protocols.

All three AES exhibited good capabilities against Class B fires (flammable liquids), but had difficulty extinguishing the Class A fires (ordinary combustibles). All of the large Class B fires were quickly extinguished during this test series. Only one of the 14 Class A fires (wood cribs) was extinguished. This occurred when the wood crib was ignited only two minutes prior to discharge of the system, instead of the six minutes required by MSC/Cir. 1007. Due to the inability to extinguish Class A fires, not one of the three systems successfully met the requirements of the MSC/Circ. 1007.

Modifications to MSC/Circ. 1007 are recommended in this report and are based on the results of these tests. These modifications apply to test procedures, instrumentation and fire scenarios. For example, the six-minute preburn time of the wood crib fire in one of the tests makes it too challenging for this technology. Consideration should be given to whether this fire scenario is representative of typical machinery space hazards. It is also recommended that the larger Class B fires be reduced by 50 percent to make them more challenging/difficult to extinguish.

Although these tests demonstrate the potential for AES to protect shipboard machinery spaces, the technology, as tested, is currently not ready for implementation. Additional product development work is required to increase the capabilities against Class A fires and the hardware needs to be hardened to survive the thermal conditions produced by the fire prior to discharge. The IMO test protocol also needs to be modified to address the issues identified in this investigation.

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

AES	Aerosol Extinguishing Systems
C	Celsius
CG	U.S. Coast Guard
cm	centimeter
cm^2	square centimeter
CO	carbon monoxide
CO_2	carbon dioxide
dc	Direct Current
FMRC	Factory Mutual Research Corporation
g	gram
g/m^3	grams per cubic meter
HAI	Hughs Associates, Inc.
H_2O	water
IDLH	Immediately Dangerous to Life or Health
IMO	International Maritime Organization
kg	kilogram
kg/s	kilograms per sec
kW	kilowatt
kPa	kilopascal
L	Liter
Lpm	Liter per minute
m	meter
m^2	square meter
m^3	cubic meter
mm	millimeter
MPa	mega Pascal
MSC	Maritime Safety Committee
MW	megawatt
NFPA	National Fire Protection Association
N_2	nitrogen
O_2	oxygen
ODM	optical density meters
Pa	Pascal
W	watt

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1.0 INTRODUCTION

The U.S. Coast Guard (CG) is currently considering the use of Aerosol Extinguishing Systems (AES) for protecting shipboard machinery spaces. The International Maritime Organization (IMO) has developed guidelines and a test protocol for approving these systems described in Maritime Safety Committee/Circular (MSC/Circ.) 1007 "Guidelines for the Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing Systems" (International Maritime Organization, 2001). However, little test data was available on AES at the time that the MSC circular was developed.

A full-scale fire performance evaluation was conducted to define the capabilities and limitations of these systems in this application and to evaluate the adequacy of the IMO test protocol.

2.0 OBJECTIVES

The objectives of this test program were to define the capabilities and limitations of AES in shipboard machinery space applications and to compare the performance and effectiveness of these systems to other fire suppression systems/technologies currently approved by the CG. The program also evaluated the adequacy of the test protocol described in MSC/Circ. 1007.

3.0 APPROACH/TECHNICAL DISCUSSION

The approach adopted for this project was to evaluate a number of AES through full-scale fire testing with the intent to bound the capabilities and limitations of the technology for shipboard machinery space application. Numerous manufacturers of AES were contacted but only three chose to participate in this evaluation. These manufacturers were; Ansul, FirePro, and Flame Guard. Each system was evaluated against the current IMO test protocol (MSC/Circ. 1007) and a limited number of tests designed to assess the impact of a specific test parameter on the capabilities of the system. A detailed description of the approach and the test parameters are provided in the following sections of this report.

3.1 AES General Description

The aerosol agents are a family of fire extinguishing chemicals that are discharged as solid particles typically less than 10 microns in diameter. According to all of the manufacturer's published literature, when introduced into the flaming region of a fire, the aerosol reacts with the fire radicals produced during combustion (hydrogen, oxygen, and hydroxyls) resulting in extinguishment of the fire. The small aerosol particles provide a large surface area for capturing these radicals making them effective extinguishing agents.

There are two types of aerosol systems; condensed and dispersed. Condensed aerosols are pyrotechnically generated through the combustion of a solid compound stored in what is referred to as a generator [NFPA 2010, 2005]. Dispersed aerosols are powders that are stored in pressurized containers with a carrier gas (such as inert gases or halocarbon agents) that are released in the space through a pipe network containing valves and nozzles similar to other gaseous agents. Only condensed aerosols were included in this evaluation.

Condensed aerosol generators typically contain a less than 10 kg of chemicals (solid compound). As a result, numerous generators are required to protect a large area/volume. The generators are activated by an electric pulse originating from a control panel. The electric pulse from the control panel causes either the solid compound to ignite generating the aerosol or the activation of an inert gas generator to disperse the aerosol. The agent is then discharged from the generator in the form of very fine particles which mix with air and float throughout the hazard/protected space. These systems can be either manually activated or automatic based on signals from sensors installed in the space. For these tests, the systems were manually activated.

AES are designed based on a desired application density. The application density (g/m^3) is the amount of agent (g) discharged into the enclosure per unit volume (m^3). The following terms define key parameters associated with the agent/application density.

> Extinguishing Application Density (g/m^3): The minimum application density required to extinguish the fires associated with the hazard/application excluding any factor of safety.
>
> Design Application Density (g/m^3): The application density required for system design purposes that are based on the extinguishing application density plus a factor of safety (typically 30 percent).

Since these previously defined application densities were not known until the tests are complete, the density used for each test was referred to as the design density and as with the previous two terms, was based on the generator capacity/the weight of the solid compound in the generator (not values measured during the test).

Note that the previous Application Densities are based on the mass of the solid compound in the generators installed in the protected space. To account for inefficiencies in the hardware, the following two terms are introduced and are based on measured quantities.

> Delivered Density (g/m^3): Mass of aerosol discharged by the generators/system per unit volume of the protected space (based on the measured mass loss of the generators).
>
> Particulate Density (g/m^3): The mass of solid particles (g) suspended in the gas/air per unit volume (m^3). This is a measured parameter and is not based on the mass of the generators.

Critical reignition particulate density (g/m^3): the mass of solid particles (g) suspended in the gas/air per unit volume (m^3) required to prevent reignition of Class B fires/fuels.

3.2 Anticipated System Capabilities and Limitations

Testing conducted by the Royal Navy (i.e., United Kingdom) demonstrated that in general, AES systems are limited in their ability to extinguish fires low in the space due to agent stratification. [Connell, 2003]. The agent stratifies high in the space (at least initially) because it is discharged at a higher temperature than the surrounding air. As a result of this potential limitation, the extinguishment capabilities of these systems as a function of fire elevation were researched/defined during this test series.

The extinguishment capabilities of each system as a function of fire elevation were assessed during the telltale fire test (MSC/Circ. 1007 Fire Scenario One). A tree of telltale fires spaced one meter apart in elevation (0.5, 1.5, 2.5, 3.5, and 4.5 m) was added to the test. Each fire/telltale was instrumented for temperature to note extinguishment. The particulate density at each location was also measured. Additional telltales were also added in obstructed locations to assess each system's capabilities against obstructed fires. The locations of these telltales are provided section 4.2 of this report.

There is a concern throughout the industry that the temperature of the aerosol discharged from the generator could result in a hazard to personnel in the space (either locally or on a global scale). To address this issue, NFPA 2010 defines two safe distance parameters associated with the temperature of the agent stream; the safe distance for combustibles less than 200°C and the safe distance for personnel less than 75°C. During these tests, the temperature of the discharged aerosol was measured using an array of thermocouples installed directly in front of one of the generators (0.3, 0.6, 0.9, and 1.2 m away). The international community should consider adding similar measurements in MSC/Circ. 1007. The global increase in temperature was determined by averaging all of the air/gas thermocouples in the space during/shortly after discharge (Fire Scenario One).

Although not well documented, AES may be limited in their ability to extinguish deep-seated Class A fires. As a result of this potential limitation, the ability of these systems to extinguish deep-seated Class A fires was assessed during this investigation. The assessment consisted of adding a wood crib with a two-minute preburn to MSC/Circ. 1007 Fire Scenario Three. Consequently, Fire Scenario Three as tested consisted of wood crib fires with two and six-minute preburn times.

3.3 Science Related Issues

From a scientific standpoint, an innovative approach to measure the particulate density as a function of time needed to be developed for this test series. This measurement was the key to understanding how the system works by defining the following parameters: critical reignition particulate density; the particulate density as a function of height; and how the particulate density decays as a function of time (fall-out rate/hold time).

Short path length laser optical density meters (ODM) were developed, calibrated and tested for this application. These ODMs were developed in the laboratory of Hughes Associates, Inc. (HAI) through a side-by-side comparison with a Malvern 2600 laser diffraction particle size analyzer.

Three approaches for measuring discharge time were also developed/incorporated in this evaluation. The protocol (MSC/Circ. 1007) states that the discharge time (the time to reach 85 percent of the design density) needs to be measured during the test but gives no information on how this is to be achieved. The approaches included in this series consisted of measuring the weight of the generator during agent discharge, instrumenting the aerosol generator for surface and plume (agent stream) temperature, and using the particulate densities measured in the space by the ODMs. The results obtained using each of these three techniques are later discussed with the intent to identify an appropriate method for inclusion in the test protocol (MSC/Circ. 1007).

4.0 TEST DESCRIPTION

4.1 Test Compartment

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the CG Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The machinery space is located on the fourth deck of the Number Six cargo hold. The compartment is constructed to meet the dimensional requirements of the IMO test protocol MSC/Circ. 1007, as well as other protocols. The compartment volume is approximately 500 m^3 with nominal dimensions of 10 m × 10 m × 5 m as shown in Figure 1. The diesel engine mockup described in MSC/Circ. 1007 is located on the 4th Deck in the center of the compartment as shown in Figure 2. Air to support combustion was provided naturally through two standard watertight doors located on the fourth deck forward in the compartment. Products of combustion were exhausted from the compartment through a six m^2 vertical stack located in the overhead of the compartment (aft). The exhaust stack is equipped with a remotely activated hydraulic damper. The watertight doors and vertical stack were open during the preburn period and closed just prior to system discharge.

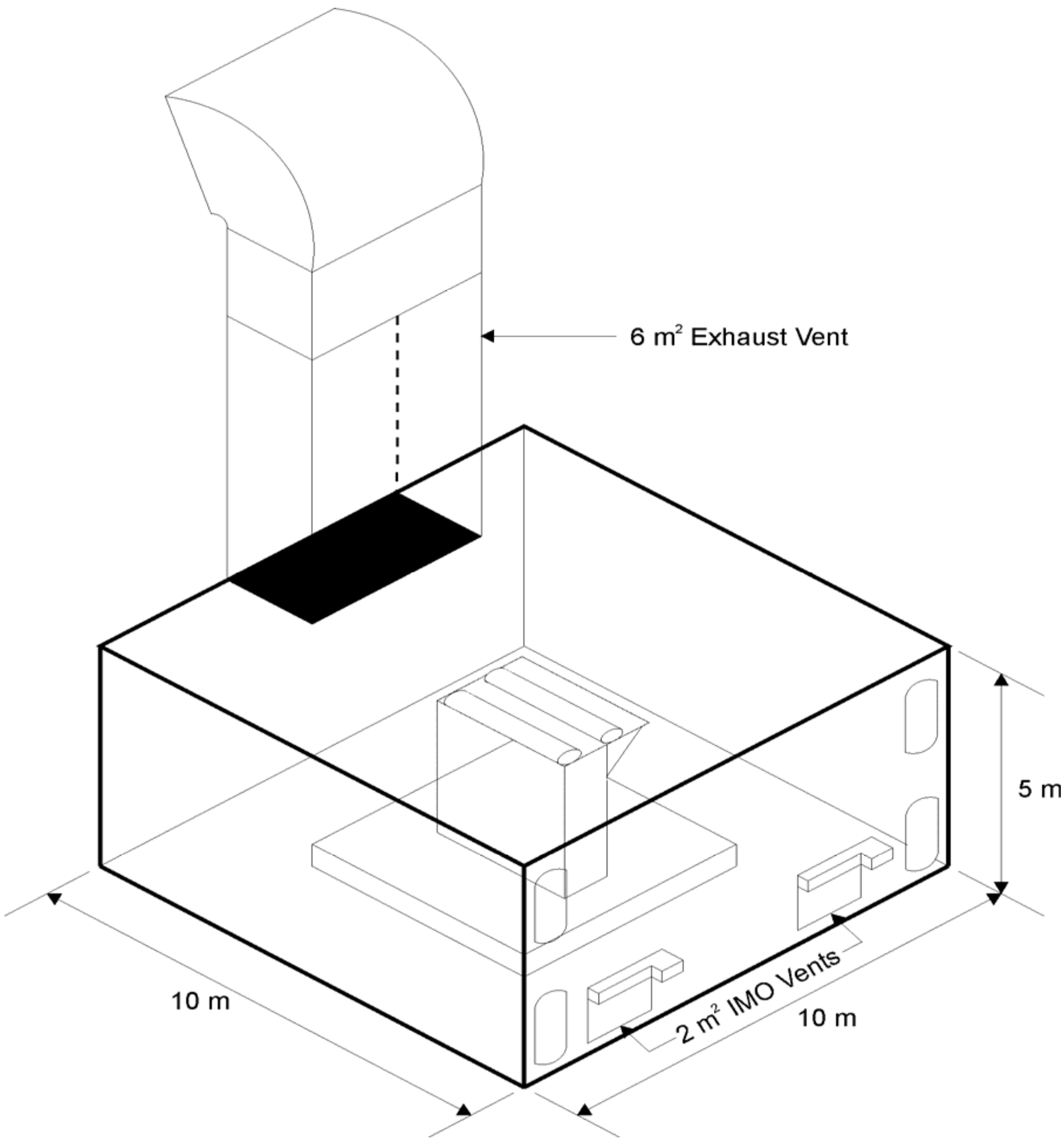


Figure 1. Machinery Space Configuration.

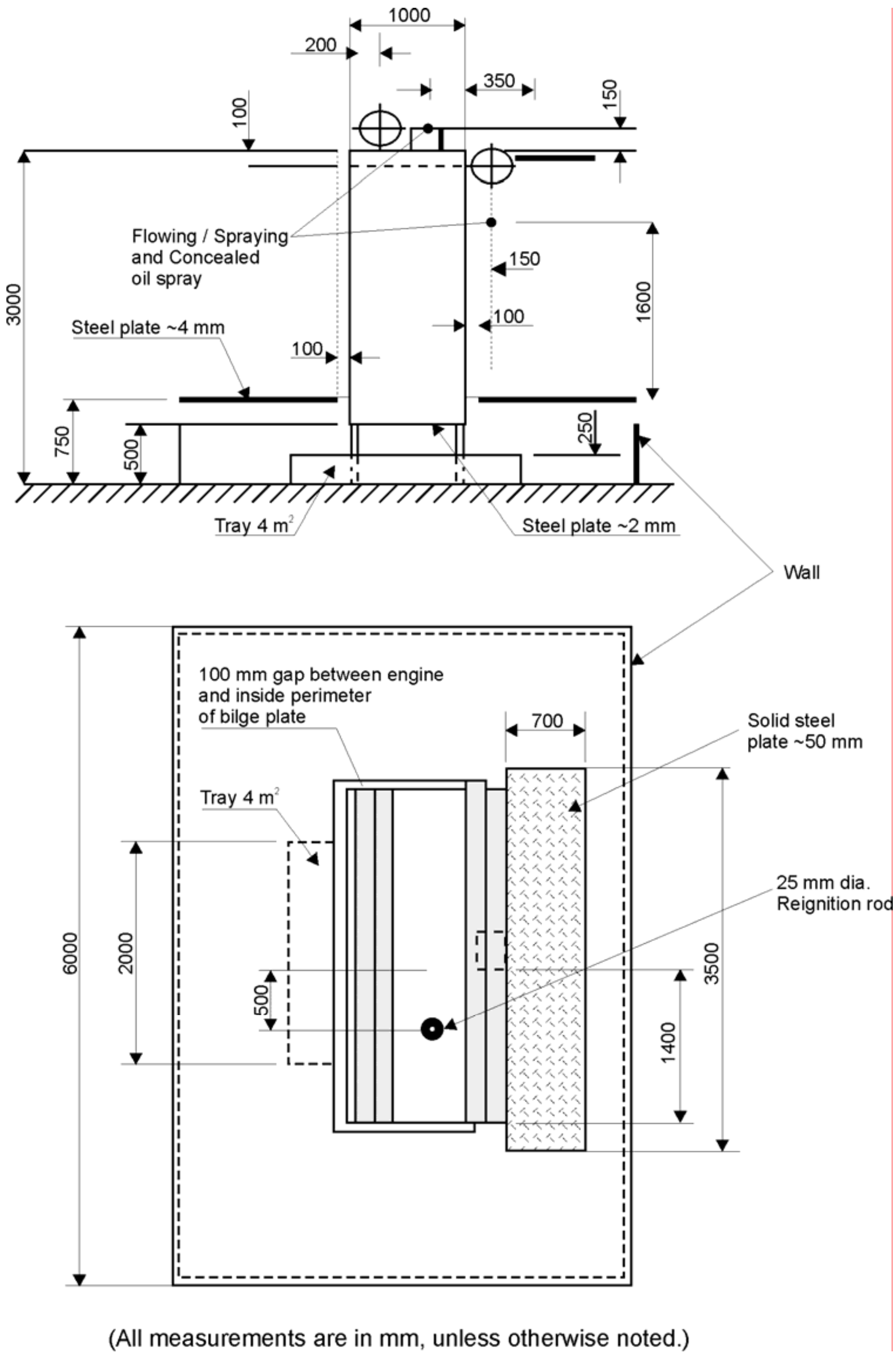


Figure 2. Diesel Engine Mockup.

4.2 Fire Scenarios

4.2.1 MSC/Circ. 1007 Fire Scenarios

A copy of MSC/Circ. 1007 is provided in Appendix A. The fire scenarios required by MSC/Circ. 1007 are listed in Table 1 and are designated by numbers (1-4). The locations of these fires are shown in Figure 3.

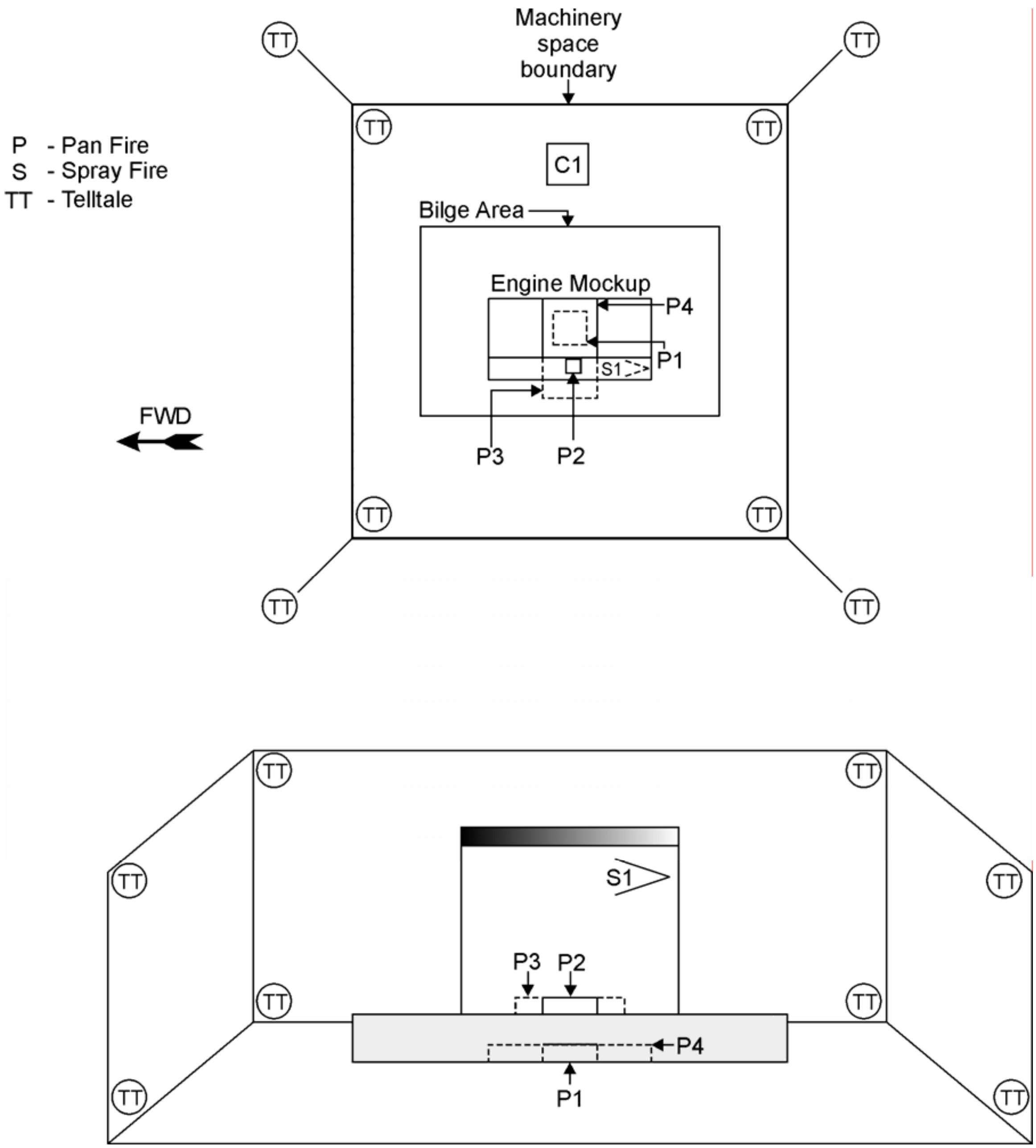
Table 1. MSC/Circ. 1007 Fire Scenarios.

Fire Scenario	Nominal Total Heat Release Rate	Components	Nominal Heat Release Rates	Location (Figure 3)
1	~24kW	82 cm^2 heptane can fires (telltales)	~3 kW/ea	Corners (TT)
2	0.49 MW	0.10 m^2 heptane pan fire 0.25 m^2 heptane pan fire	0.14 MW 0.35 MW	Side of mockup (P2) Under mockup (P1)
3	4.40 MW	Low pressure/flow heptane spray fire Wood crib 2.0 m^2 diesel pan fire	1.10 MW 0.30 MW 3.00 MW	Side of mockup (S1) Deck level (C1) Bilge Plate (P3)
4	6.00 MW	4.0 m^2 diesel pan fire	6.00 MW	Bilge (P4)

The fire scenarios in MSC/Circ. 1007 are almost identical to those used to evaluate the capabilities of inert gas systems. The tests consist of an agent distribution test (Fire Scenario One) conducted using telltales and a lower design density (77 percent of the actual design density) and three larger fire tests to evaluate the capabilities of the system against more realistic/representative fire threats.

MSC/Circ. 1007 requires that the system discharge time (time to reach 85 percent of the design density) be less than 120-seconds and that all fires need to be extinguished within 30-seconds of the end of discharge. The timing of the tests (e.g., hold times, reignition, reactivation of the heptane spray, etc.) is also based on the end of agent discharge. However, there is no guidance for measuring/determining the end of agent discharge.

The difficulty of defining the end of agent discharge during the test required some modifications to the test procedures. Additional fires were also added to Fire Scenarios One and Three to assess specific parameters. These are discussed in the following sections of this report.



Elevation

Figure 3. MSC/Circ. 1007 Fire Locations.

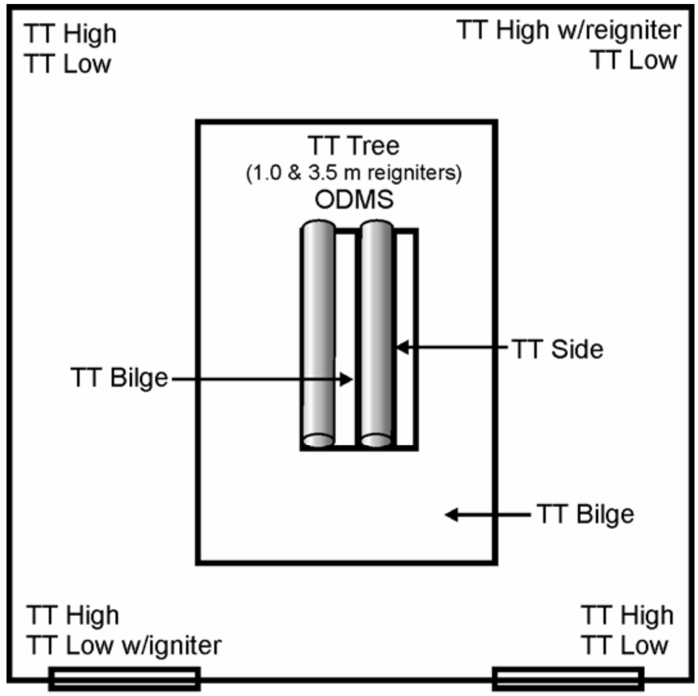
4.2.2 Fire Scenarios as Tested

Due to the difficulty in determining the end of agent discharge during the test, the timing of the test was based on an assumed two-minute discharge (the maximum time allowed in MSC/Circ. 1007). This timing applies to all four fire scenarios. Although the test timing was modified, the fires still needed to be extinguished within 30-seconds of the end of agent discharge as measured during the test. The other modifications to the individual tests are discussed on a test-by-test basis in the following sections.

4.2.2.1 Fire Scenario One

The test configuration and timing for Fire Scenario One are shown in Figure 4. With respect to deviations from MSC/Circ. 1007, eight additional telltales were added to assess the system's extinguishing capabilities as a function of fire elevation and degree of fire obstruction. The eight additional telltales consisted of a tree of five telltales aft in the compartment and three obstructed telltales; two in the bilge and one on the side of the mockup under the obstruction plate.

The telltale tree consisted of five telltales spaced one meter apart in elevation (0.5, 1.5, 2.5, 3.5, and 4.5 m). Each telltale was instrumented with a thermocouple to note extinguishment and an ODM to measure obscuration and the particulate density as a function of elevation. The 1.5 m and 3.5 m telltales where also equipped with igniters to determine the critical reignition particulate density during the reignition sequence.



Sequence

0:00 Start Data/Video
1:00 Ignite Telltales
2:00 Clear Space
4:00 Activate System
6:00 System Discharge Complete
16:00 Reignition
18:00 Reignition
20:00 Reignition
22:00 Test Complete
25:00 Secure Data/Video
Ventilate Space

Figure 4. Fire Scenario One Configuration and Timing.

The timing of the reignition sequence was also varied from that of MSC/Circ. 1007. Based on preliminary tests conducted in the lab at HAI, it was determined that a two-minute time interval was required to ignite, extinguish (within 30 seconds) and verify extinguishment prior to the next reignition sequence. As a result, the reignition tests were conducted 10, 12, and 14 minutes after the end of discharge as compared to 10, 11, 12, 13, and 14 minutes described in MSC/Circ. 1007. In many instances, the reignition tests were continued (at 2-minute increments) until sustained burning was achieved (well past the time requirements stated in MSC/Circ. 1007).

Silicon nitride heating elements (Glo-Stix Igniter (universal)) were used to reignite the telltales during this test series. Per the manufacturer's information, the element surface temperature exceeded 1200°C within six seconds of activation.

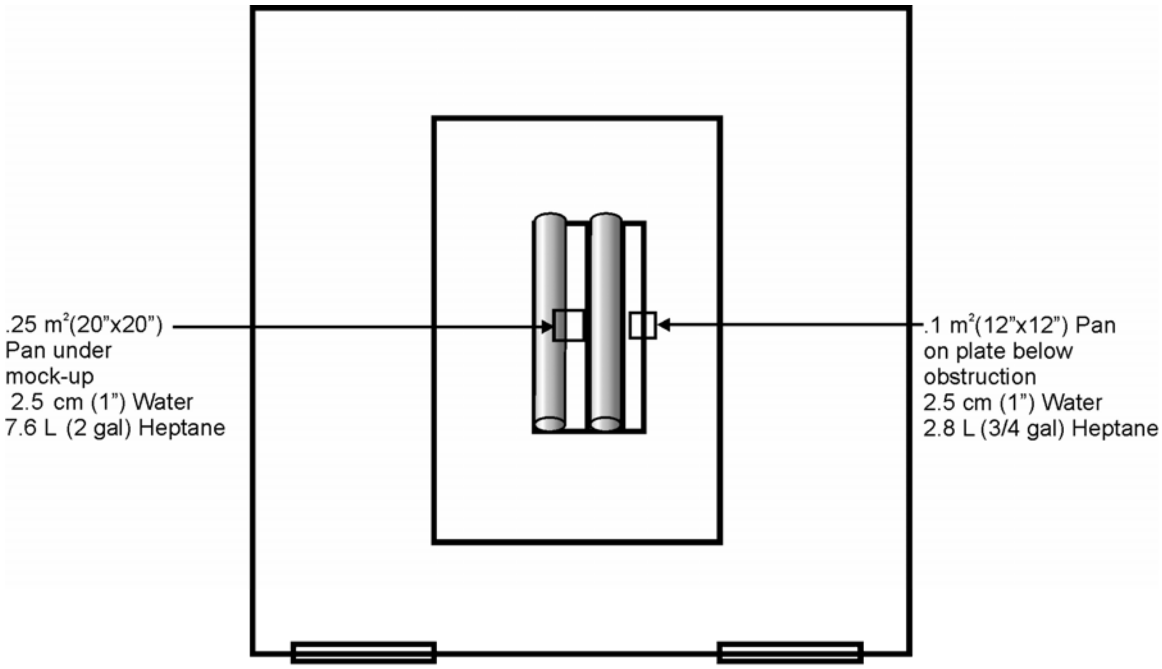
4.2.2.2 Fire Scenario Two

Fire Scenario Two was conducted as described in MSC/Circ. 1007. The test configuration and timing are shown in Figure 5.

4.2.2.3 Fire Scenario Three

The test configuration and timing for Fire Scenario Three are shown in Figure 6. With respect to deviations from MSC/Circ. 1007, two fires were added to better assess the system's extinguishing capabilities against Class A fires. Since AES may be limited in their ability to extinguish deep seated Class A fires, a wood crib with a two-minute preburn and a pool fire with fuel (heptane) soaked lagging (fiberglass mat) was added to the scenario. The fuel soaked mat configuration is similar to that used by Factory Mutual Research Corporation (FMRC) to approve water mist systems for turbine enclosures.

As shown in Figure 6, the wood crib with the 6-minute preburn was moved toward the back of the compartment (~ 4 m from the aft bulkhead) and the second wood crib (two-minute preburn) was positioned ~ 4 m from the forward bulkhead. The heptane soaked mat was located on the same side of the mockup near the center of the compartment (on the bilge plate).



Sequence

0:00 Start Data/Video
1:00 Ignite Pan Fires
2:00 Clear Space
3:00 Activate System
5:00 System Discharge Complete
20:00 Test Complete
23:00 Secure Data/Video
Ventilate Space

Figure 5. Fire Scenario Two Configuration and Timing.

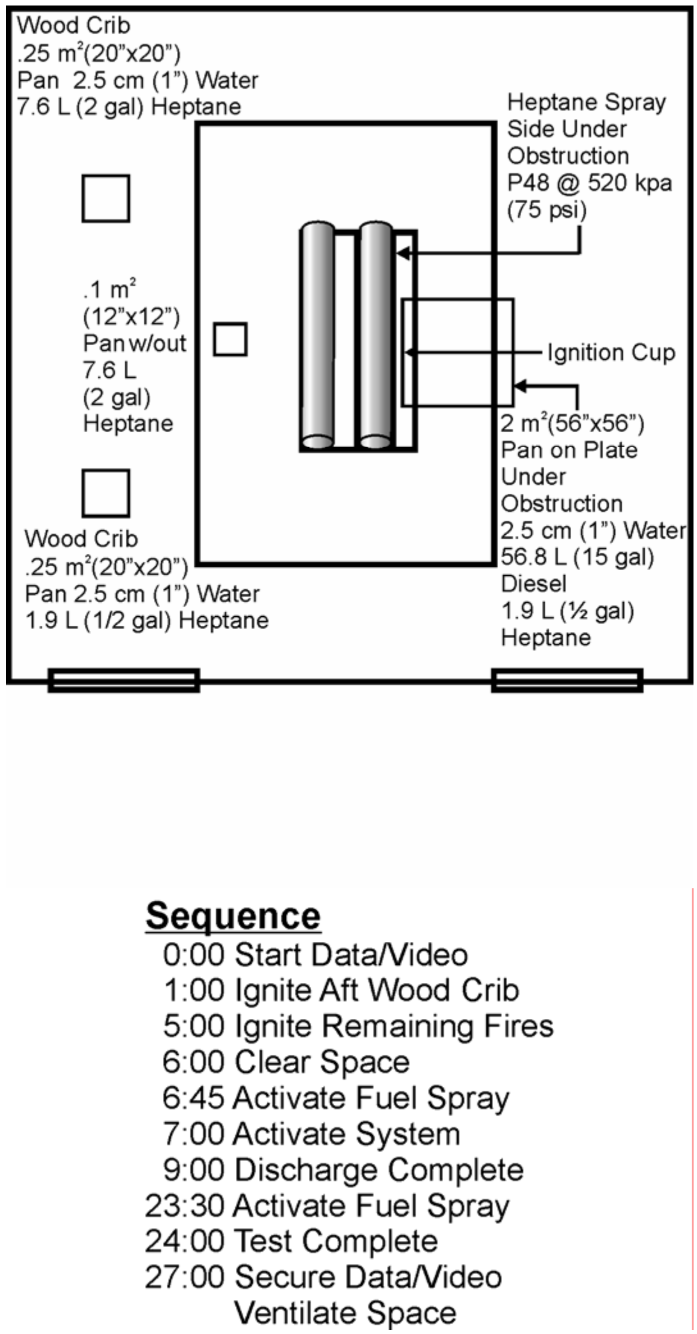


Figure 6. Fire Scenario Three Configuration and Timing.

4.2.2.4 Fire Scenario Four

Fire Scenario Four was conducted as described in MSC/Circ. 1007. The test configuration and timing are shown in Figure 7.

4.2.3 Test/Fire Specifics

The fuel pans used during these tests are square in shape and constructed of 3.2 mm steel plate with welded joints. The pans are 22.9 cm in depth with side dimensions of 31.6 cm, 50 cm, 144 cm, and 200 cm for the 0.2 m^2, 0.25 m^2, 2 m^2, and 4 m^2 pans, respectively. These pans were filled with a 2.5 cm deep layer of water and a 5 cm deep layer of either heptane or diesel fuel. Heptane was added to the 2 m^2 and 4 m^2 diesel pans to initiate the fire (1.9 L and 3.8 L, respectively).

The wood cribs used in Fire Scenario Three consisted of four layers of six members each. Each member (spruce or fir) measured 3.8 × 3.8 × 45 cm (actual) and was required by MSC/Circ. 1007 to have a moisture content between 9 percent and 13 percent. However, the wood cribs used during these tests only had a moisture content of 6 percent. This lower moisture content makes these cribs more difficult to extinguish. The wood cribs were placed on angle iron frames 0.3 m above the deck. The cribs were ignited using a 0.25 m^2 pan that was fueled with either 1.9 L or 7.6 L of heptane (depending on the preburn time). The wood crib was weighed both before and after the test to determine the mass loss that occurred during the test.

The spray fires were produced using a fine atomizing nozzle Model P-48 manufactured by Bete Fog Nozzle Inc. The heptane spray fires were produced using a pressurized fuel tank and a pipe network constructed of 1.2 cm stainless steel tubing. Both a manual quarter turn ball valve and a remotely actuated solenoid valve were used to control the fuel flow. The fuel tank was pressurized with nitrogen from a regulated cylinder to 520 kPa. At this pressure, the system produced a spray fire with a nominal heat release rate of 1.1 MW (0.005 kg/s). The fuel spray was shut off 15-seconds after extinguishment.

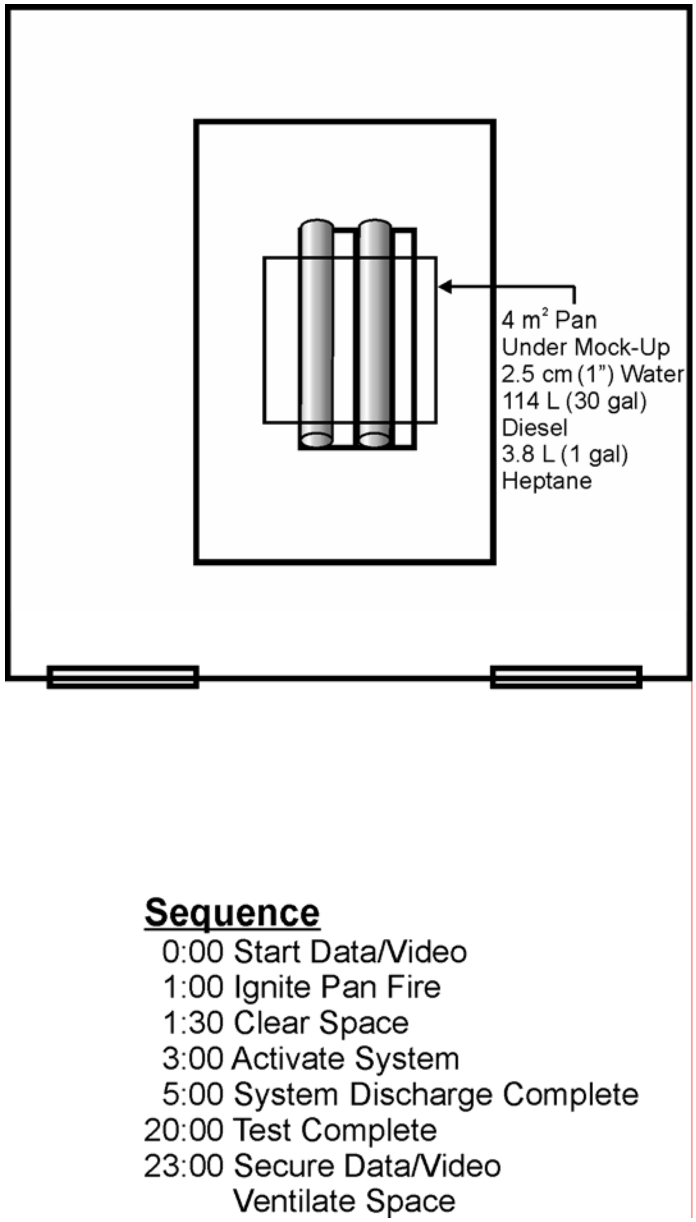


Figure 7. Fire Scenario Four Configuration and Timing.

The fires were ignited to achieve the following preburn times prior to agent discharge (wood cribs 360 and 120-seconds, pan fires 120-seconds, and spray fires 15-seconds).

In order to successfully pass these tests per the IMO requirements, all Class B fires must be extinguished within 30-seconds of the end of agent discharge and no reignition must occur at any time during the test. In addition to this extinguishment time requirement, the mass loss of the wood crib in Fire Scenario Three cannot exceed 60 percent of its original weight. This implies that the wood crib must also be extinguished during the tests.

4.3 AES Design Parameters

Three systems/manufacturers were evaluated during this test series; Ansul, FirePro, and Flame Guard. Per MSC/Circ. 1007, the generators were symmetrically installed throughout the space within one meter of the overhead and the systems were designed to discharge their agent in less than two-minutes. The generic system configuration adopted for this test series was to space the aerosol generators uniformly around the diesel engine mockup as shown in Figure 8. The design density in Fire Scenario One (the telltale fire test) was 77 percent of that used in the larger fire tests (Fire Scenarios Two-Four and parametric assessments). The initial designs were developed based on published manufacturer's data (design manuals) and are summarized in Table 2. In actuality, many of these designs needed to be modified (increases in the design density) to increase the capabilities of the system.

To expedite the testing, removable mounts/panels were installed at the eight locations shown in Figure 8. After each test, the mount/panels were lowered and a new generator was installed at each location.

The Fire pro and Flame Guard generators were activated using a control system provided by the CG; Ansul provided their own control system. The CG control system provided 12V DC with almost unlimited current capability at each generator location. The activation switch/button was located in the control room on the second deck. After each test, the power supply for the system was removed to prevent accidental activation of the generators during the reinstall for the next test.

A brief/general description of each system is provided in the subsequent sections of this report.

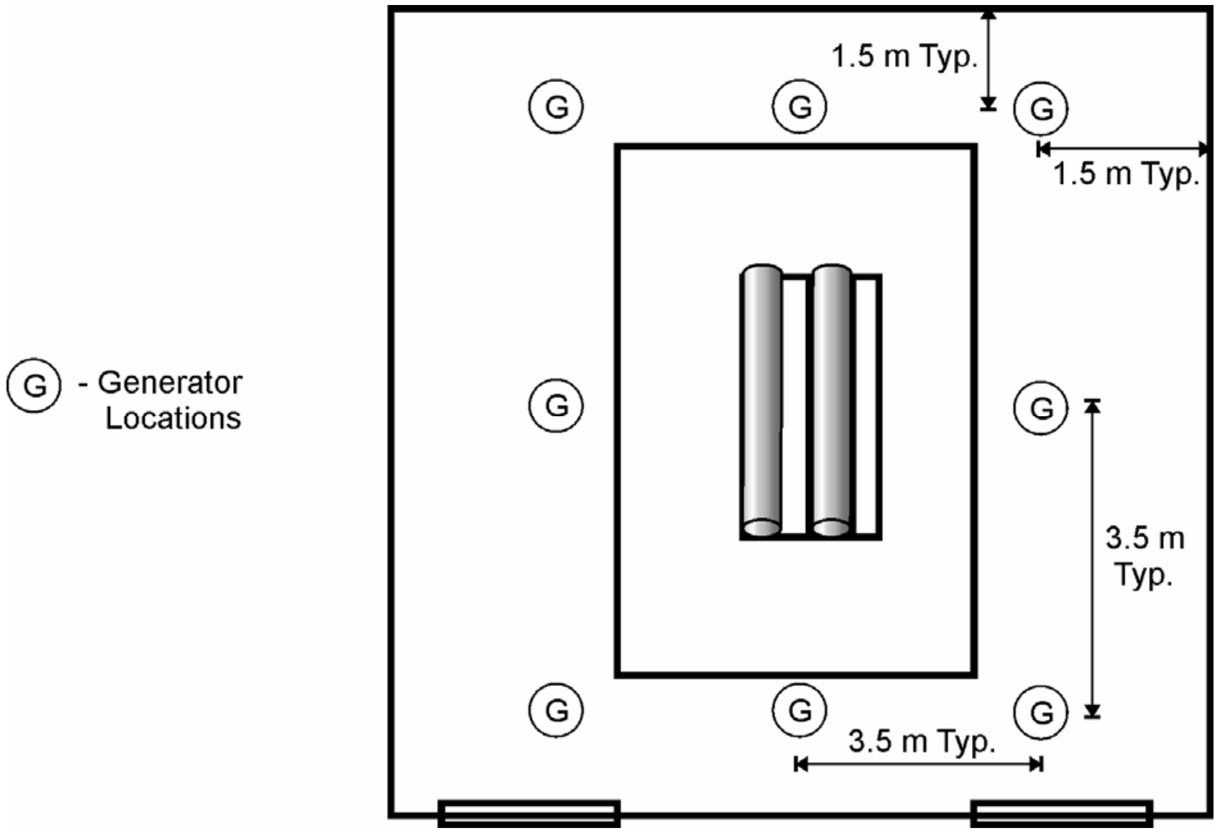


Figure 8. AES Generator Locations.

4.3.1 System One

System One is a condensed AES with generators that cover the spectrum of size, shapes, and types (a wide range of discharge times and agent stream temperatures). A combination of generator types were evaluated during these tests.

Table 2. AES Summary Information.

System	System One	System Two	System Three
System Type	Condensed	Condensed	Condensed
Composition (present by weight)	K_2CO_3 (0.5), $KHCO_3$ (0.1), KNO_3 (0.08), NH_4HCO_3 (0.25), other Potassium compounds (0.07)	KNO_3 (0.75), Epoxy Resin Powder (0.23), and Mg (0.02)	KNO_3 (0.77), Epoxy Resin Polymer (0.18), K_2CO_3 (0.04), and Mg (0.01)
Hazard/Rating	Class A, Class B, Class C, Class E, Class F	Class B and Class C	Class A, Class B, Class C
Class B Extinguishing Concentration	40 g/m^3	100 g/m^3	84 g/m^3
Discharge Time	~ 120s	~ 90s	~ 20s
Design Density Fire Scenario One	45 g/m^3	106 g/m^3	91 g/m^3
Design Density Fire Scenarios Two-Four	60 g/m^3	132 g/m^3	114 g/m^3

The initial intent was to test System One with a design density of 45 g/m^3 for Fire Scenario One and 60 g/m^3 for Fire Scenarios Two-Four. These design densities were varied based on the results of the tests and the number and size (capacity) of generators available for testing. A range of generator sizes/models were used to produce these densities. The generator sizes ranged from 2.4-6.7 kg. Although a range of generator sizes were included in this evaluation, the agent was still uniformly distributed throughout the space.

4.3.2 System Two

System Two is a prototype condensed AES still under development for machinery space applications. The system was tested with a design density of 106 g/m^3 for Fire Scenario One and a design density of 132 g/m^3 for Fire Scenarios Two-Four. At this time in the development process, only 1.1 kg generators (upright) were available. Due to the upright design, many tests were conducted with the generators located on the deck aiming upward as opposed to in the overhead in the pendent position as required by MSC/Circ. 1007.

4.3.3 System Three

The third system is also a condensed AES that is being marketed overseas (currently well developed). The system is available in a range of generator sizes although only one size (5.7 kg) was tested during this evaluation The 5.7 kg generators were selected for this evaluation based on their discharge momentum and the fact that they are designed for spaces with higher ceilings/overheads (five meters high). The initial intent was to test System Three with a design density of 91 g/m^3 for Fire Scenario One and a design density of 114 g/m^3 for Fire Scenarios Two-Four. These design densities were increased based on the results of the tests.

4.4 Machinery Space Washdown System

One of the primary concerns associated with expediting these tests was the residual agent/powder remaining in the space (suspended in the air and deposited on all of the surfaces within the space) after each test. A significant portion of the particulate was suspended in the air on completion of the test and was removed by ventilating the space. In an attempt to rapidly clean the surfaces within the space, a water washdown system was installed in the overhead of the compartment.

The washdown system consisted of a three by three grid of Bete TF29-180-16 nozzles installed in the overhead of the space with a nominal 3.0 m nozzle spacing as shown in Figure 9. The system discharged 340 Lpm at an operating pressure of 2.8 bar. The system was activated for approximately 30-seconds to clean the surfaces within the space between the different manufacturers (every three days).

4.5 Instrumentation

Both the test compartment and the AES (generators) were instrumented during this test series. The instruments installed in the test compartment were used to monitor the thermal conditions in the space, the status of each fire, and the particulate density history during each test. The AES instrumentation was used to monitor the discharge characteristics of the system (e.g., the discharge time, discharge rate (g/s) and the temperature of the agent stream). The CG’s data acquisition system was used to collect the data during this evaluation. The data were collected at a rate of ten scans per second (ten Hertz). The instrumentation scheme is shown in Figure 10. The details on these instruments are provided in the following sections of this report.

4.5.1 Machinery Space and Fire Monitoring Instrumentation

The machinery space was instrumented to measure the air/gas temperatures, fire/flame temperature (to note extinguishment time), fuel system pressure, the gas concentrations in the compartment (CO, CO_2, and O_2) and the particulate density (during the telltale fire tests). A more detailed description of these instruments is provided in the following sections

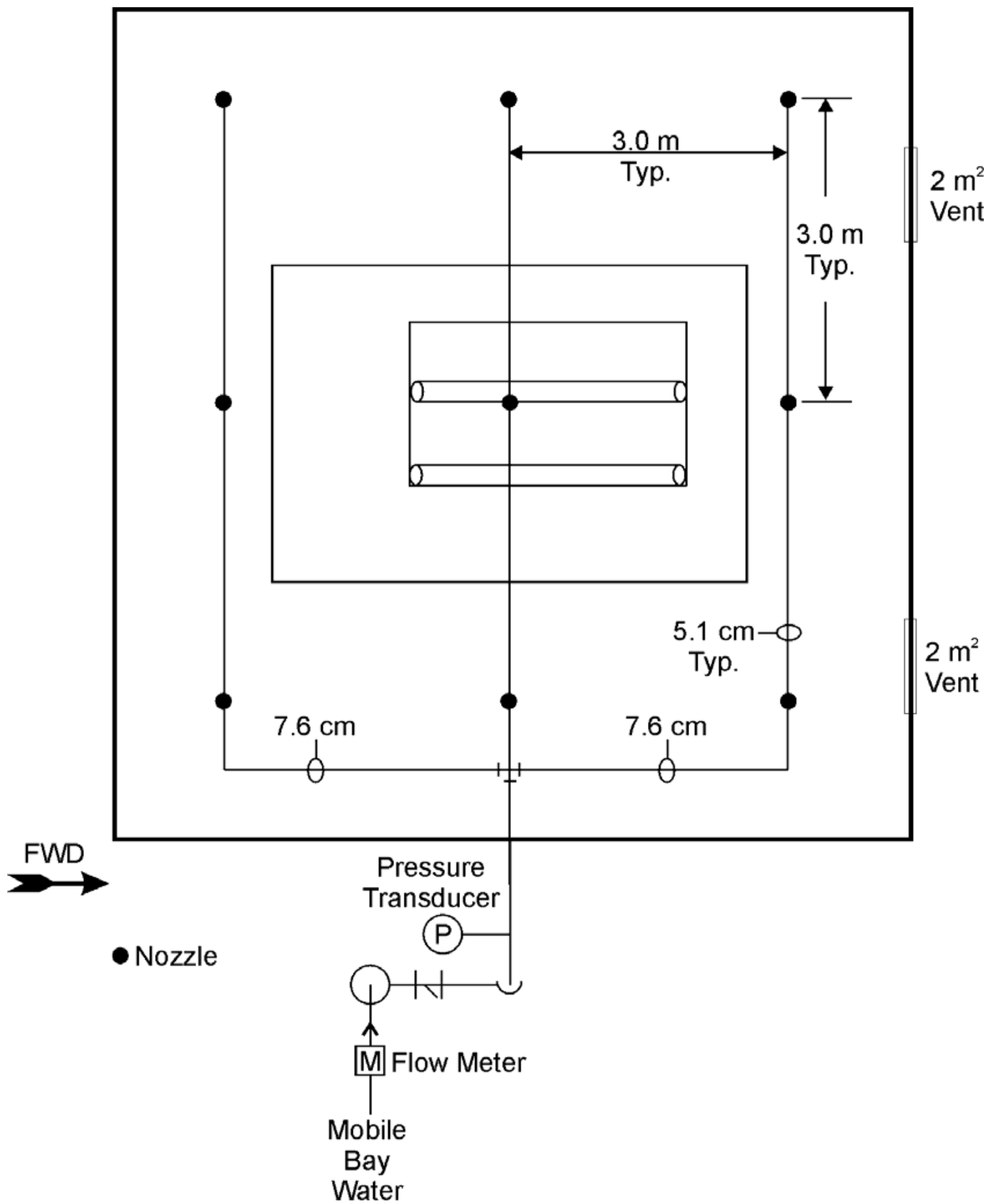


Figure 9. Water Washdown.

4.5.1.1 Air/Gas Temperature Measurements

One thermocouple tree was installed in the center of the compartment just aft of the diesel engine mockup to measure the air/gas temperatures in the space during the test. The tree consisted of nine thermocouples positioned at the following heights above the lower deck (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 m). Inconel sheathed Type K thermocouples (0.32 cm diameter Omega Model KMQIN-125G-600) were used for this application.

4.5.1.2 Compartment Pressure Measurements

The compartment pressure was measured at two locations in the space (the forward and port bulkheads 1.5 m above the deck). Setra Model 280E pressure transducers with a range of ± 2.48 kPa were used for this application. These instruments have an accuracy of 0.01 percent of full-scale.

4.5.1.3 Gas Concentration Measurements

Carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) concentrations were measured near the center of the compartment at five elevations (0.5, 1.5, 2.5, 3.5, and 4.5 m) above the deck as shown in Figure 10. MSA Lira 3000 Analyzers with a full-scale range of 10 percent by volume were used to measure the carbon monoxide concentration, MSA Lira 303 Analyzers with a full-scale range of 25 percent by volume were used to monitor the carbon dioxide concentration, and Rosemont 755 Analyzers were used to monitor the oxygen concentration with full-scale range of 25 percent by volume.

The gas samples were pulled from the compartment through 9.5 mm stainless steel tubing using a vacuum sampling pump at a flow rate of 1 Lpm, resulting in a transport delay on the order of ten to 20-seconds.

4.5.1.4 Particulate Density Measurements

Particulate densities were only measured during the telltale fire tests. The products of combustion produced by the larger fires would void the accuracy of these measurements (as well as potentially damage the instruments due to the resulting compartment temperature).

Particulate densities were measured using prototype laser optical density meters (ODMs) developed, tested and calibrated in the lab at HAI. Each ODM consisted of a Thorlabs red light laser (Model CPS 186) and a Huygen photocell (Model 856 Type 2 with viscor coating). The laser and photocell were housed in 3.8 cm PVC pipe with a 10 cm opening between the two devices (10 cm path length).

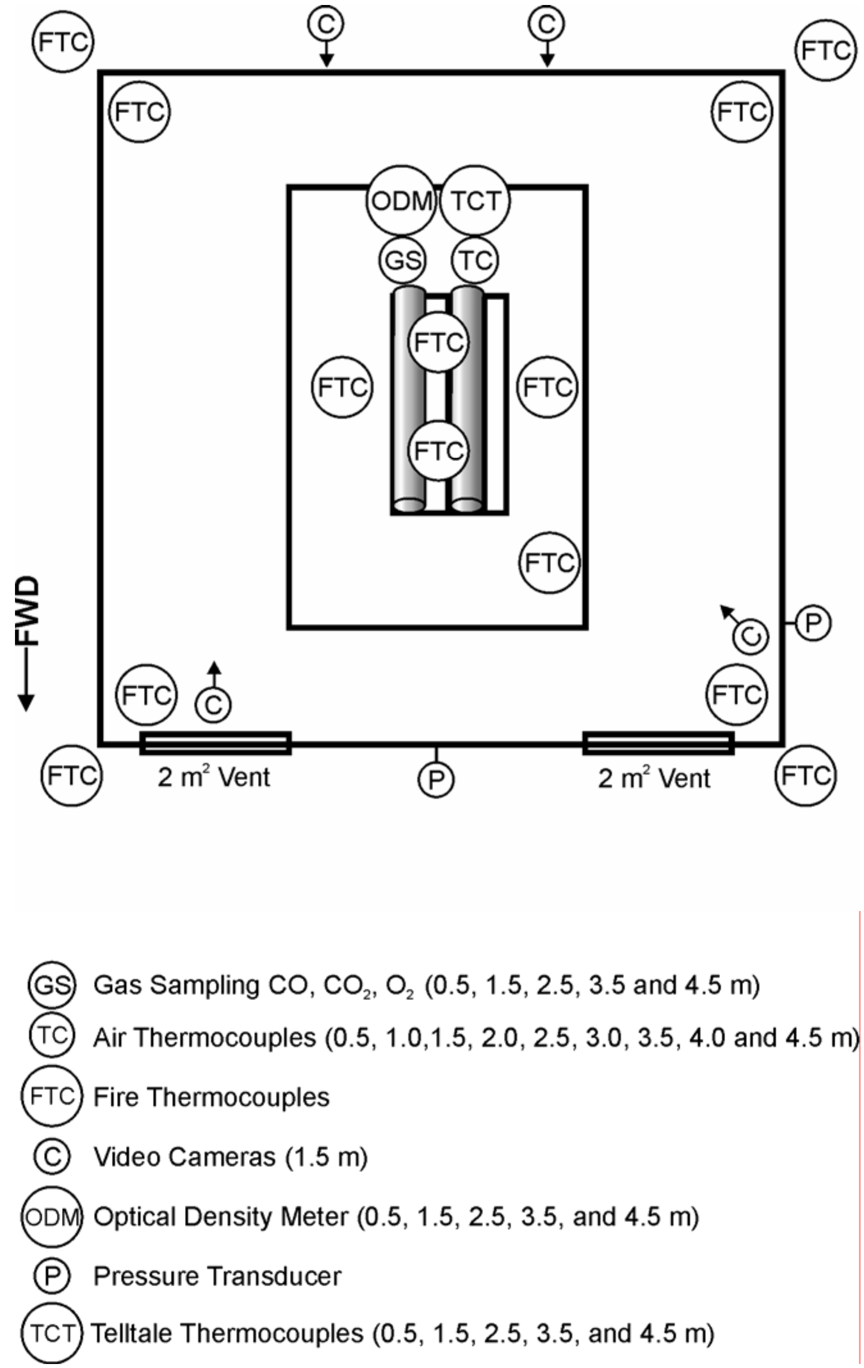


Figure 10. Instrumentation.

The ODMs were installed in the compartment at five elevations; 0.5, 1.5, 2.5, 3.5, and 4.5 m (on a tree adjacent to the gas concentration measurement locations). These measurements were used to estimate both the particulate density and the visibility in the space.

4.5.1.5 Fuel System Pressure Measurements

The spray fire fuel system pressure was monitored approximately six meters upstream of the nozzle where the fuel line enters the test chamber. The pressure was monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 1.7 MPa. This instrument has an accuracy of 0.01 percent full-scale.

4.5.2 AES Instrumentation

Each AES was instrumented to measure the agent discharge time and rate during each test. A more detailed description of these instruments is listed as follows.

4.5.2.1 AES Discharge Measurements

The discharge time and rate was primarily determined based on the weight loss of the generators installed at the forward port corner of the compartment. A 226.8 kg load cell (BLH U3G1-C) was used for this application.

Other measurements including the agent stream temperatures and the particulate density histories were used to confirm/validate these measurements.

4.5.2.2 AES Temperature Measurement

The temperature of the aerosol discharged from one generator was measured during each test. The temperature of the aerosol was measured using an array of thermocouples installed directly in front of the generator at the following locations; 0.3, 0.6, 0.9, and 1.2 m away from the generator. The surface temperature of the generator was also measured. Inconel sheathed Type K thermocouples (0.32 cm diameter) Omega Model KMQIN-125G-600 were used for both applications.

4.5.3 Video Equipment

Four video cameras (three standard and one Infrared) were used to visually document the events of each test. Two cameras were located on each end (forward and aft) of the compartment viewing the area around the diesel engine mockup as shown in Figure 10. The Infrared (IR) camera was located in the forward port corner of the space. A microphone was also installed in the center of the space to provide the audio for the four video cameras.

5.0 PROCEDURES

The tests were initiated from the control room located on the second deck level forward of the test compartment. Prior to the start of the test, the pans were fueled, and the compartment ventilation condition set. The two lower watertight doors and the six m^2 stack vent were opened prior to the start of the test. The video and data acquisition systems were activated, marking the beginning of the test. One minute after the start of the data acquisition system, the fires were ignited, and the compartment was cleared of test personnel. The ignition sequence timing was driven by the fires specific to the test scenario. Wood crib fires were ignited 360 and 120-seconds prior to system activation, pan fires were ignited 120-seconds prior to system activation, and spray fires were ignited 15-seconds prior to agent discharge. Ten-seconds prior to AES activation, the two lower doors and exhaust stack were closed. The fuel for the spray fire was secured 15-seconds after the fire was extinguished (determined by a rapid decrease in temperature measured in the flaming region of the fire and potentially verified with video coverage). The test continued for at least 17-minutes after AES activation. On completion of the test, the space was ventilated to remove any remaining aerosol particulates suspended in the air.

6.0 RESULTS AND DISCUSSION

A total of 18 full-scale fire tests were conducted during this evaluation. The results of these tests are discussed in the following sections. The nomenclature used to identify each test is as follows:

S # (System One-Three) T # (Test number with that particular system)

6.1 General

6.1.1 Resulting Conditions

Once an AES is activated, a combustion process occurs within the generator that expels a thick white smoke (agent) throughout the space. The particle sizes are small (sub ten micron) allowing the agent to remain suspended in the air for a long period of time. These suspended particles significantly reduce the visibility in the space. The temperatures of the generator surface and the stream of agent near the generator can exceed hundreds of degrees Celsius. The discharge of the agent increases the temperature in the space and the combustion gases tend to dilute the oxygen concentration in the space. The conditions produced by the three systems during the telltale fire tests (Fire Scenario One) are summarized in Table 3. Higher design densities should (i.e., those that include the factor of safety) vary these conditions proportionally to the increase in design density. These parameters/conditions will be discussed in detail in the following sections.

6.1.1.1 System Conditions

The design densities shown in Table 3 were based on the number and size of the generators installed in the space for the test. The delivered density was based on the mass loss of the generators during agent discharge. Also shown in this table are two particulate densities; one calculated and one measured. The calculated value was determined based on the gas concentrations (CO, CO_2, and O_2) and the delivered density. More specifically, the value was determined based on the amount (mass) of aerosol that would need to be burned to dilute the O_2 concentration to the measured value (assuming a specific ratio of CO, CO_2, H_2O and N_2). The measured value was determined using an average of the five optical density meters installed in the space and a calibration curve developed for each agent during small-scale tests. The particulate densities listed for the large fire tests are extrapolations of the telltale test results scaled as a function of the increased design densities.

An interesting point to be noted from these measurements is that only about 20-30 percent of the mass of the agent discharged is converted into potassium-based compounds suspended in the air (particulate density). The rest is released as a gas containing various amounts of CO, CO_2, H_2O, and N_2.

The discharge times for the three systems varied from approximately 20-seconds to almost two-minutes. These discharge times are approximations based on the following measurements; mass loss of a generator, temperatures measured at the generator outlet and the particulate density measured in the space. Techniques for measuring the discharge times will be discussed later in the report.

Table 3. System Discharge Characteristics.

	System One	**System Two**	**System Three**
Design density (g/m^3)	59	106	137
Delivered density (g/m^3)	56	101	86
Particulate density calc. (g/m^3)	22	18	13
Particulate density measured (g/m^3)	18	19	15
Discharge time (s)	~120	~90	~20
Peak comp. temp. (°C)	50	73	45
Temperature increase (°C)	25	45	17
Peak comp. pressure (Pa)	45	700	65
Visibility (m)	0.3	0.3	0.3
Safe distance comb. (m)	0.7	0.5	0.3
Safe distance personnel (m)	1.6	1.5	0.9
Gen. surf temp. (°C)	70	270	45
CO conc. (%)	0.35	0.8	0.7
CO_2 conc. (%)	0.5	1.6	1.1
O_2 conc. (%)	20.35	19.1	19.7

The temperatures of the agent streams as they exited the generators were typically hundreds of degrees Celsius. NFPA 2010 defines two safe distance parameters associated with the agent stream; safe distance for combustibles less than 200°C and safe distance for personnel less than 75°C. The measured safe distances for these systems are listed in Table 3. In general, combustible materials should be kept at least 0.5 m away from the generators while the safe distance for humans ranged from 0.9-1.6 m.

The generator surface temperatures ranged from 45-270°C. In all cases, the paint near/around the generator outlet burned away during the discharge.

6.1.1.2 Space Conditions

As stated previously, the agent is discharged as a hot white smoke that reduces visibility and increases the air/gas temperature in the space. These two conditions combined will make it extremely difficult to exit the space after agent discharge. As shown in Table 3, the visibility was reduced to about 0.3 m assuming an illuminated source. The average gas temperatures were also observed to increase from 17-45°C above ambient depending on the system. The discharge of the system only had a limited effect on the compartment pressure (increases of 45-700 Pa).

The gas concentrations (increases and decreases) are fairly proportional with the delivered density (independent of the system). More specifically, a delivered density of 100 g/m^3 will typically produce the following concentrations ~ 19.1 percent O_2, 1.6 percent CO_2 and 0.8 percent CO. It needs to be noted that these concentrations would be proportionally higher (and lower for O_2) for higher design densities.

With respect to the gas concentrations mentioned previously, only the CO concentrations pose a potential health risk for personnel in the space. The National Institute for Occupational Safety and Health defines a 0.12 percent CO concentration as Immediately Dangerous to Life or Health (IDLH). The values measured during these tests were significantly higher than this IDLH. Since toxicity data tend to vary significantly for acute exposures, an acceptable CO concentration should be defined in MSC/Circ. 1007.

With respect to particulate densities, most systems produced a well mixed environment within two to three-minutes of activation. Once well mixed, the particulate density typically decayed at a rate of about three percent per minute independent of the system. As a result, the particulate density in the space at the end of the test (15-minutes after the end of agent discharge) was less than 40 percent of that produced immediately after discharge. The particulate density histories for the three systems are shown graphically in Figure 11.

The decay rate of the particulate densities observed during these tests appears to be a function of both the particle size and the leakage area; not just the leakage area as published by the manufacturers. This is supported by the gas concentrations measured in the space during these tests. The gas concentrations remain steady during the 15-minute hold time while the particulate densities decay to less than 40 percent of the original value. If leakage was the contributing factor during this test, dilution of the gases in the space with fresh air would have occurred and been measured. The gas concentrations and particulate densities measured during one of the telltale fire tests are shown in Figure 12. As shown in this figure, the particulate density still decayed while the gas concentrations remained constant for the duration of the test.

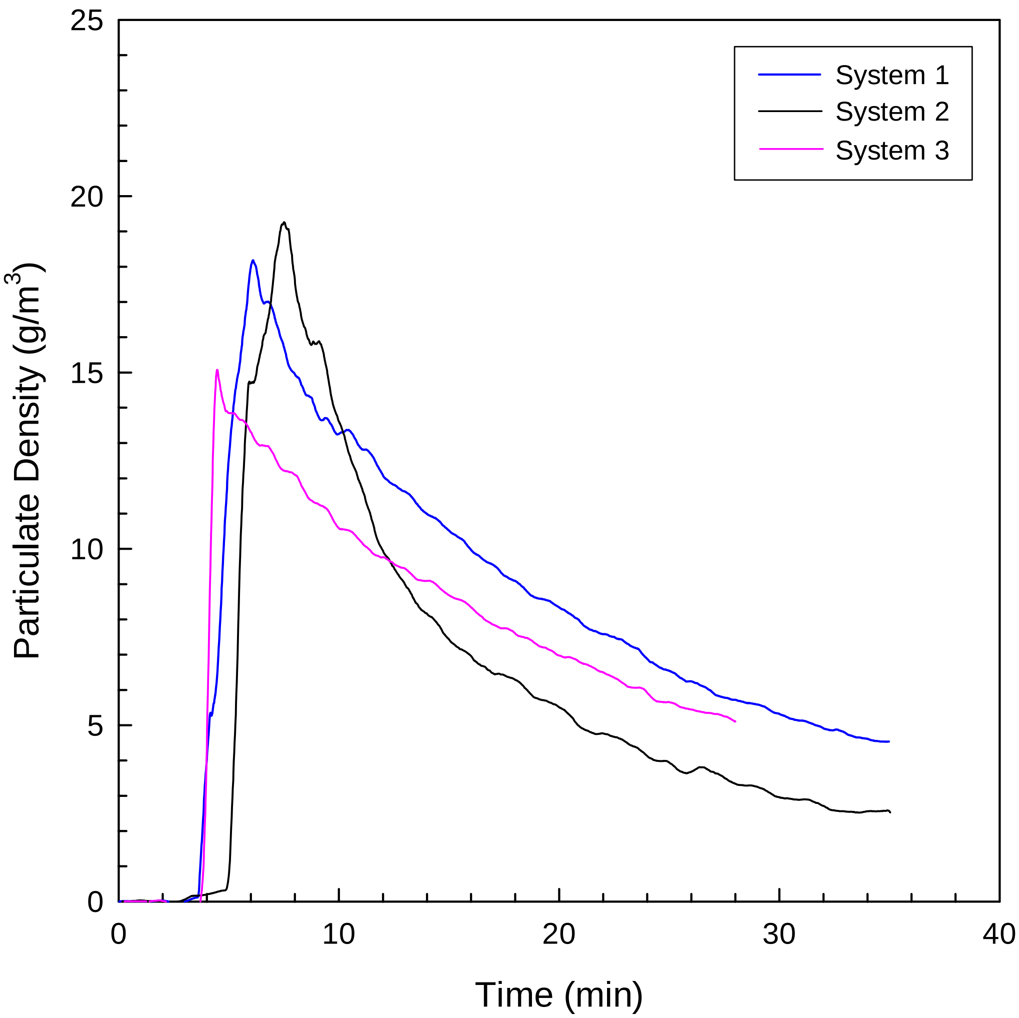


Figure 11. Particulate Density Histories.

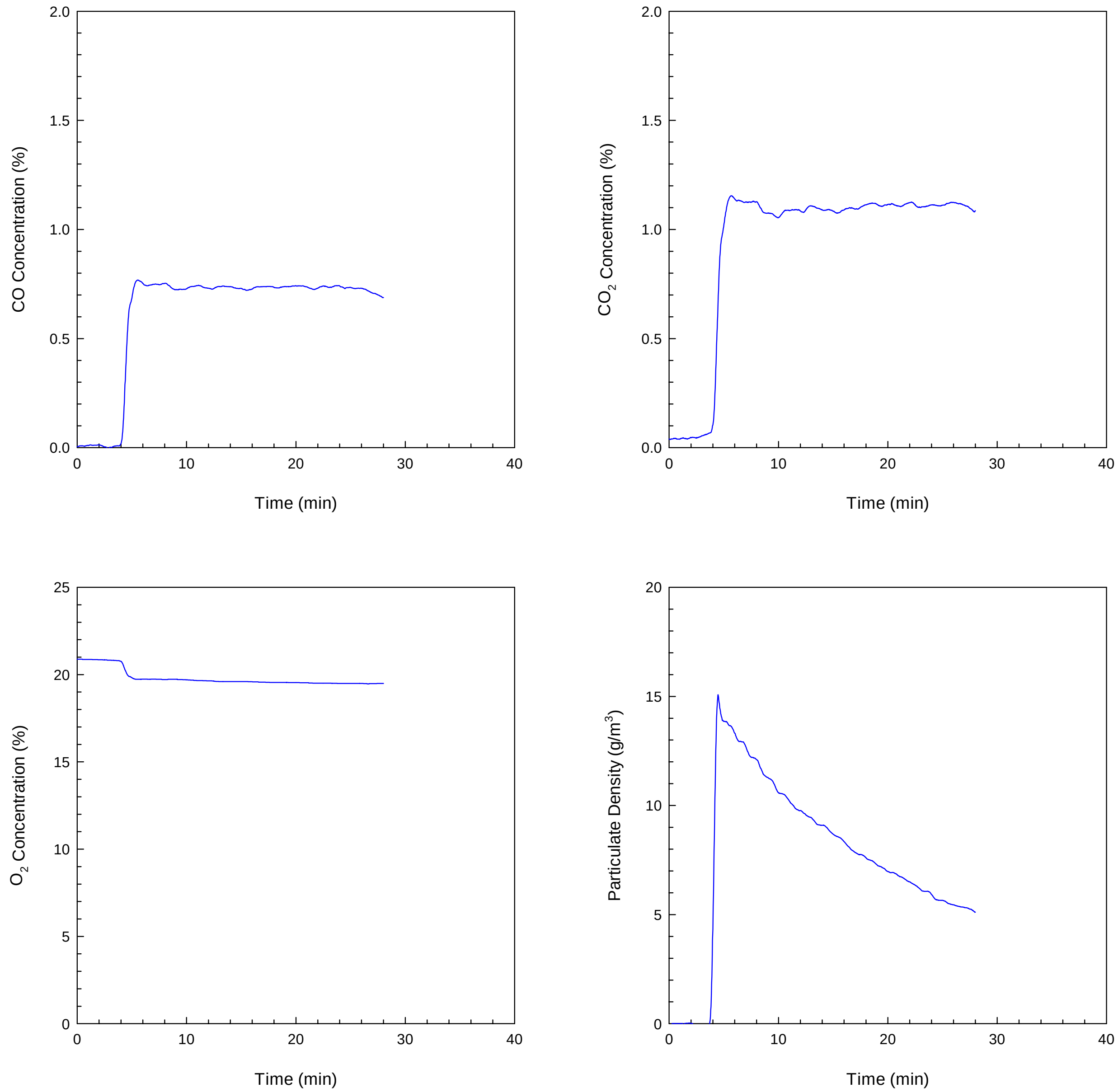


Figure 12. Gas Concentrations and Particulate Density Decay Comparison.

6.1.2 Extinguishing Capabilities

The extinguishment times provided in this report were determined using the temperatures measured above the fire (in the flame) during each test. The extinguishment time was the time from system activation (not the end of agent discharge as discussed in MSC/Circ. 1007) until the fire was extinguished. This approach was adopted for this investigation since an acceptable measure for the end of agent discharge has yet to be identified. Extinguishment was believed to have occurred when the temperature measured above the fire began to rapidly decrease and continued to decrease for the duration of the test. An example is provided in Figure 13.

The extinguishing capabilities of the three systems are summarized in Table 4.

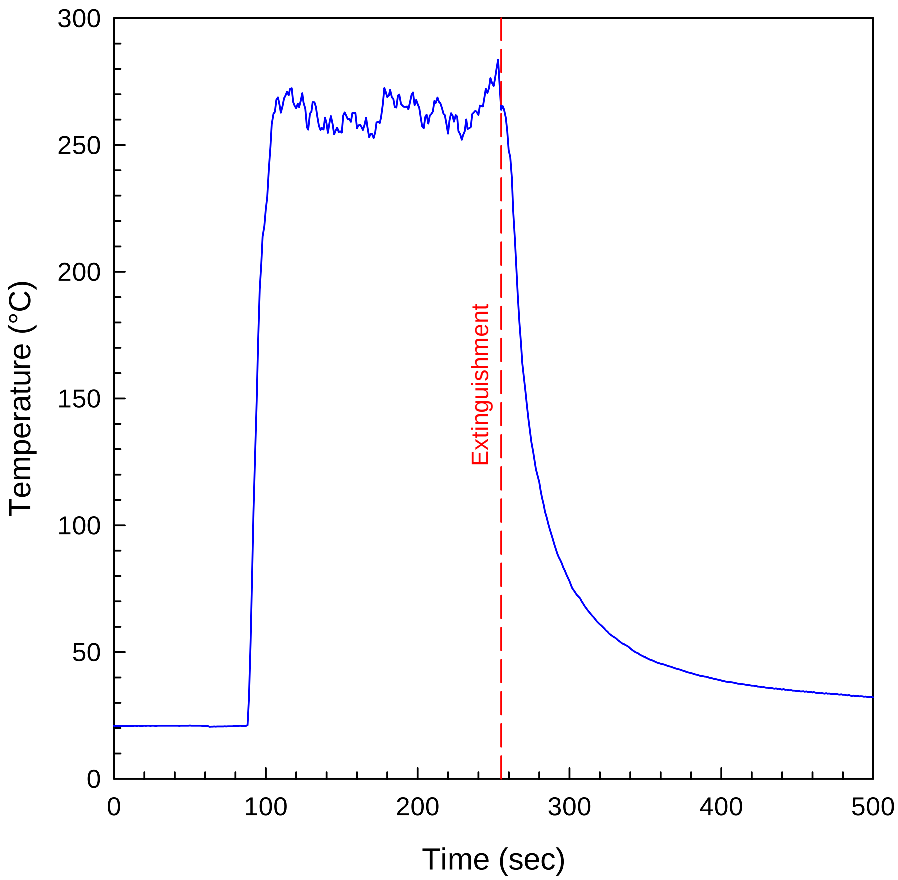


Figure 13. Typical Fire Temperature History.

Table 4. Extinguishment Capabilities (Summary).

Fire Scenario		Tested	Extinguished	% Ext.
Class A	2:00 preburn	7	1	14
	6:00 preburn	7	0	0
Class B	Fuel soaked mat	4	4	100
	Telltales	112	103	92
	Pan fires	8	8	100
	Spray fires	4	4	100

As shown in Table 4, AES are limited in their ability to extinguish deep seated Class A fires. More specifically, none of the systems were capable of extinguishing a wood crib with the required six-minute preburn (MSC/Circ. 1007 Fire Scenario Three). Only one of the systems was capable of extinguishing the wood crib with the two-minute preburn (System Three). This was accomplished with a delivered density of 149 g/m^3 which is 1.67 times that required to successfully complete the telltale fire test (Fire Scenario One). The particulate density for this test was estimated to be approximately 26 g/m^3. The design densities of Systems One and Two would only need to be increased by about 15 percent to produce similar particulate densities and potentially similar capabilities. The wood crib with the six-minute preburn appears to be outside the capabilities of this technology.

All three systems exhibited good capabilities against the Class B fires. All of the large Class B fires were quickly extinguished during this test series (in some instances with only a fraction of the agent required to complete the telltale fire test). Some of the systems initially had difficulty extinguishing the obstructed telltale fires in Fire Scenario One but that was eventually resolved by increasing the design density used during the test.

With respect to agent mixing, agent hold time, and critical reignition particulate densities, the prototype optical density meters provided meaningful data in understanding these parameters.

The fire extinguishment times and ODM measurements demonstrate that systems with faster discharge times (and greater thrust/momentum) produce better agent mixing and extinguish fires much faster than the systems with longer discharge times and lower momentum.

Based on the reignition tests, the particulate densities produced shortly after agent discharge (once the space became well mixed) were at least two to three times the critical value. More specifically, the peak particulate densities produced by these three systems ranged from 15-20 g/m^3 while the critical reignition density appears to be on the order of five g/m^3. As a result, the hold times to prevent reignition of Class B fuels are on the order of 20-25 minutes for the design densities used in the telltale fire tests. This is shown in Figure 14. These hold times should increase proportionally with the increase in design density for the larger fire tests (e.g., a 30 percent increase in hold time).

6.2 System Capabilities/Results

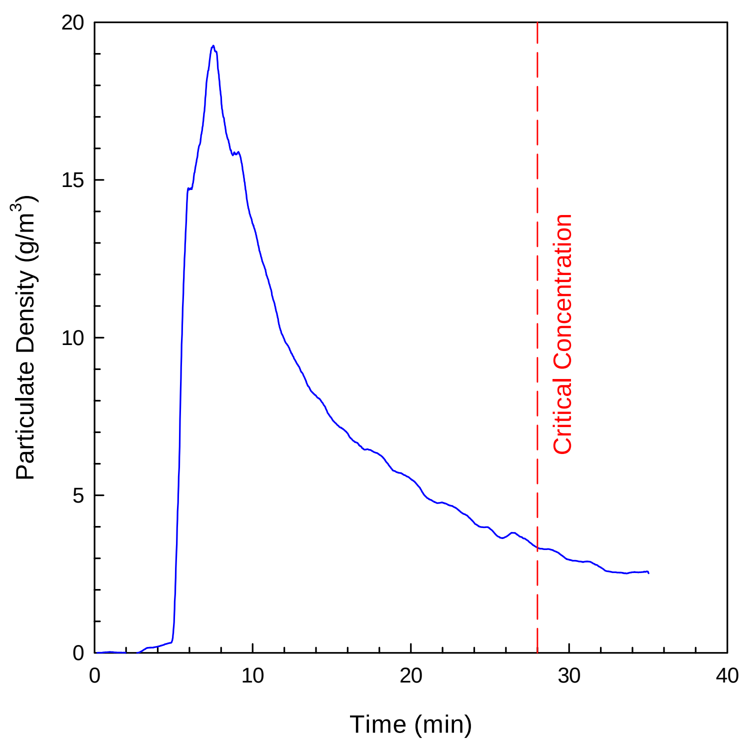
6.2.1 System One Results

System One is a condensed AES with generators that cover the spectrum of size, shapes, and types (a wide range of discharge times and agent stream temperatures). Combinations of generator types were evaluated during these tests.

The system was tested with a design density of 45-59 g/m^3 for the telltale tests (Fire Scenario One) and between 53-80 g/m^3 for the larger fire tests (Fire Scenarios Two-Four). Multiple generator sizes and types were used during each test to produce these design densities. The system configuration for each test is provided in Appendix B.

The discharge times varied significantly between the types of generators (25 to 160-seconds per manufacturer's data) used to produce the first system (System One). As a result, the discharge time was estimated to be approximately 120-seconds for each test. This was based both on the manufacturer's data and the measurements made in the space during the test.

Five tests were conducted with System One; two telltale fire tests, and three large fire tests (all conducted against Fire Scenario Three). The results of these tests are summarized in Tables 5 and 6.



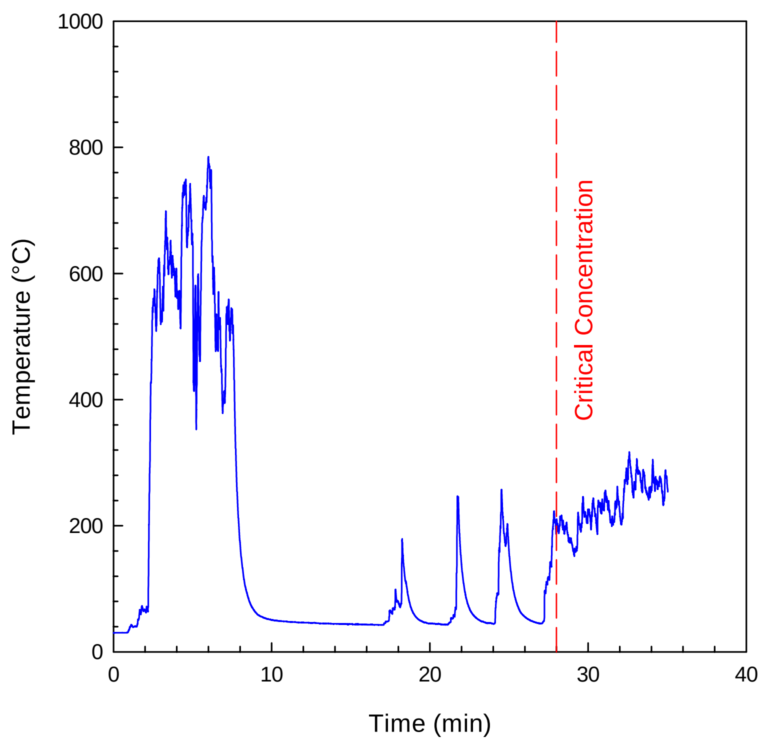


Figure 14. Critical Extinguishing Concentration (System Two).

Table 5. System One Telltale Fire Test Results (Extinguishment Times (seconds)).

TEST	S1T1 *	S1T2
Discharge time (s)	~ 120	~ 120
Design density (g/m^3)	45.2	59.0
Delivered density (g/m^3)	43.0	56.0
Particulate density calc. (g/m^3)	17.0	22.0
Particulate density measured (g/m^3)	14.0	18.0
Corner Telltales		
Fwd Port Upper	65	38
Aft Port Upper	58	70
Aft Stbd Upper	59	84
Fwd Stbd Upper	63	53
Fwd Port Lower	NO	98
Aft Port Lower	NO	104
Aft Stbd Lower	227	96
Fwd Stbd Lower	NO	147
Telltale Tree		
0.5 m	NO	114
1.5 m	NO	22
2.5 m	85	65
3.5 m	63	71
4.5 m	66	53
Additional Telltales		
Side of mockup	NO	75
Under mockup	NO	192
Under bilge plate	NO	114

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 150-seconds
* Test repeated due to unsealed opening (leaks) in the overhead of the compartment.

Table 6. System One Large Fire Test Results (Extinguishment Times (seconds)).

MSC/Circ. 1007 Fire Scenario	TEST	S1T3	S1T4	S1T5
1	Discharge time(s)	~ 120	~ 120	~ 120
	Design density	69.3	52.3	79.2
	Delivered density	9.7*	50.2	72.7**
	Particulate density est. g/m^3	3.1	16.1	23.4
2	0.1 m^2 heptane pan under obstruction plate			
	0.25 m^2 heptane pan under mockup			
3	0.1 m^2 heptane pan w/insulation	123	---	---
	Wood crib (2:00 preburn)	NO	NO	NO
	Wood crib (6:00 preburn)	NO	NO	NO
	2.0 m^2 diesel pan	343	---	---
	Spray fire (heptane)	40	---	---
4	4.0 m^2 diesel pan in bilge			

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 150-seconds
* Only two of 14 generators activated
** One of the 11 generators did not activate

During the first test (S1T1), a significant amount of agent was lost through unsealed openings in the test enclosure. These leaks were sealed and the test was repeated (S1T2) with a slightly higher design density to compensate for any missed/unsealed openings. As shown in Table 5, during Test 2 (S1T2), System One was capable of extinguishing all of the telltales required by MSC/Circ. 1007 within the allotted 30-second time period. With respect to the additional telltales added by the CG, only the one located under the mockup was outside the allotted time (72-seconds vs. the 30-second requirement). This illustrates the difficulty and additional time required to distribute the agent in highly obstructed areas. Since the fires in MSC/Circ. 1007 were all extinguished within the allotted time, the manufacturer decided to proceed with the larger fires rather than to increase the design density in an attempt to lower the extinguishment time of the telltale located under the mockup to an acceptable level.

The conditions in the space produced by the discharge of the system were identified during these telltale fire test(s). More specifically, these conditions were identified during Test 2 (S1T2) with a design density of 59 g/m^3. The gas concentrations and temperatures measured in the compartment during the test are shown in Figure 15. The particulate density and visibility in the space are shown in Figure 16. The surface temperature of the generator and the agent stream temperatures are shown in Figure 17. These conditions are summarized in Table 3 and were initially discussed in Section 6.1.1.

During the discharge of System One, the temperature in the space increased 25°C above ambient (on average) and the visibility was reduced to about 0.3 m (assuming an illuminated source/target). The discharge of System One had only a limited effect on the gas concentrations in the space. The O_2 concentration in the space dropped to 20.5 percent and the CO and CO_2 increased to 0.35 percent and 0.5 percent, respectively. Based on the temperatures measured in the agent stream, the safe distance from the generators to combustibles and personnel were determined to be 0.7 m and 1.6 m, respectively.

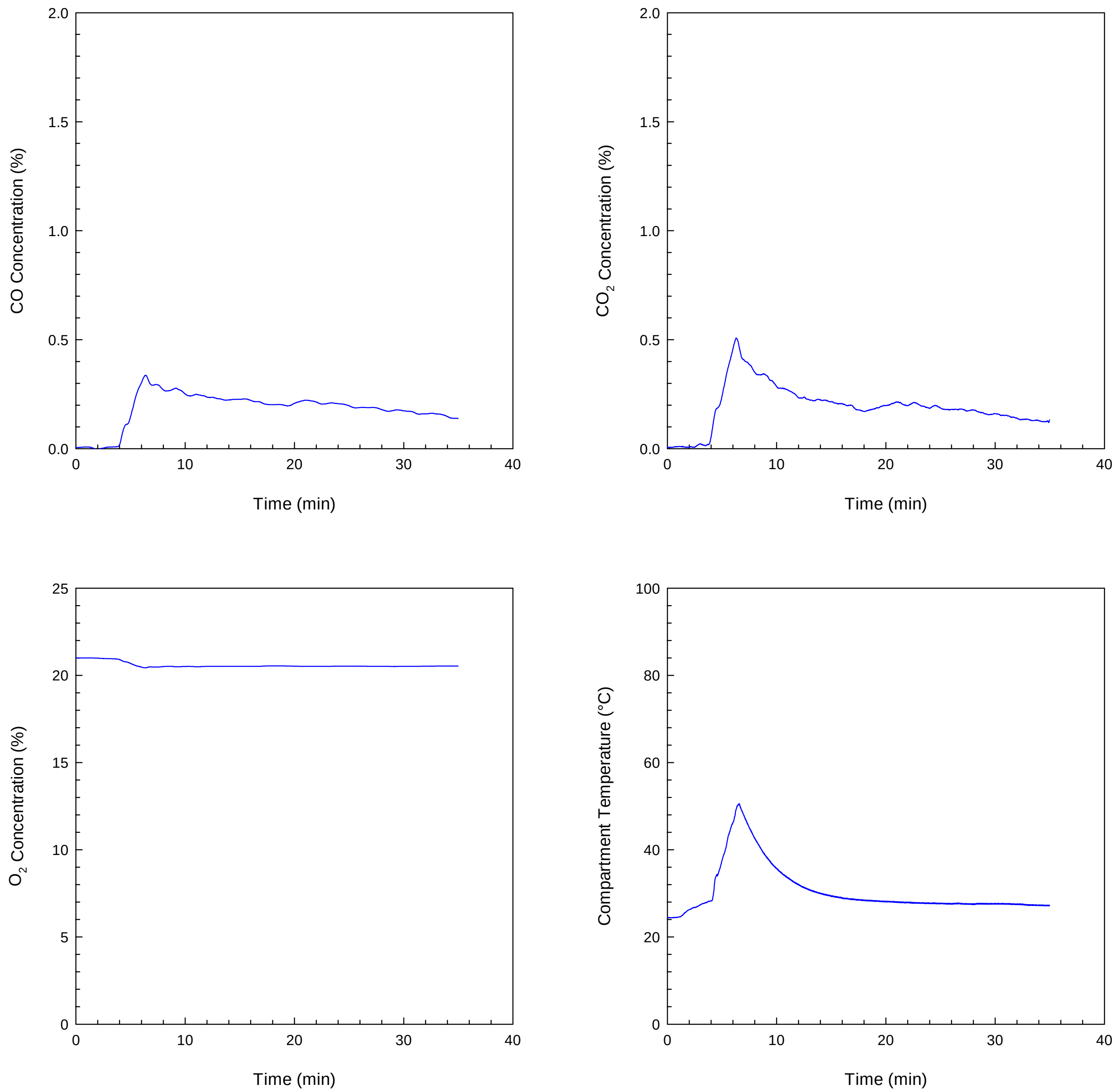


Figure 15. System One Compartment Conditions.

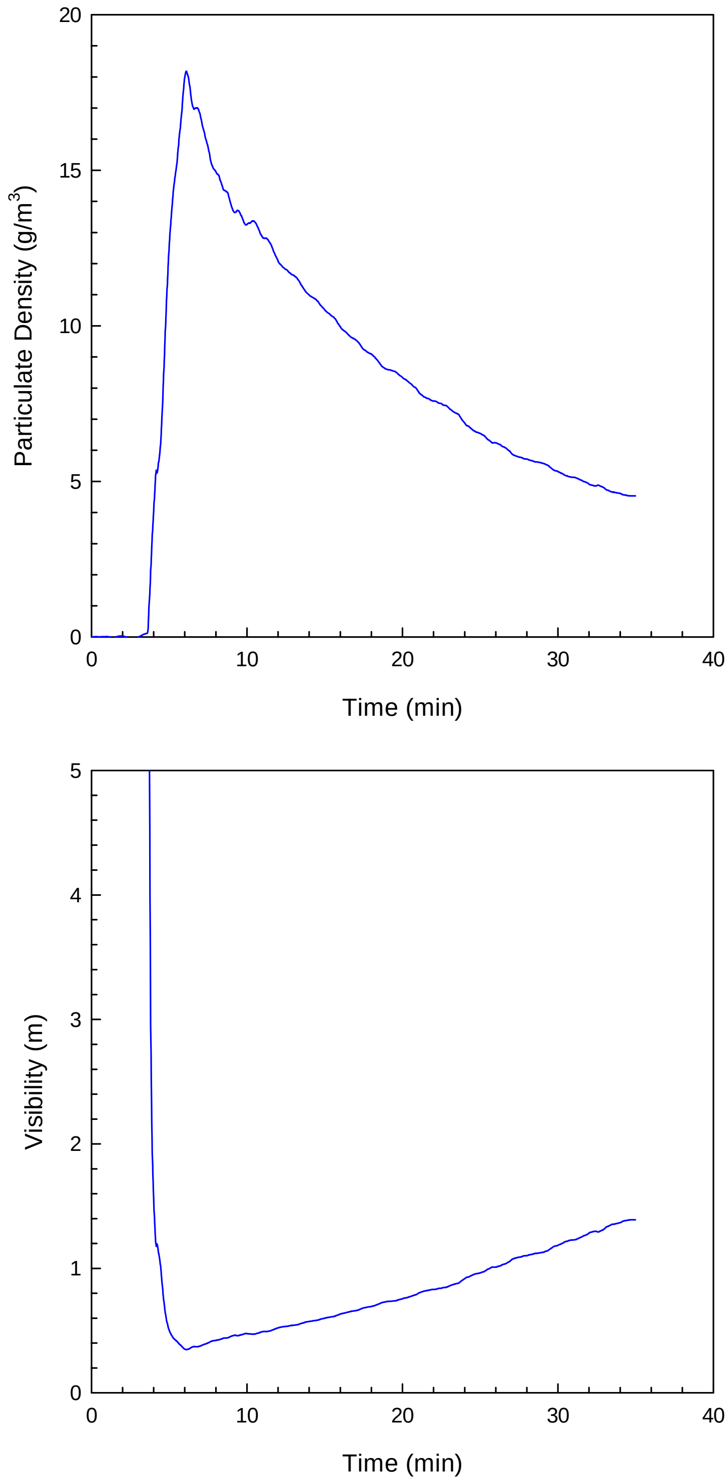


Figure 16. System One Particulate Density and Visibility.

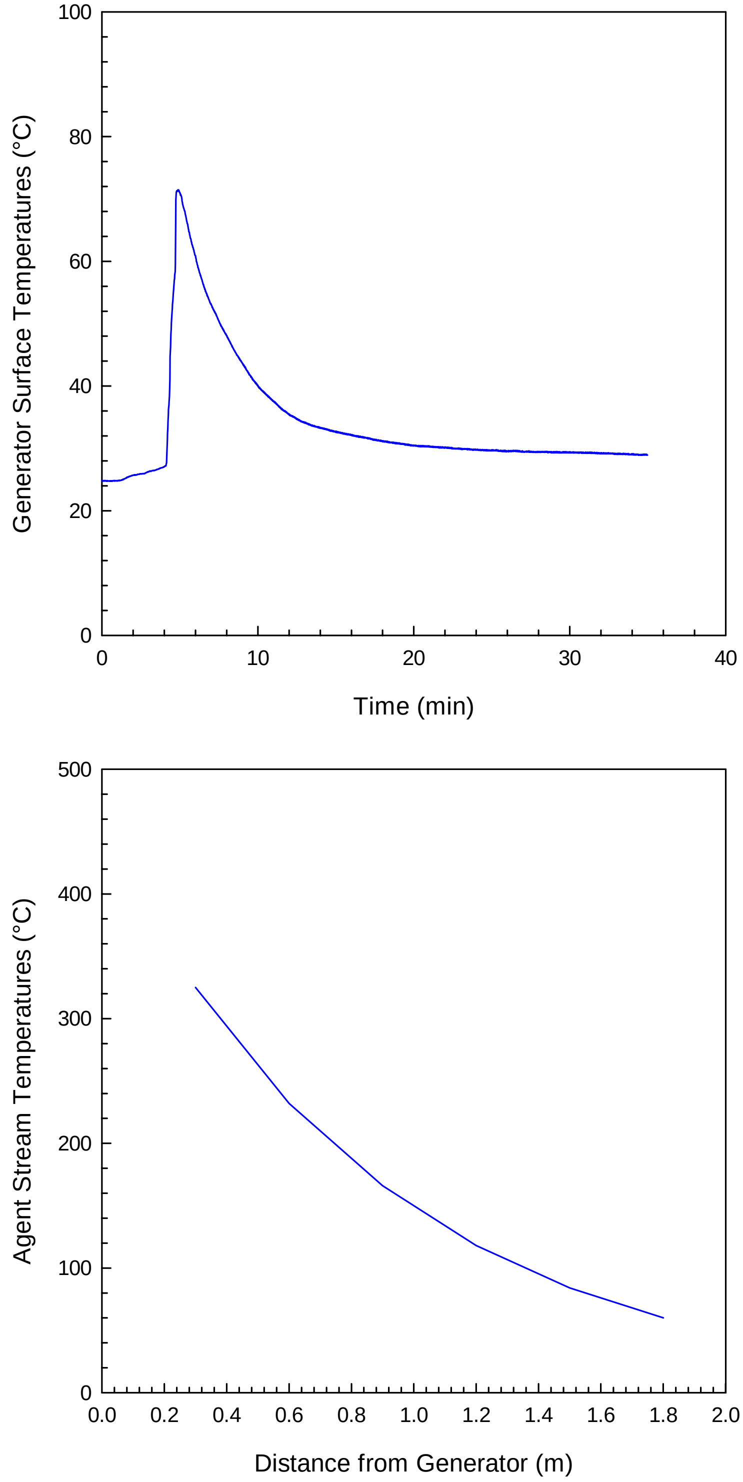


Figure 17. System One Generator Surface and Agent Stream Temperatures.

The delivered density of System One was about 95 percent of the design density (56 g/m^3 vs. 59 g/m^3). The system produced a particulate density which was approximately 30 percent of the delivered density. The peak particulate density for System One was on the order of 18 g/m^3. As with the other systems, the particulate density decayed at a rate of about three percent per minute (reference Figure 16).

The critical reignition particulate density was determined during the reignition test to be on the order of about 5.8 g/m^3 and occurred approximately 23-minutes after the end of agent discharge (23-minute hold time). This value is approximately 30 percent of the peak particulate density (the particulate density measured shortly after discharge). The reignition test results for System One are shown in Figure 18.

The capabilities of System One against the large fires are shown in Table 6. During two of the large fire tests, the hardware (activation wiring) was damaged by the heat produced during the preburn period. As a result, hardware modifications/hardening will be required prior to use in an actual application/installation.

As shown in Table 6, System One was unable to extinguish any of the Class A fires. On the other hand, the system was capable of extinguishing the Class B fires with a much lower design density than the other two systems (56 g/m^3 versus 75 g/m^3 and 101 g/m^3). In fact, during the third test (S1T3), where only two of the 14 generators activated, the system was capable of extinguishing all of the Class B fires with a delivered density of about ten g/m^3. Further testing is recommended to determine if the Class A fires (wood crib) could be extinguished with a higher design density. The particulate density estimated for the only successful Class A fire tests (S3T7) conducted during this test series could be produced by increasing the design density by 15 percent.

6.2.2 System Two Results

System Two is a prototype condensed AES still under development for machinery space application. The system was tested with a design density of 106 g/m^3 for Fire Scenario One and a design density of 132 g/m^3 for Fire Scenarios Two-Four. At this time in the development process, only 1.1 kg generators (upright) were available. The discharge time for these generators was estimated to be approximately 90-seconds. Also, due to the upright design, many tests were conducted with the generators located on the deck aiming upward as opposed to in the overhead in the pendent position as required by MSC/Circ. 1007. In short, it was decided to ease the installation requirements of the protocol and focus on the capabilities of the agent rather than the system. It is understood that numerous hardware modifications will be required prior to considering this system for an actual installation.

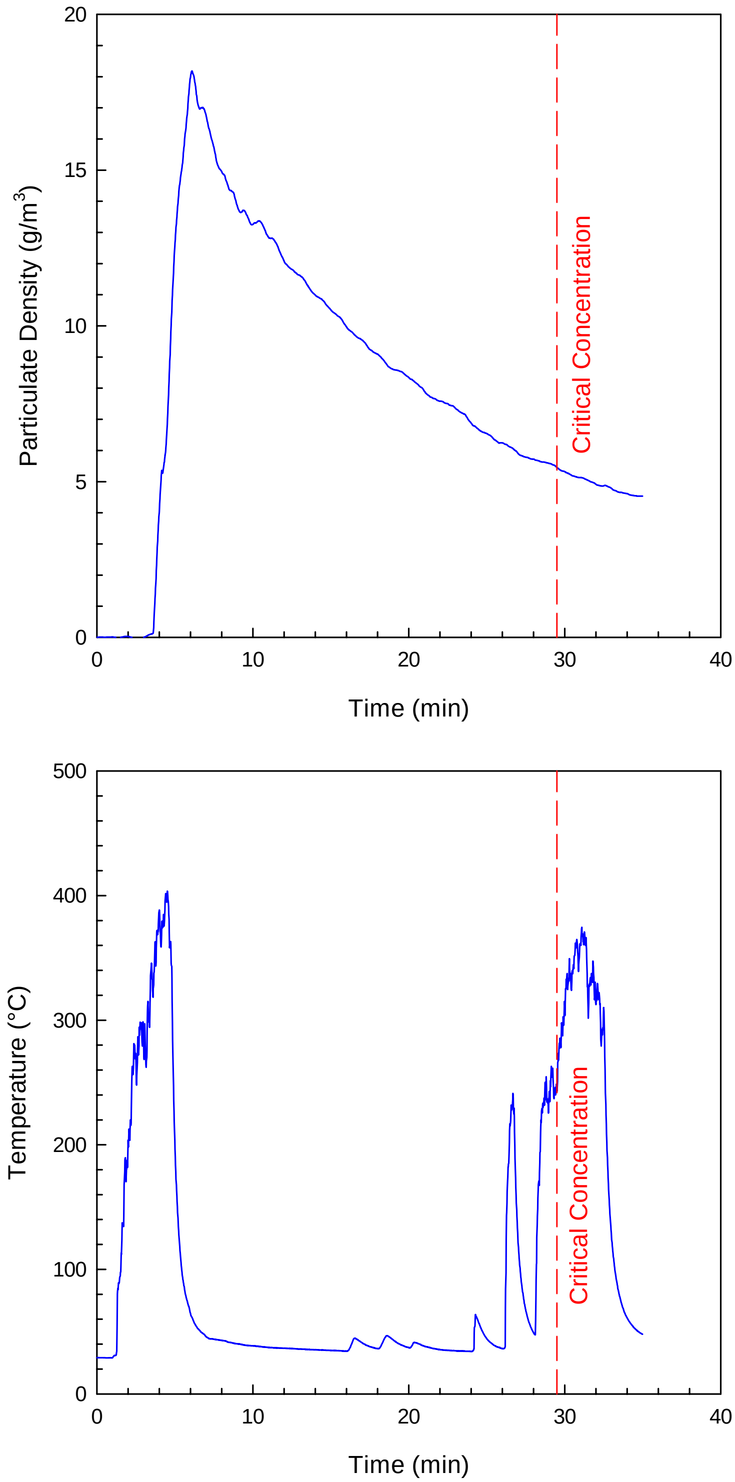


Figure 18. System One Reignition Test Results.

Six tests were conducted with System Two; two telltale fire tests and four large fire tests. The results of these tests are summarized in Tables 7 and 8. The system configuration for each test is provided in Appendix B.

Table 7. System Two Telltale Fire Test Results (Extinguishment Times (seconds)).

TEST	S2T1	S2T2
Discharge time(s)	~ 90	~ 90
Design density (g/m^3)	105.6	105.6
Delivered density (g/m^3)	101.4	101.4
Particulate density calc. (g/m^3)	18.0	18.0
Particulate density measured (g/m^3)	19.0	19.0
Corner Telltales		
Fwd Port Upper	79	46
Aft Port Upper	84	35
Aft Stbd Upper	88	37
Fwd Stbd Upper	46	56
Fwd Port Lower	171	100
Aft Port Lower	179	138
Aft Stbd Lower	109	124
Fwd Stbd Lower	183	185
Telltale Tree		
0.5 m	225	144
1.5 m	190	110
2.5 m	325	52
3.5 m	70	44
4.5 m	81	43
Additional Telltales		
Side of mockup	215	68
Under mockup	208	136
Under bilge plate	184	155

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 120-seconds

Table 8. System Two Large Fire Test Results (Extinguishment Times (seconds)).

MSC/Circ. 1007 Fire Scenario	TEST	S2T3	S2T4	S2T5	S2T6
1	Discharge time(s)	~ 90	~ 90	~90	~90
	Design density (g/m^3)	132.0	132.0	132.0	132.0
	Delivered density (g/m^3)	112.2*	126.7	126.7	126.7
	Particulate density est. (g/m^3)	21.0	23.7	23.7	23.7
2	0.1 m^2 heptane pan under obstruction plate				25
	0.25 m^2 heptane pan under mockup				75
3	0.1 m^2 heptane pan w/insulation	88	---		
	Wood crib (2:00 preburn)	NO	NO		
	Wood crib (6:00 preburn)	NO	NO		
	2.0 m^2 diesel pan	101	---		
	Spray fire (heptane)	68	---		
4	4.0 m^2 diesel pan in bilge			57	

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 120-seconds
* Nine of the 60 generators did not activate

During the initial test (S2T1), the generators were mounted in the overhead aiming upward. In this configuration, although all of the telltales were extinguished, the agent stratified high in the space producing excessively long extinguishment times for the fires located at the lower elevations. As a result, the second test (S2T2) was conducted with the generators located in the corners installed on the deck/floor aiming upward.

During the second test (S2T2), some stratification still occurred but the extinguishment times of the lower telltales were significantly reduced. Although three of the eight telltales required by MSC/Circ. 1007 took longer to extinguish than the allotted 30-seconds, (as well as three additional telltales not required by the protocol), the decision was made to proceed with the larger fire tests. In short, the particulate densities appear to be adequate to extinguish these fires but the hardware could not quickly distribute/mix the agent throughout the space in its current form/configuration.

The conditions in the space produced by the discharge of the system were identified during these telltale fire test(s). The gas concentrations and temperatures measured in the compartment during the test are shown in Figure 19.

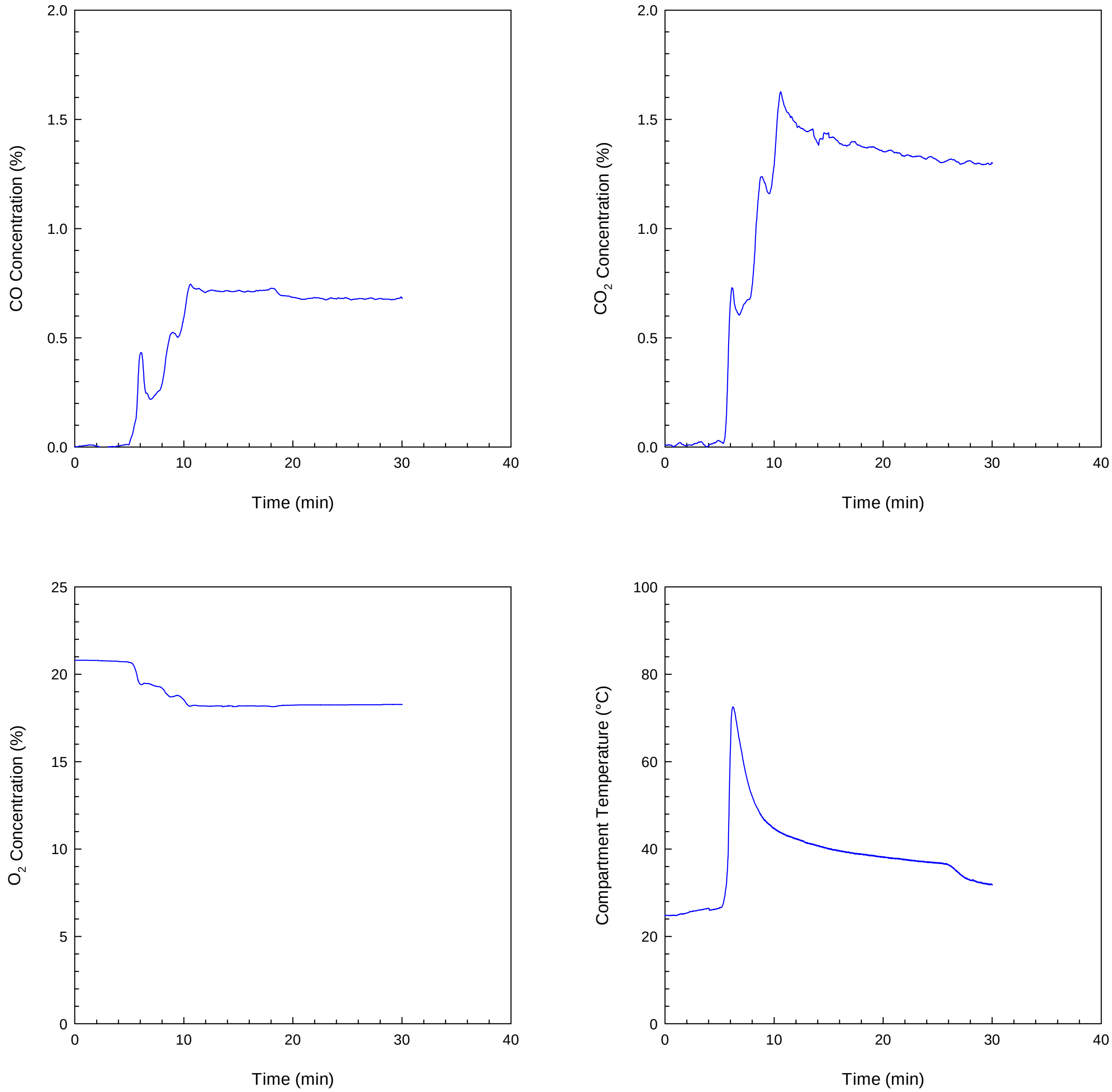


Figure 19. System Two Compartment Conditions.

The particulate density and visibility in the space are shown in Figure 20. The surface temperature of the generator and the agent stream temperatures are shown in Figure 21. These conditions are summarized in Table 3 and were initially discussed in Section 6.1.1.

During the discharge of System Two, the temperature in the space increased 45°C above ambient (on average) and the visibility was reduced to about 0.3 m (assuming an illuminated source/target). The discharge of the system had a moderate effect on the gas concentrations in the space. The O_2 concentration in the space dropped to 19.1 percent and the CO and CO_2 increased to 0.8 percent and 1.6 percent, respectively. Based on the temperatures measured in the agent stream, the safe distances from the generators to combustibles and personnel were determined to be 0.5 m and 1.5 m, respectively.

The delivered density of System Two was about 95 percent of the design density (101 g/m^3 vs. 106 g/m^3). The system produced a particulate density which was approximately 20 percent of the delivered density. The peak particulate density for System Two was on the order of 19 g/m^3. As with the other systems, the particulate density decayed at a rate of about three percent per minute (reference Figure 20).

The critical reignition particulate density was determined during the reignition test to be on the order of about 4.0 g/m^3 and occurred about 23-minutes after the end of agent discharge (23-minute hold time). This value is approximately 30 percent of the peak particulate density measured shortly after discharge. The reignition test results for System Two are shown in Figure 22.

The capabilities of System Two against the large fires are shown in Table 8. The system was tested against all three of the large fire tests in MSC/Circ. 1007 (Fire Scenarios Two-Four). As shown in this table, System Two was also unable to extinguish any of the Class A fires, but was capable of extinguishing all of the other fires (Class B) within the time allotted by MSC/Circ. 1007. In fact, all but one of the Class B fires was extinguished during system discharge.

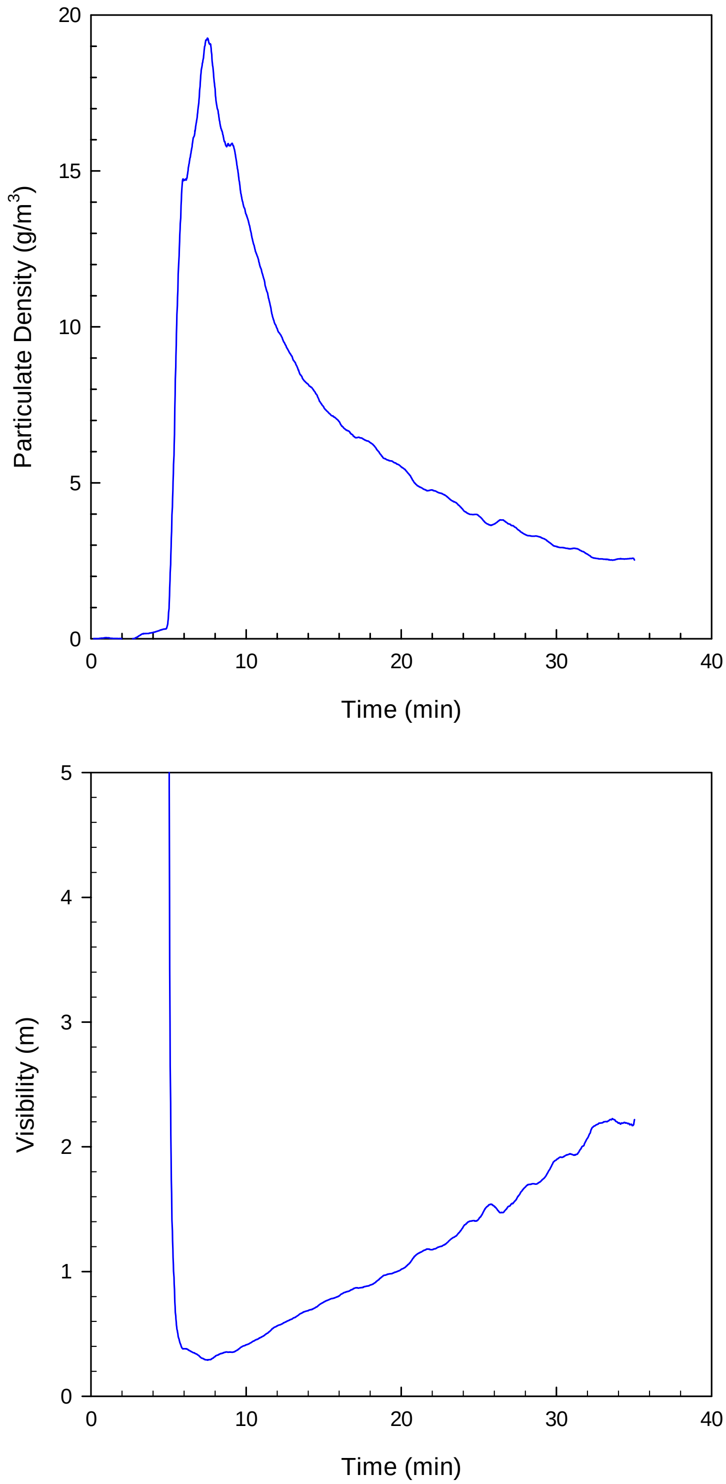
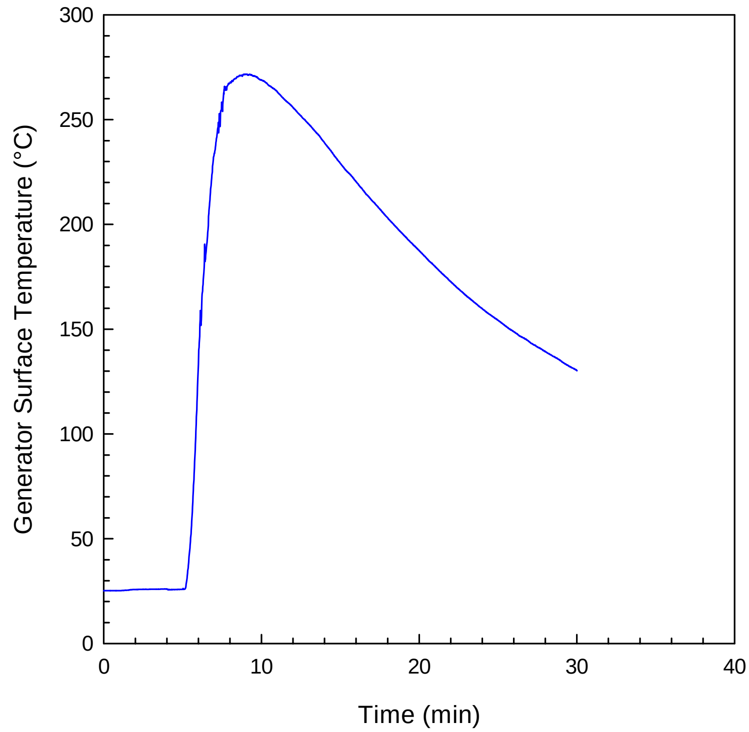


Figure 20. System Two Particulate Density and Visibility.



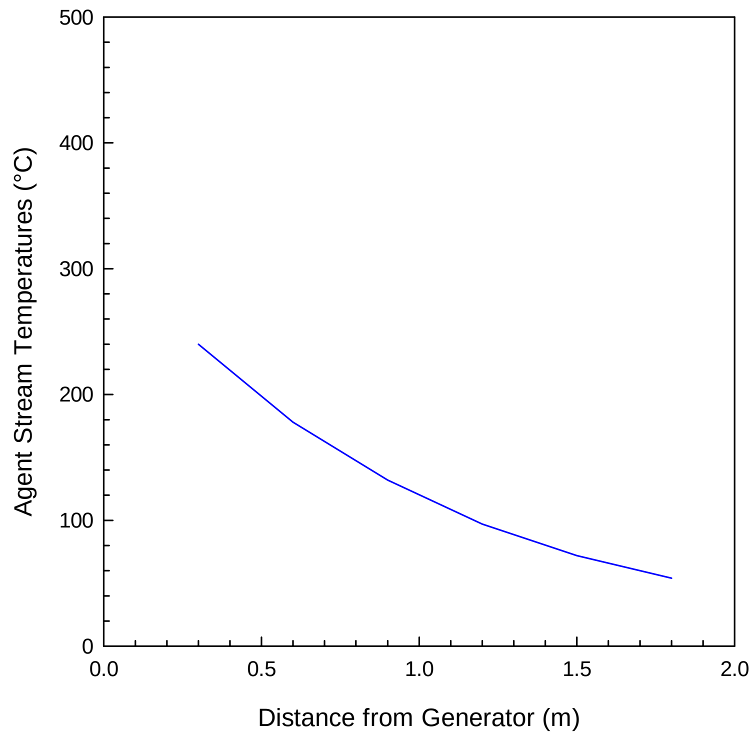
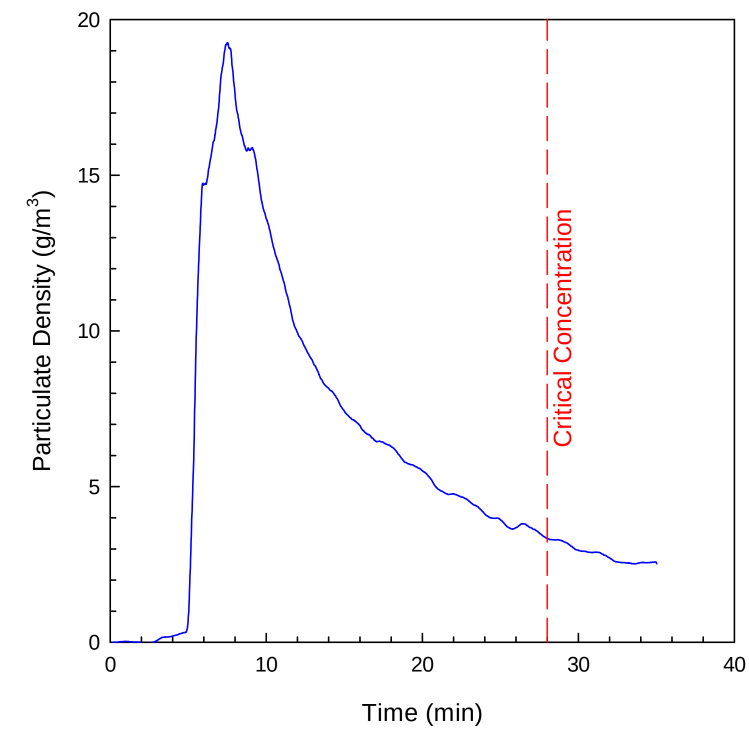


Figure 21. System Two Generator Surface and Agent Stream Temperatures.



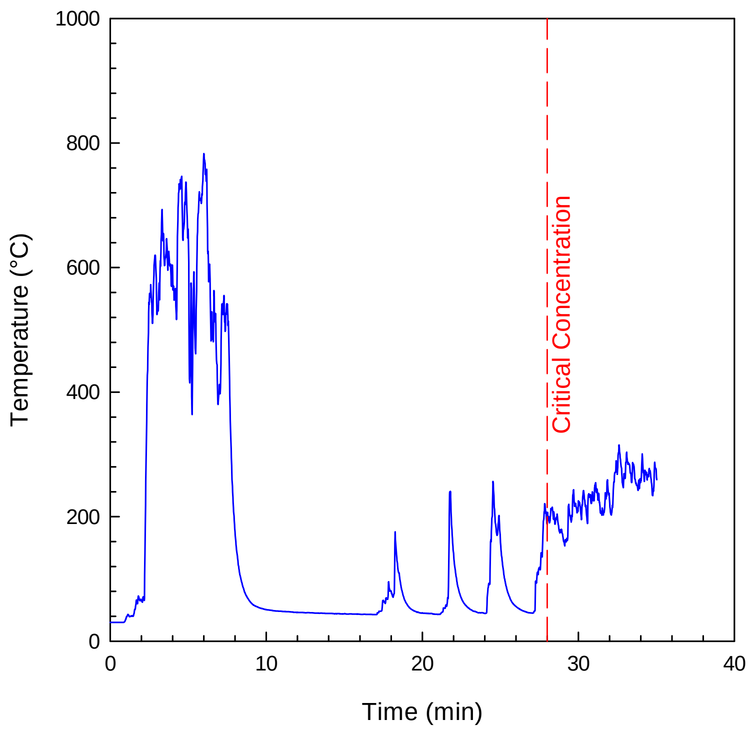


Figure 22. System Two Reignition Test Results.

6.2.3 System Three Results

The third system is a condensed AES that is being marketed overseas (currently well developed). The system is available in a range of generator sizes although only one size (5.7 kg) was tested during this evaluation. The system was tested with design densities ranging from 91 g/m^3 - 137 g/m^3 for Fire Scenario One and design densities ranging from 182 g/m^3 to 228 g/m^3 for Fire Scenarios Two-Four.

Although the generator capacity was published to be 5.7 kg, only 3.75 kg of aerosol was discharged by each generator. This manufacturer bases the capacity of the generator on the amount of chemical (solid compound) contained in the generator (which can be misleading). This explains the difference between the design and delivered densities listed in the table of results. The manufacturer should consider defining the capacity of the generator based on the amount of agent discharged rather than the amount of product contained within the generator.

Also, the increases in design densities between tests are a function of adding pairs of 5.7 kg generators in an attempt to keep the distribution uniform throughout the space. Smaller increases could have been achieved through the use of/addition of smaller generators.

Seven tests were conducted with System Three; three telltale fire tests and four large fire tests. The results of these tests are summarized in Tables 9 and 10. The system configuration for each test is provided in Appendix B.

The first three tests were conducted against the telltale fire scenario. The design density was increased between each test until all of the telltale fires were extinguished within the 30-seconds allotted by MSC/Circ. 1007. This was accomplished during the third test (S3T3) with a delivered density of 86 g/m^3.

Table 9. System Three Telltale Fire Test Results (Extinguishment Times (seconds)).

TEST	S3T1	S3T2	S3T3
Discharge time(s)	~ 20	~ 20	~ 20
Design density (g/m^3)	91.2	114.0	136.8
Delivered density (g/m^3)	60.0	75.0	86.0
Particulate density calc. (g/m^3)	9.1	12.2	13.0
Particulate density measured (g/m^3)	10.5	12.2	15.0
Corner Telltales			
Fwd Port Upper	48	54	38
Aft Port Upper	30	51	32
Aft Stbd Upper	50	31	31
Fwd Stbd Upper	56	39	46
Fwd Port Lower	30	330	25
Aft Port Lower	38	59	25
Aft Stbd Lower	348	55	25
Fwd Stbd Lower	57	49	48
Telltale Tree			
0.5 m	284	26	29
1.5 m	NO	22	28
2.5 m	31	29	24
3.5 m	458	32	31
4.5 m	37	47	31
Additional Telltales			
Side of mockup	55	38	21
Under mockup	21	22	20
Under bilge plate	27	36	42

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 50-seconds

Table 10. System Three Large Fire Test Results (Extinguishment Times (seconds)).

MSC/Circ. 1007 Fire Scenario	TEST	S3T4	S3T5	S3T6	S3T7
1	Discharge time(s)	~ 20	~ 20	~ 20	~ 20
	Design density (g/m^3)	182.4	182.4	182.4	228.0
	Delivered density (g/m^3)	113.0*	120.0	120.0	149.0
	Particulate density est. (g/m^3)	19.7	20.9	20.9	26.0
2	0.1 m^2 heptane pan under obstruction plate		28		
	0.25 m^2 heptane pan under mockup		35		
3	0.1 m^2 heptane pan w/insulation	46			30
	Wood crib (2:00 preburn)	NO			35
	Wood crib (6:00 preburn)	NO			NO
	2.0 m^2 diesel pan	22			21
	Spray fire (heptane)	20			23
4	4.0 m^2 diesel pan in bilge			12	

Extinguishment times measured from system activation
Exceeds extinguishment time criteria of 50-seconds
* One of the 16 generators did not activate

The conditions in the space produced by the discharge of the system were identified during the telltale fire test(s). More specifically, the conditions were identified during the third test (S3T3) with a delivered density of 86 g/m^3. The gas concentrations and temperatures measured in the compartment during the test are shown in Figure 23. The particulate density and visibility in the space are shown in Figure 24. The surface temperature of the generator and the agent stream temperatures are shown in Figure 25. These conditions are summarized in Table 3 and were initially discussed in Section 6.1.1.

During the discharge of System Three, the temperature in the space increased by about 17°C above ambient (on average) and the visibility was reduced to about 0.3 m (assuming an illuminated source/target). The discharge of the system had a moderate effect on the gas concentrations in the space. The O_2 concentration in the space dropped to 19.7 percent and the CO and CO_2 increased to 0.7 percent and 1.1 percent, respectively. Based on the temperatures measured in the agent stream, the safe distance from the generators to combustibles and personnel were determined to be 0.3 m and 0.9 m, respectively.

The delivered density of System Three was about 65 percent of the design density (86 g/m^3 vs. 137 g/m^3). The system produced a particulate density which is approximately 20 percent of the delivered density. The peak particulate density for System Three was on the order of 15 g/m^3. As with the other systems, the particulate density decayed at a rate of about three percent per minute (Figure 24).

The critical reignition particulate density was determined during the reignition test to be on the order of about 5.1 g/m^3 and occurred approximately 23-minutes after the end of agent discharge (23-minute hold time). This value is approximately 30 percent of the peak particulate density measured shortly after discharge. The reignition test results for System Three are shown in Figure 26.

The capabilities of System Three against the large fires are shown in Table 10. As with the other two systems, the activation system/wiring will need to be hardened (made with high temperature components) prior to use in an actual application/installation.

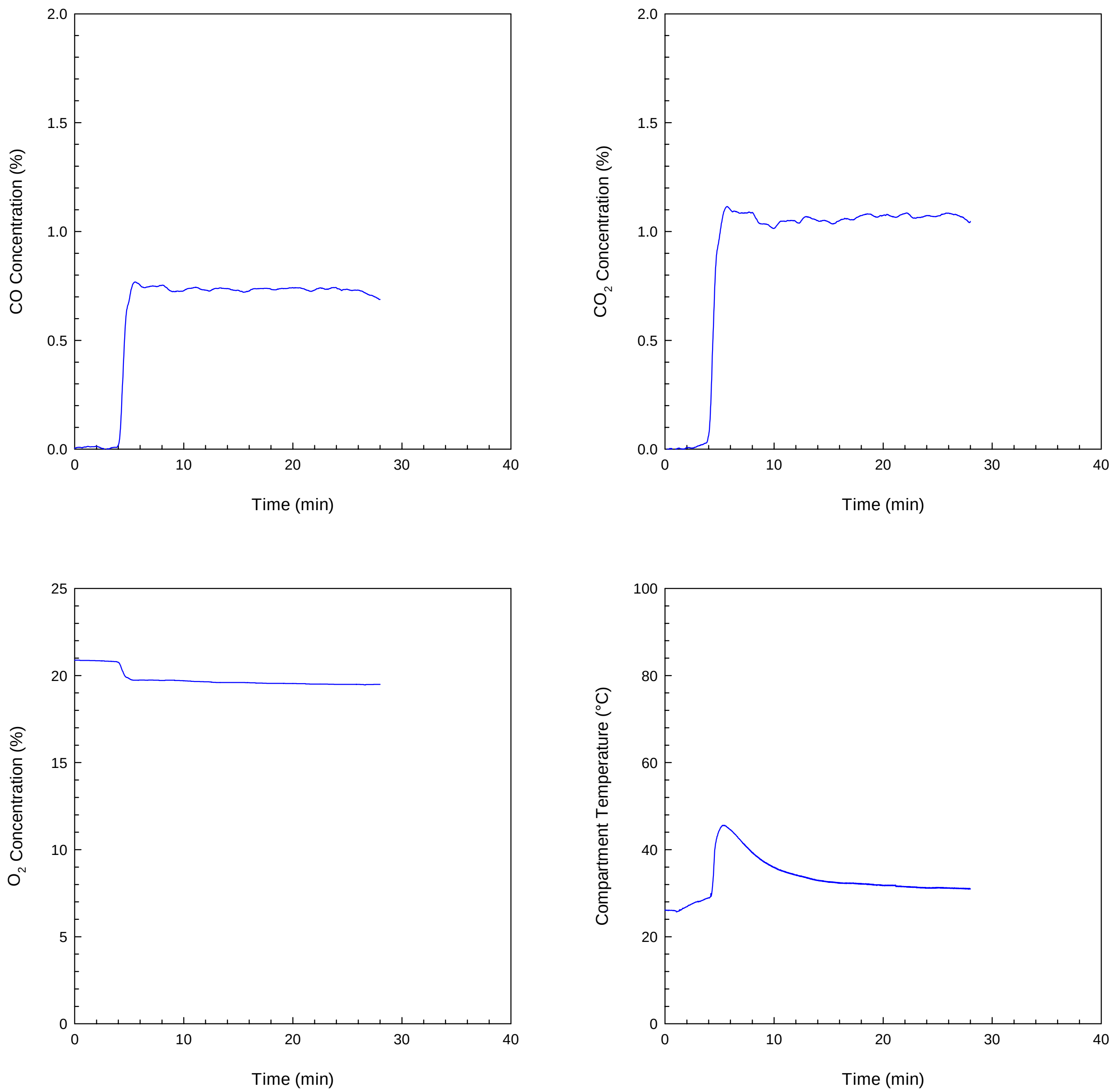
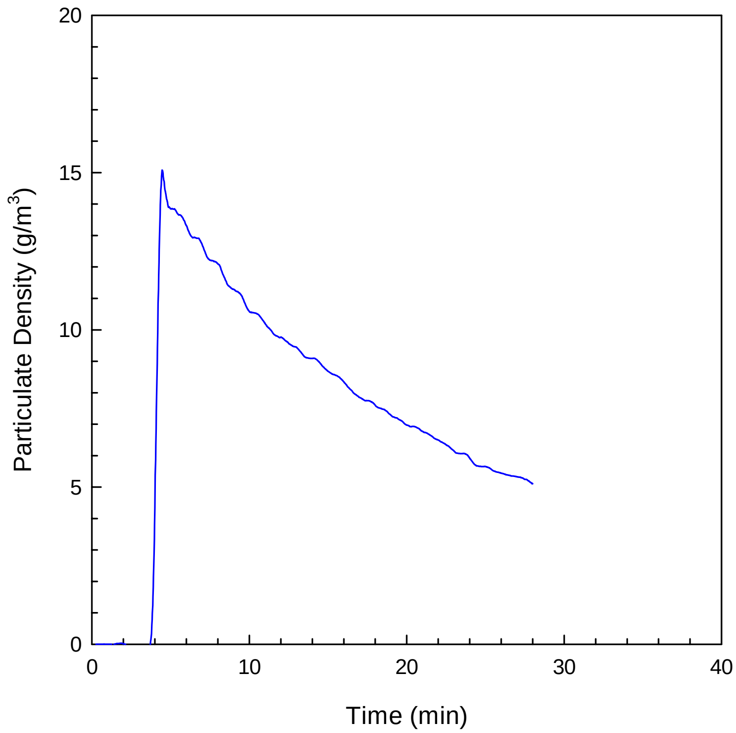


Figure 23. System Three Compartment Conditions.



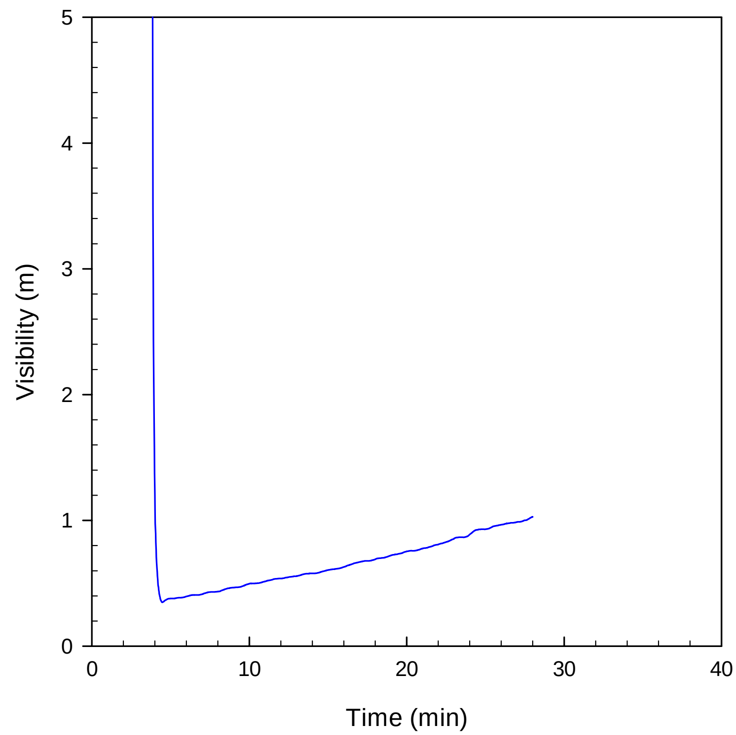


Figure 24. System Three Particulate Density and Visibility.

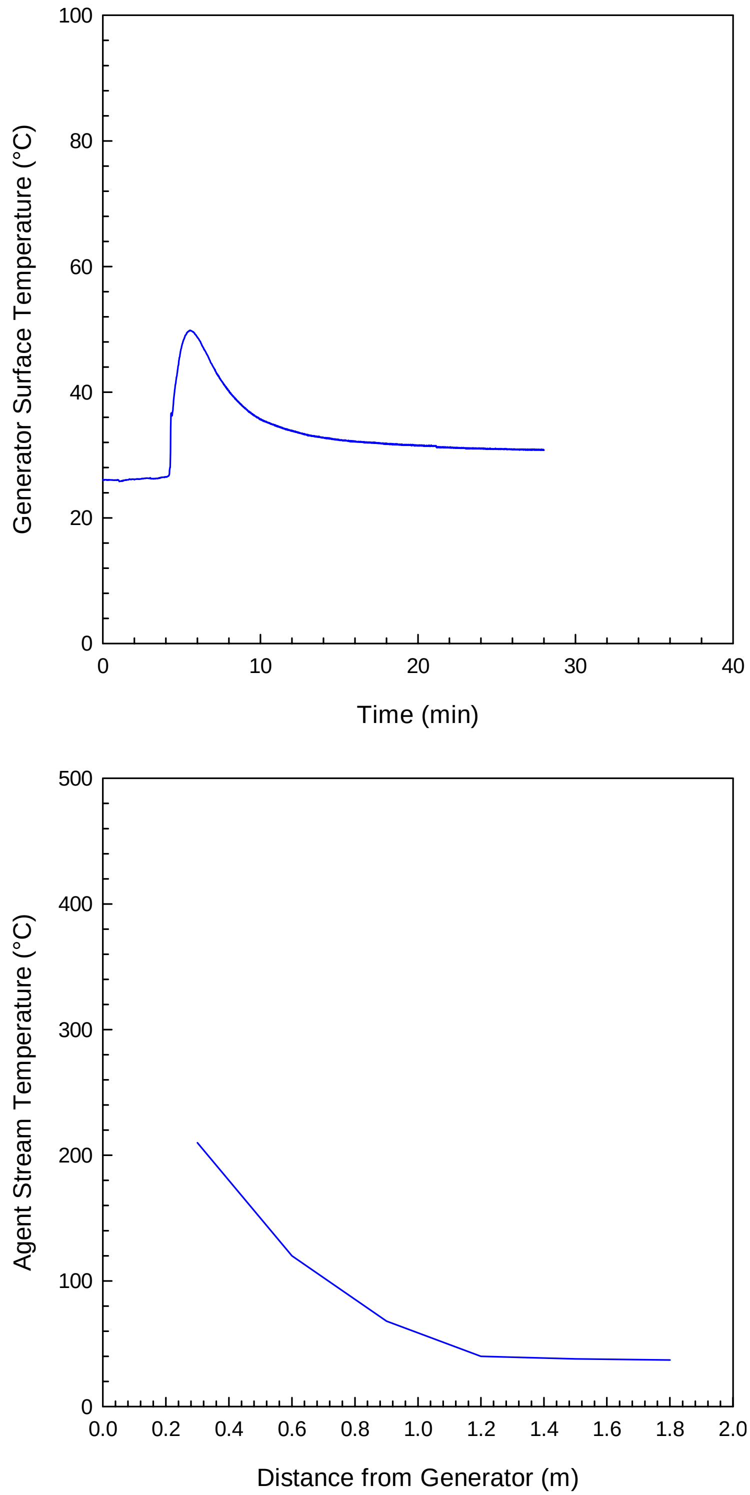


Figure 25. System Three Generator Surface and Agent Stream Temperatures.

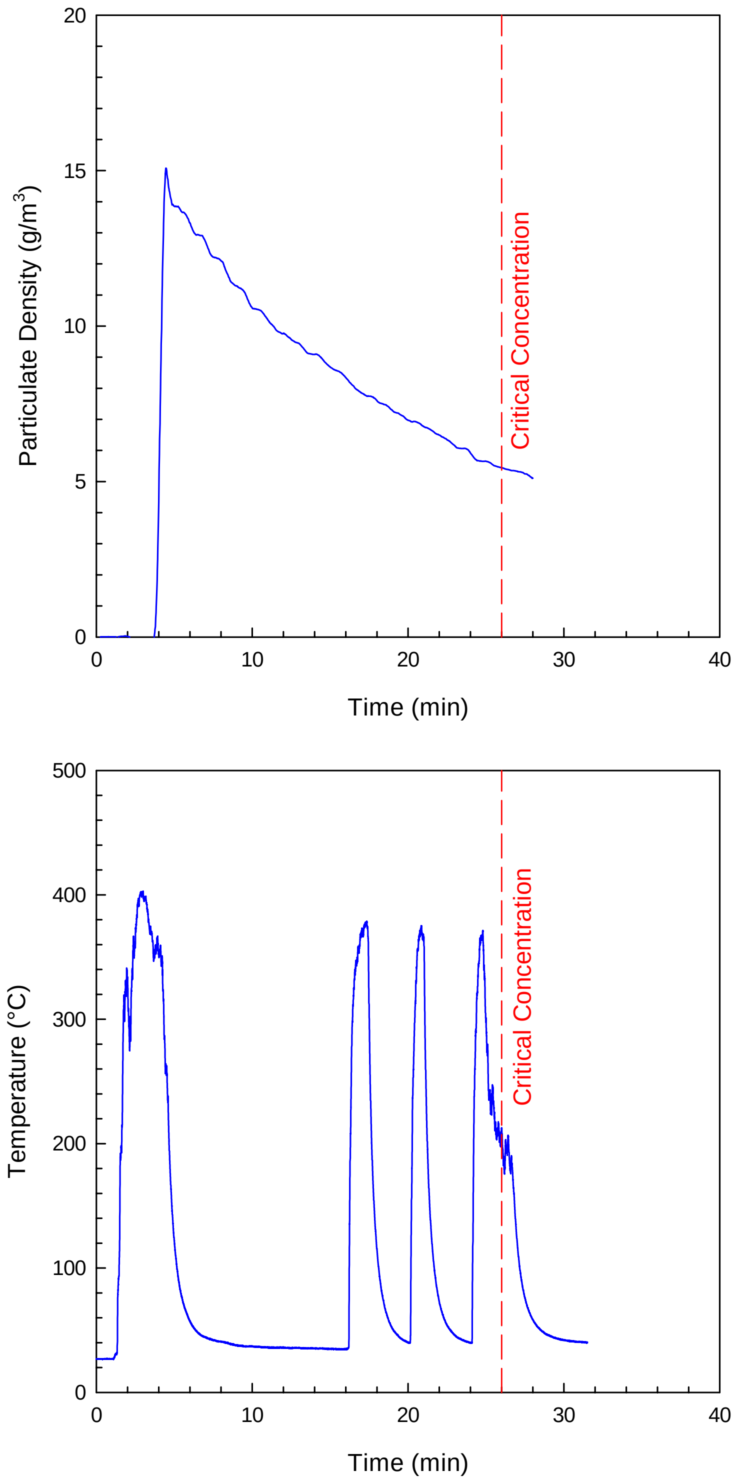


Figure 26. System Three Reignition Test Results.

The first large fire test conducted with System Three (S3T4) was against Fire Scenario Three of MSC/Circ. 1007. The test was conducted with a delivered density of 113 g/m^3. During the test, all of the Class B fires were quickly extinguished but the two Class A fires continued to burn for the duration of the test. The fifth and sixth tests conducted with the system were conducted against Fire Scenarios Two and Four, respectively. During both tests, the fires were quickly extinguished well within the time allotted by MSC/Circ. 1007. The final test (S3T7) was conducted against Scenario Three (a repeat of S3T4) with a higher design density (delivered density of 149 g/m^3). During this test, only the wood crib with the six-minute preburn was not extinguished. This was the only test conducted during the entire test program where a Class A fire (wood crib - 2:00 preburn) was extinguished. This was achieved with a particulate density of 26 g/m^3 (estimated).

6.3 Protocol Issues

6.3.1 General Issues

In MSC/Circ. 1007, the test timing is based on the end of agent discharge (e.g., agent hold time requirements and reignition test sequence). Besides the fact that MSC/Circ. 1007 lacks a technique for determining when discharge is complete, it is difficult to make this determination during the test (real-time). As a result, it is recommended that the timing for each test be based on system activation rather than the end of agent discharge. Assuming a two-minute discharge time, the test will be complete 17-minutes after system activation. Hold time, reignition, and extinguishment time should also be adjusted to use time of system activation.

MSC/Circ. 1007 requires that the agent be discharged at a rate sufficient to achieve 85 percent of the minimum design density in 120-seconds or less. Three techniques were used during these tests to define the discharge time; agent stream temperature, generator mass loss and particulate density. The discharge times determined using these three techniques were very similar and are shown in Figure 27. As shown in this figure, all three measurements worked fairly well and produced similar results during the telltale fire test. However, the discharge stream temperature and optical density measurements will become skewed by the heat and smoke produced during the large fire tests. As a result, measuring the mass loss of a generator using a load cell is recommended for this application.

During these tests, the mass loss was measured at only one of the eight generator locations. This worked well when only one type/size of generator was used during the test but was shown to be problematic for systems that used multiple types and sizes of generators in a single system. Two potential solutions to this problem are to either weigh the generators at all the locations using load cells or require that only one type/size of generator be installed in the system.

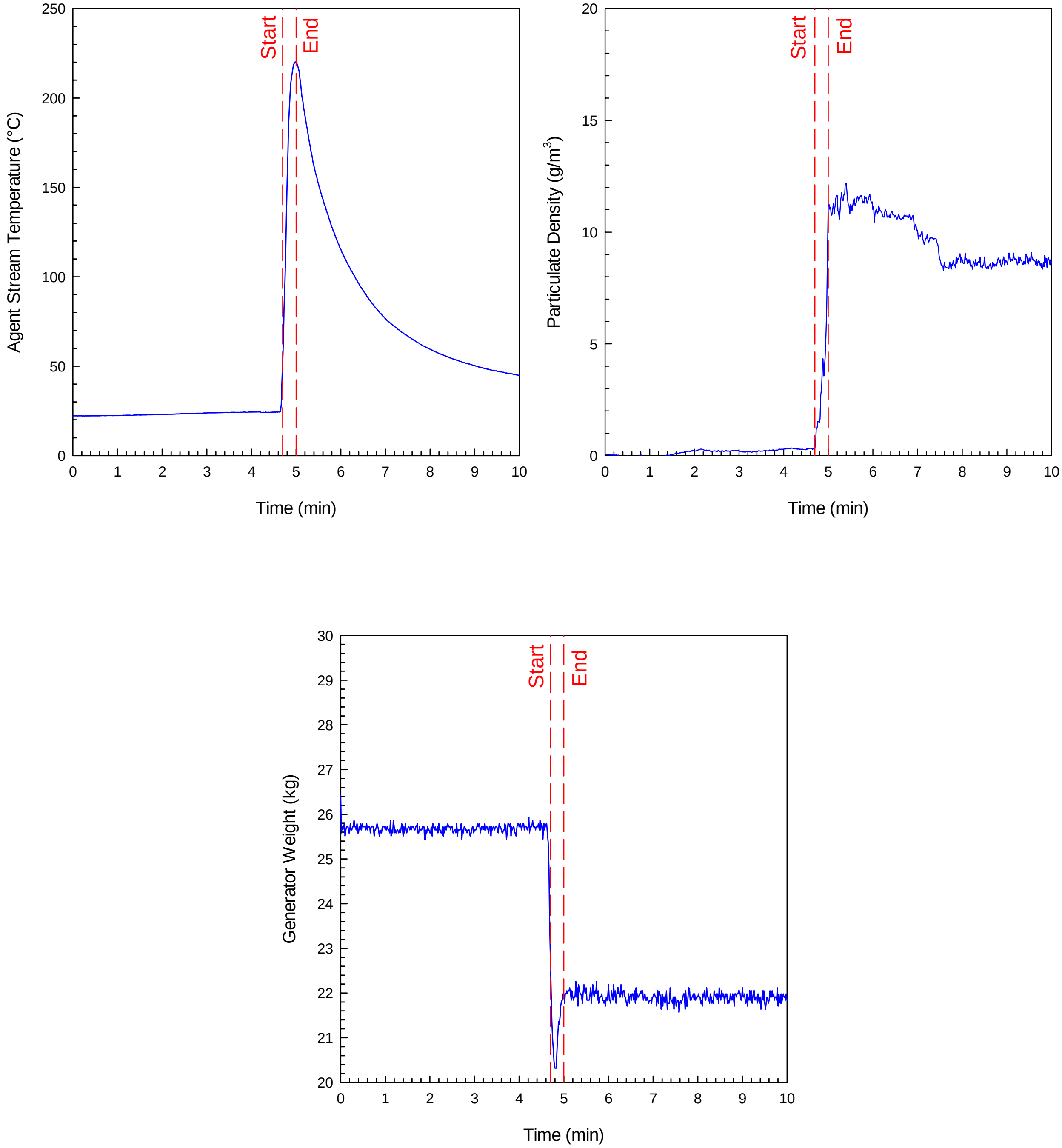


Figure 27. Discharge Time Estimation Techniques.

If the load cell is adopted for making this measurement, the end of discharge should be defined as the time when all of the agent has been discharged by the generator. The current 85 percent requirement is difficult to pinpoint due to the thrust produced by the discharge of the agent. This is shown in Figure 28.

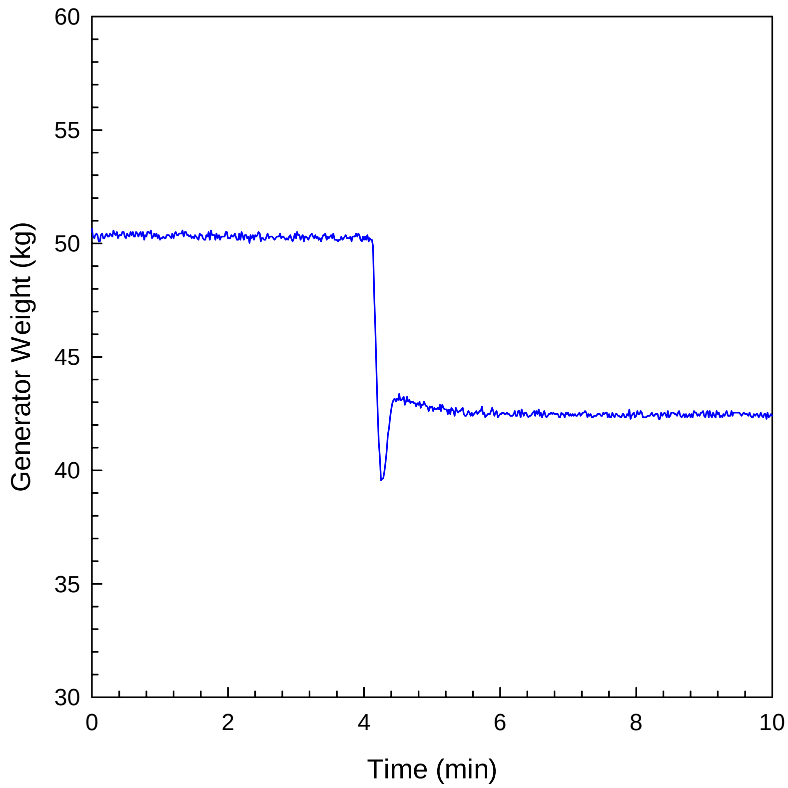


Figure 28. Typical Generator Weight Loss Data.

Although not an issue during these tests, the start of discharge may also need to be defined. There appears to be a five to ten-second delay from the time the system is activated (switch thrown in the control room) to the time the agent is jetted from the generator. The load cell recommended previously can be used to define both the start and end of agent discharge.

6.3.2 Fire Scenario Specific Issues

6.3.2.1 Fire Scenario One Issues (Telltale Fire Test)

With respect to test procedures, as currently written, MSC/Circ. 1007 requires the reignition of two of the telltales at one-minute intervals starting ten-minutes after discharge and continuing until the end of the test. Based on preliminary tests conducted in the lab at HAI, it was determined that a two-minute time interval (or greater) was required to ignite, extinguish (within 30-seconds) and verify extinguishment prior to the next ignition sequence. As a result, it is recommended that MSC/Circ. 1007 be modified to require reignition tests 10:00, 12:00, and 14:00 after discharge (not 10:00, 11:00, 12:00, 13:00, and 14:00 as currently written).

The results of the tests conducted against Fire Scenario One are summarized in Table 11. As shown in this table, the most challenging telltale fires are the ones located on the deck and/or in the bilge area (i.e., low in the compartment). It is recommended that additional telltales be added to the test to better evaluate the systems capabilities against obstructed fires. These should be added in the bilge and/or under the diesel engine mockup.

6.3.2.2 Fire Scenario Two Issues

The results of the tests conducted against Fire Scenario Two are summarized in Table 12. As shown in this table, the second system (System Two) was capable of extinguishing the two pan fires during the discharge of the agent while the third system (System Three) extinguished these fires ten to 15-seconds after agent discharge. This fire scenario appears to be challenging and should remain as written in MSC/Circ. 1007.

6.3.2.3 Fire Scenario Three Issues

The results of the tests conducted against Fire Scenario Three are summarized in Table 13. As shown in this table, none of the three systems were capable of successfully completing the test as written. A wood crib with a six-minute preburn appears to be outside the capabilities of the technology as a whole.

The question becomes whether a wood crib with a six-minute preburn is a realistic scenario. Due to the nature of this fuel package (highly obstructed deep seated Class A fire), this fire may be more challenging than the typical shipboard machinery space fire scenario. However, there is no limit on combustibles in machinery spaces. This test is also required in the approval of both halocarbon and inert gas fire extinguishing systems. These issues need to be considered when making adjustments to MSC/Circ. 1007.

Table 11. Fire Scenario One Test Results (Extinguishment Times (seconds)).

TEST	S1T1	S1T2	S2T1	S2T2	S3T1	S3T2	S3T3
Discharge time(s)	~ 120	~ 120	~ 90	~ 90	~ 20	~ 20	~ 20
Design density (g/m^3)	45.2	59.0	105.6	105.6	91.2	114.0	136.8
Delivered density (g/m^3)	43.0	56.0	101.4	101.4	60.0	75.0	86.0
Particulate density calc. (g/m^3)	17.0	22.0	18.0	18.0	9.1	12.2	13.0
Particulate density measured (g/m^3)	14.0	18.0	19.0	19.0	10.5	12.2	15.0
Corner Telltales							
Fwd Port Upper	65	38	79	46	48	54	38
Aft Port Upper	58	70	84	35	30	51	32
Aft Stbd Upper	59	84	88	37	50	31	31
Fwd Stbd Upper	63	53	46	56	56	39	46
Fwd Port Lower	NO	98	171	100	30	330	25
Aft Port Lower	NO	104	179	138	38	59	25
Aft Stbd Lower	227	96	109	124	348	55	25
Fwd Stbd Lower	NO	147	183	185	57	49	48
Telltale Tree							
0.5 m	NO	114	225	144	284	26	29
1.5 m	NO	22	190	110	NO	22	28
2.5 m	85	65	325	52	31	29	24
3.5 m	63	71	70	44	458	32	31
4.5 m	66	53	81	43	37	47	31
Additional Telltales							
Side of mockup	NO	75	215	68	55	38	21
Under mockup	NO	192	208	136	21	22	20
Under bilge plate	NO	114	184	155	27	36	42

Extinguishment times measured from system activation

Exceeds extinguishment time criteria

Table 12. Fire Scenario Two Test Results (Extinguishment Times (seconds)).

TEST	S2T6	S3T5
Discharge time(s)	~ 90	~ 20
Design density (g/m^3)	132.0	182.4
Delivered density (g/m^3)	126.0	120.0
Particulate density est. (g/m^3)	23.7	20.9
0.1 m^2 heptane pan under obstruction plate	25	28
0.25 m^2 heptane pan under mockup	90	35

Extinguishment times measured from system activation
Exceeds extinguishment time criteria

Anticipating that the wood crib with the six-minute preburn would be extremely challenging for this technology, a wood crib with a two-minute preburn and a heptane soaked mat (fiberglass) were added to the fire test scenario. All of the systems were capable of extinguishing the heptane soaked mat but only one system was capable of extinguishing the wood crib with the two-minute preburn (System Three). This was accomplished with an estimated particulate density of 26.0 g/m^3. The design densities of Systems One and Two would only need to be increased by about 15 percent to produce similar particulate densities and potentially similar capabilities.

If the wood crib component of Fire Scenario Three is changed to a two-minute preburn, the amount of heptane used to ignite the crib will also need to be reduced from 7.6 L to 1.9 L.

It should also be noted that the wood crib was extinguished with a design density 70 percent greater than that required to pass the telltale fire test. This may require that the current 30 percent factor of safety between the telltale fire test and the larger fire tests be re-evaluated.

The overall size (heat release rate) of the fire scenario needs to be reduced. Due to the oxygen depletion and turbulence caused by the larger fire(s), the Class B fires, (both the spray and the pan) are easy to extinguish. This was shown in Test S1T3 where these fires were extinguished with less than 20 percent of the agent required to pass the telltale fire test. A 50 percent reduction of both the heptane spray fire and the diesel pan fire should be considered to make these fires more challenging/more difficult to extinguish.

Table 13. Fire Scenario Three Test Results (Extinguishment Times (seconds)).

TEST	S1T3	S1T4	S1T5	S2T3	S2T4	S3T4	S3T7
Discharge time(s)	~ 120	~ 120	~ 120	~ 90	~ 90	~ 20	~ 20
Design density (g/m^3)	69.3	52.8	79.2	132.0	132.0	182.4	228.0
Delivered density (g/m^3)	9.7[1]	50.2	72.7[2]	112.2[3]	126.7[4]	113.0	149.0
Particulate density est. (g/m^3)	3.1	16.1	23.4	21.0	23.7	19.7	26.0
0.1 m^2 heptane pan w/insulation	123	---	---	88	---	46	30
Wood crib (2:00 preburn)	NO	NO	NO	NO	NO	NO	35
Wood crib (6:00 preburn)	NO	NO	NO	NO	NO	NO	NO
2.0 m^2 diesel pan	343	---	---	101	---	22	21
Spray fire	40	---	---	68	---	20	23

Extinguishment times measured from system activation

Exceeds extinguishment time criteria

[1] 12 of 14 units did not activate

[2] One of 11 units did not activate.

[3] Nine of 60 units did not activate

[4] One of 16 units did not activate

With respect to test procedures, the reignition test (activation of the heptane fuel spray) at the end of Scenario Three should be removed. Even if the two to three-minute fire exposure to the side of the engine mockup was adequate to heat the steel well above the auto ignition temperature of heptane (which it is not), the temperature of the steel would rapidly cool to near ambient during the 15-minute hold time. As a result, the test provides no information about the capabilities of the systems. If the international community is insistent on having a reignition test in this scenario, a spark or hot wire igniter should be added to the test scenario.

6.3.2.4 Fire Scenario Four Issues

The results of the tests conducted against Fire Scenario Four are summarized in Table 14. As shown in this table, Systems Two and Three were both capable of extinguishing the test fire about halfway through agent discharge. This suggests that due to the size (heat release rate) of the fire (oxygen depletion and turbulence) this scenario is unstable and does not adequately challenge the AES. As with Scenario Three, reducing the size of this fire by 50 percent should be considered.

Table 14. Fire Scenario Four Test Results (Extinguishment Times (seconds)).

TEST	S2T5	S3T6
Discharge time(s)	~ 90	~ 20
Design density (g/m^3)	137.0	182.4
Delivered density (g/m^3)	126.0	120.0
Particulate density est. (g/m^3)	23.7	20.9
4.0 m^2 diesel pan in bilge	57	12

Extinguishment times measured from system activation
Exceeds extinguishment time criteria

6.4 Approval Considerations

Approval standards for AES should address the reliability of the overall system and the reliability of the individual generators making up the system. All three of the tested systems had some generators that did not activate. No attempt was made to determine the reasons for the failures observed in these tests other than to rule out the role of the activation system up to the individual units. Some sort of component reliability standard should be required to determine failure rates that can be included in system design and installation.

Discharge of the systems reduces visibility within the space to about 0.3 m. Due the temperature of the discharge from the units, installation standards should address means of preventing personnel within a space from being to close to units in case of accidental discharge.

Machinery space fire suppression systems are manually activated. In many instances, considerable delays in system activation have occurred. Often these systems are only considered after it becomes evident that the fire is beyond the capability of the crew to suppress. The master of the vessel will not activate the system until all personnel are accounted for or until the master believes that those in the space are deceased. Thus, the system must be sufficiently hardened to survive in the space until activated.

The CG has not approved electrically activated fire suppression systems based on concerns of reliability and survivability. Although the three systems included in this evaluation were electrically activated, mechanical activation should be feasible.

Currently, the only aerosol fire suppression agents on the Environmental Protection Agency's Significant New Alternatives Policy list are limited to unoccupied spaces. The system must be listed for use in occupied spaces to be used in machinery space applications.

7.0 SUMMARY

A total of 18 tests were conducted in this evaluation utilizing the equipment from three AES manufacturers (Ansul, FirePro and Flame Guard). Each manufacturer was responsible for the design of their respective system. The delivered densities of these systems ranged from about 45-150 g/m^3. The systems were tested against the current IMO's test protocol for approving aerosol extinguishing systems for machinery space applications (MSC/Circ. 1007, Guidelines for the Approval of Fixed Aerosol Fire-Extinguishing Systems Equivalent to Fixed Gas Fire-Extinguishing System").

The conditions produced by the discharge of the AES (and discussed in the following paragraphs) were measured during the telltale fire tests that were conducted at a lower design density than would be used in an actual installation. As a result, these conditions need to be scaled based on the design density used in the final system design.

The aerosol is discharged as a hot white smoke that reduces the visibility in the space (to about 0.3 m assuming an illuminated source/target) and increases the temperature (on average between 20-45°C above ambient). The temperature of the agent as it exits the generator is typically hundreds of degrees Celsius. As a result, combustible materials should be kept at least 0.5 m away from the generator while the safe distance for humans ranged from about 0.9-1.6 m.

The gas concentrations (CO, CO_2, and O_2) in the space are also effected by the agent/system discharge. The effects of the discharge on these concentrations were shown to be fairly proportional to the delivered density of the system. More specifically, a system with a delivered density of 100 g/m^3 will produce the following gas concentrations in the space: CO-0.8 percent, CO_2-1.6 percent and O_2-19.1 percent. These effects should scale proportionally with delivered density.

The particulate densities produced by the three systems range from about 15-20 g/m^3. This is only about 20-30 percent of the mass of the agent discharged by the generators. The remaining 70-80 percent is discharged as a gas containing various amounts of CO, CO_2, H_2O, and N_2.

The particulate densities were shown to decay at a rate of about three percent per minute (even in a well sealed space). As a result, the particulate density typically decays by over 50 percent during the 15-minute agent hold time period required in MSC/Circ. 1007.

Although the particulate densities decayed over time, all three systems had no problems meeting the hold time requirements. The critical particulate densities (the density below which reignition of Class B fuels can occur) were identified to be on the order of five g/m^3. This is approximately one-third of the peak particulate density produced by the system(s). As a result, each system provided reignition protection for about 23-minutes after the end of agent discharge. This would be even longer for higher design densities used in an actual installation.

With respect to the extinguishment capabilities of these systems, all three systems exhibited good capabilities against Class B fires, but had difficulty extinguishing the Class A fires. All of the large Class B fires were quickly extinguished during this test series but only one of the 14 Class A fires (wood cribs) were extinguished. The one wood crib that was extinguished was conducted with a two-minute preburn rather than the six-minute preburn required by MSC/Circ. 1007. The delivered density (149 g/m^3) used during the successful Class A fire test was over 70 percent higher than that required to extinguish the telltale fires in Scenario One (86 g/m^3). The estimated particulate density used during the successful Class A fire test was approximately 26 g/m^3.

The two systems that did not extinguish the wood crib produced lower particulate densities and may have been able to extinguish the wood crib with the two-minute preburn if the systems' densities were increased. The wood crib with the six-minute preburn appears to be outside of the capabilities of this technology.

As a result of these limited capabilities against Class A fires, none of the three systems successfully met the requirements of the current IMO test protocol (MSC/Circ. 1007).

Modifications to MSC/Circ. 1007 are recommended based on the results of these tests. These modifications apply to procedures, instrumentation and fire scenarios. Two fire scenario issues worth noting include the preburn time of the wood crib in Scenario Three and the overall size/heat release rate of Fire Scenarios Three and Four. The six-minute preburn time of the wood crib in Scenario Three makes this fire too challenging for this technology. Consideration should be given to whether this fire scenario is representative of typical machinery space hazards. It was also recommended that the size of the Class B fires in Scenarios Three and Four be reduced by 50 percent to make them more challenging/difficult to extinguish. The high heat release rates of these fires reduce the oxygen concentration in the space and produce significant turbulence making them easier to extinguish than smaller fires.

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APPENDIX A – MSC/Circ. 1007

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MSC/Circ.1007
26 June 2001

GUIDELINES FOR THE APPROVAL OF FIXED AEROSOL FIRE-EXTINGUISHING SYSTEMS EQUIVALENT TO FIXED GAS FIRE-EXTINGUISHING SYSTEMS, AS REFERRED TO IN SOLAS 74, FOR MACHINERY SPACES

1 The Maritime Safety Committee, [at its seventy-fourth session (30 May to 8 June 2001)], approved the Guidelines for the approval of fixed aerosol fire-extinguishing systems equivalent to fixed gas fire-extinguishing systems, as referred to in SOLAS 74, for machinery spaces, as set out in the annex.

2 Member Governments are invited to apply the annexed Guidelines when approving fixed aerosol fire-extinguishing systems for use in machinery spaces of category A.

***

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ANNEX

GUIDELINES FOR THE APPROVAL OF FIXED AEROSOL FIRE-EXTINGUISHING SYSTEMS EQUIVALENT TO FIXED GAS FIRE-EXTINGUISHING SYSTEMS, AS REFERRED TO IN SOLAS 74, FOR MACHINERY SPACES

General

1 Fixed aerosol fire-extinguishing systems for use in machinery spaces of category A equivalent to fire-extinguishing systems required by SOLAS regulation II-2/7* should prove that they have the same reliability which has been identified as significant for the performance of fixed gas fire-extinguishing systems approved under the requirements of SOLAS regulation II-2/5**. In addition, the system should be shown by testing according to the appendix to have the capability of extinguishing a variety of fires that can occur in machinery spaces.

2 Aerosol fire-extinguishing systems involve the release of a chemical agent to extinguish a fire by interruption of the process of the fire.

There are two methods considered for applying the aerosol agent to the protected space:

.1 condensed aerosols are created in pyrotechnical generators through the combustion of the agent charge; and

.2 dispersed aerosols that are not pyrotechnically generated and are stored in containers with carrier agents (such as inert gases or halocarbon agents) with the aerosol released in the space through valves, pipes and nozzles.

Definitions

3 *Aerosol* is a non ozone depleting fire-extinguishing medium consisting of either condensed aerosol or dispersed aerosol.

4 *Generator* is a device for creating a fire-extinguishing medium by pyrotechnical means.

5 *Design density* (g/m^3) is the mass of an aerosol forming composition per m^3 of the enclosure volume required to extinguish a specific type of fire, including a safety factor.

6 *Agent – medium* for the purpose of these guidelines, these words are interchangeable.

Principal requirements

7 All requirements of SOLAS regulations II-2/5.1***, 5.3.1, 5.3.2 to 5.3.3 except as modified by these guidelines, should apply, where applicable.

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* Refer to regulation II-2/10.5 of SOLAS chapter II-2, as adopted by resolution MSC.99(73).

** Refer to regulation II-2/10.4 of SOLAS chapter II-2, as adopted by resolution MSC.99(73).

*** Refer to regulation II-2/10.9.1.1.1 of SOLAS chapter II-2, as adopted by resolution MSC.99(73).

8 The minimum agent density should be determined and verified by the full-scale testing described in the test method, as set out in the appendix.

9 For aerosol systems, the discharge time should not exceed 120 s for 85% of the design density. Systems may need to discharge in a shorter time for other reasons than for fire-extinguishing performance.

10.1 The quantity of extinguishing agent for the protected space should be calculated at the minimum expected ambient temperature using the design density based on the net volume of the protected space, including the casing.

10.2 The net volume of a protected space is that part of the gross volume of the space, which is accessible to the fire-extinguishing agent.

10.3 When calculating the net volume of a protected space, the net volume should include the volume of the bilge, the volume of the casing and the volume of free air contained in air receivers that in the event of a fire may be released into the protected space.

10.4 The objects that occupy volume in the protected space should be subtracted from the gross volume of the space. They include, but are not necessarily limited to:

.1 auxiliary machinery;
.2 boilers;
.3 condensers;
.4 evaporators;
.5 main engines;
.6 reduction gears;
.7 tanks; and
.8 trunks.

10.5 Subsequent modifications to the protected space that alter the net volume of the space should require the quantity of extinguishing agent to be adjusted to meet the requirements of this paragraph and paragraphs 10.1, 10.2, 10.3, 10.4, 11.1, 11.2 and 11.3.

11.1 No fire suppression system should be used which is carcinogenic, mutagenic or teratogenic at concentrations expected during use. All systems should employ two separate controls for releasing the extinguishing medium into a protected space. Means should be provided for automatically giving audible warning of the release of fire-extinguishing medium into any space in which personnel normally work or to which they have access. The alarm should operate for a suitable period* before the medium is released. Unnecessary exposure to aerosol media, even at concentrations below an adverse effect level, should be avoided.

* Refer to the Interpretations of vague expressions and other vague wording in SOLAS chapter II-2 (MSC/Circ.847).

11.2 Pyrotechnically generated aerosols: Pyrotechnically generated aerosol systems for spaces that are normally occupied should be permitted in concentrations where the aerosol particulate matter does not exceed the adverse effect level as determined by a scientifically accepted technique* and any gases produced by the pyrotechnic generator do not exceed the No Observed Adverse Effect Level (NOAEL) for the critical toxic effect as determined in a short term toxicity test.

11.3 Dispersed aerosols: Dispersed aerosol systems for spaces that are normally occupied should be permitted in concentrations where the aerosol particulate matter does not exceed the adverse effect level as determined by a scientifically accepted technique**. If the carrier gas is a halocarbon, it may be used up to its NOAEL. If a halocarbon carrier gas is to be used above its NOAEL, means should be provided to limit exposure to no longer than the time specified according to a scientifically accepted physiologically based pharmacokinetic** (PBPK) model or its equivalent which clearly establishes safe exposure limits both in terms of extinguishing media concentration and human exposure time. If the carrier is an inert gas, means should be provided to limit exposure to no longer than 5 min for inert gas systems designed to concentrations below 43% (corresponding to an oxygen concentration of 12%, sea level equivalent of oxygen) or to limit exposure to no longer than 3 min for inert gas systems designed to concentrations between 43% and 52% (corresponding to between 12% and 10% oxygen, sea level equivalent of oxygen).

11.4 In no case should a dispersed aerosol system be used with halocarbon carrier gas concentrations above the Lowest Observed Adverse Effect Level (LOAEL) nor the Approximate Lethal Concentration (ALC) nor should a dispersed aerosol system be used with an inert gas carrier at gas concentrations above 52% calculated on the net volume of the protected space at the maximum expected ambient temperature, without the use of controls as provided in SOLAS regulations II-2/5.2.5.1 and 5.2.5.2.***

12 The system and its components should be suitably designed to withstand ambient temperature changes, vibration, humidity, shock, impact, clogging, electromagnetic compatibility and corrosion normally encountered in machinery spaces. Generators in condensed aerosol systems should be designed to prevent self-activation at a temperature below 250°C.

13 The system and its components should be designed, manufactured and installed in accordance with standards acceptable to the Organization. As a minimum, the design and installation standards should cover the following elements:

- .1 safety:
  - .1 toxicity;

---

* Reference is made to the United States' EPA's Regional Deposited Dose Ratio Program "Methods of Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry" EPA/600/8-90/066F, October 1994.

** Refer to document FP 44/INF.2 (United States) – Physiologically based pharmacokinetic model to establish safe exposure criteria for halocarbon fire extinguishing agents.

*** Refer to regulation II-2/10.4.1.1.1 of SOLAS chapter II-2, as adopted by resolution MSC.99(73).

  - .2 noise, generator/nozzle discharge;
  - .3 decomposition products; and
  - .4 obscuration;
- .2 storage container design and arrangement:
  - .1 strength requirements;
  - .2 maximum/minimum fill density, operating temperature range;
  - .3 pressure and weight indication;
  - .4 pressure relief; and
  - .5 agent identification, production date, installation date and hazard classification;
- .3 agent supply, quantity, quality standards, shelf life and service life of agent and igniter;
- .4 handling and disposal of generator after service life;
- .5 pipes and fittings:
  - .1 strength, material properties, fire resistance; and
  - .2 cleaning requirements;
- .6 valves:
  - .1 testing requirements; and
  - .2 elastomer compatibility;
- .7 generators/nozzles:
  - .1 height and area testing requirements; and
  - .2 elevated temperature resistance;
- .8 actuation and control systems:
  - .1 testing requirements; and
  - .2 backup power requirements;

.9 alarms and indicators:

.1 predischarge alarm, agent discharge alarms and time delays;

.2 supervisory circuit requirements;

.3 warning signs, audible and visual alarms; and

.4 annunciation of faults;

.10 enclosure integrity and leakage requirements:

.1 enclosure leakage;

.2 openings; and

.3 mechanical ventilation interlocks;

.11 design density requirements, total flooding quantity;

.12 agent flow calculation:

.1 verification and approval of design calculation method;

.2 fitting losses and/or equivalent length;

.3 discharge time;

.13 inspection, maintenance, service and testing requirements; and

.14 handling and storage requirements for pyrotechnical components.

14 The generator/nozzle type, maximum generator/nozzle spacing, maximum generator/nozzle installation height and minimum generator/nozzle pressure should be within limits tested.

15 Installations should be limited to the maximum volume tested.

16 Agent containers may be stored within a protected machinery space if the containers are distributed throughout the space and the provisions of SOLAS regulation II-2/5.3.3, as applicable, are met. he arrangement of generators, containers, electrical circuits and piping essential for the release of any system should be such that in the event of damage to any one power release line through fire or explosion in the protected space (i.e. a single fault concept), at least the design density of the fire-extinguishing charge as required in paragraph 10 above can still be discharged having regard to the requirement for uniform distribution of medium throughout the space.

17 The release of an extinguishing agent may produce significant over and under pressurization in the protected space. Measures to limit the induced pressures to acceptable limits may have to be provided.

18 For all ships, the fire-extinguishing system design manual should address recommended procedures for the control of products of agent decomposition. The performance of fire-extinguishing arrangements on passenger ships should not present health hazards from decomposed extinguishing agents, (e.g., on passenger ships, the decomposition products should not be discharged in the vicinity of asembly stations).

19 Spare parts and operating and maintenance instructions for the system should be provided as recommended by the manufacturer.

APPENDIX

TEST METHOD FOR FIRE TESTING OF FIXED AEROSOL FIRE-EXTINGUISHING SYSTEMS

1 Scope

1.1 This test method is intended for evaluating the extinguishing effectiveness of fixed aerosol fire-extinguishing systems for the protection of machinery spaces of category A.

1.2 The test method is applicable to aerosols and covers the minimum requirements for fire-extinguishing.

1.3 The test programme has two objectives:

.1 establishing the extinguishing effectiveness of a given agent at its tested concentration; and

.2 establishing that the particular agent distribution system puts the agent into the enclosure in such a way as to fully flood the volume to achieve an extinguishing concentration at all points.

2 Sampling

The components to be tested should be supplied by the manufacturer together with design and installation criteria, operational instructions, drawings and technical data sufficient for the identification of the components.

3 Method of test

3.1 *Principle*

This test procedure is intended for the determination of the effectiveness of different aerosol agent extinguishing systems against spray fires, pool fires and class A fires.

3.2 *Apparatus*

3.2.1 Test room

The tests should be performed in 100 m^2 room, with no horizontal dimension less than 8 m, with a ceiling height of 5 m. The test room should be provided with a closable access door measuring approximately 4 m^2 in area. In addition, closable ventilation hatches measuring at least 6 m^2 in total area should be located in the ceiling. larger room may be employed if approvals are sought for larger volumes.

3.2.2 Integrity of test enclosure

The test enclosure should be nominally leaktight when doors and hatches are closed. The integrity of seals on doors, hatches and other penetrations (e.g., instrumentation access ports) should be verified before each test.

3.2.3 Engine mock-up

.1 An engine mock-up of size (width x length x height) 1 m x 3 m x 3 m should be constructed of sheet steel with a nominal thickness of 5 mm. The mock-up should be fitted with two steel tubes diameter 0.3 m and 3 m length that simulate exhaust manifolds and a solid steel plate. At the top of the mock-up, a 3 m^2 tray should be arranged. (see figures 1, 2 and 3).

.2 A floor plate system 4 m x 6 m x 0.75 m high should surround the mock-up. Provision should be made for placement of the fuel trays, as described in table 1, and located as described in table 2.

3.2.4 Instrumentation

Instrumentation for the continuous measurement and recording of test conditions should be employed. The following measurements should be made:

.1 temperature at three vertical positions (e.g., 1 m, 2.5 m and 4.5 m);

.2 enclosure pressure;

.3 gas sampling and analysis, at mid-room height, for oxygen, carbon dioxide, carbon monoxide and other relevant products;

.4 means of determining flame-out indicators;

.5 fuel nozzle pressure in the case of spray fires;

.6 fuel flow rate in the case of spray fires;

.7 discharge nozzle pressure; and

.8 means of determining generator discharge duration.

3.2.5 Generators/nozzles

3.2.5.1 For test purposes, generators/nozzles should be located within 1 m of the ceiling.

3.2.5.2 If more than one generator/nozzle is used, they should be symmetrically located.

3.2.6 Enclosure temperature

The ambient temperature of the test enclosure at the start of the test should be noted and serve as the basis for calculating the concentration that the agent would be expected to achieve at that temperature and with that agent weight applied in the test volume.

3.3 *Test fires and programme*

3.3.1 Fire types

The test programme, as described in table 3, should employ test fires as described in table 1 below.

Table 1
Parameters of test fires

Fire	Type	Fuel	Fire size, MW	Remarks
A	76 - 100 mm ID can	Heptane	0.0012 to 0.002	Tell tale
B	0.25 m^2 tray	Heptane	0.35	
C	2 m^2 tray	Diesel /Fuel oil	3	(see NOTE 1)
D	4 m^2 tray	Diesel /Fuel oil	6	(see NOTE 1)
E	Low pressure, low flow spray	Heptane 0.03 ± 0.005 kg/s	1.1	
F	Wood crib	Spruce or fir	0.3	(See Note 2)
G	0.10 m^2 tray	Heptane	0.14	

Notes to table 1:

1 Diesel/Fuel oil means light diesel or commercial fuel oil.

2 The wood crib should be substantially the same as described in ISO Standard 14520, *Gaseous fire extinguishing systems, Part 1: General Requirements* (2000). The crib should consist of six, trade size 50 mm x 50 mm by 450 mm long, kiln dried spruce or fir lumber having a moisture content between 9% and 13%. The members should be placed in 4 alternate layers at right angles to one another. Members should be evenly spaced forming a square structure.

Ignition of the crib should be achieved by burning commercial grade heptane in a square steel tray 0.25 m^2 in area. During the pre-burn period the crib should be placed centrally above the top of the tray a distance of 300 to 600 mm.

Table 2
Spray fire test parameters

Fire type	Low pressure, Low flow(E)
Spray nozzle	Wide spray angle (80°) full cone type
Nominal fuel pressure	8.5 Bar
Fuel flow	0.03 ± 0.005 kg/s
Fuel temperature	20 ± 5°C
Nominal heat release rate	1.1 ± 0.1 MW

3.3.2 Test programme

3.3.2.1 The fire test programme should employ test fires singly or in combination, as outlined in table 3 below.

Table 3
Test programme

Test No.	Fire combinations (See table 1)
1	A: Tell tales, 8 corners. (See note).
2	B: 0.25 m^2 heptane tray under mock-up G: 0.10 m^2 heptane tray on deck plate located below solid steel obstruction plate Total fire load: 0.49 MW
3	C: 2 m^2 diesel/fuel oil tray on deck plate located below solid steel obstruction plate F: Wood crib positioned as in figure 1 E: Low pressure, low flow horizontal spray - concealed - with

		impingement on inside of engine mock-up wall. Total fire load: 4.4 MW
4	D:	4 m^2 diesel tray under engine mock-up Total fire load: 6 MW

Note to table 3:

Tell-tale fire cans should be located as follows:

.1 in upper corners of enclosure 150 mm below ceiling and 50 mm from each wall; and

.2 in corners on floors 50 mm from walls.

3.3.2.2 All applicable tests of table 3 should be conducted for every new fire-extinguishing media.

3.3.2.3 Only test 1 is required to evaluate new nozzles and related distribution system equipment (hardware) for systems employing fire-extinguishing media that have successfully completed the requirements of paragraph 3.3.2.2 above. Test 1 should be conducted to establish and verify the manufacturer's minimum nozzle design pressure.

3.4 *Extinguishing system*

3.4.1 System installation

The extinguishing system should be installed according to the manufacturer's design and installation instructions. The maximum vertical distance should be limited to 5 m.

3.4.2 Agent

3.4.2.1 Design density

The agent design density is the net mass of extinguishant per unit volume (g/m^3) required by the system designer for the fire protection application.

3.4.2.2 Test density

The test density of agent to be used in the fire-extinguishing tests should be the design density specified by the manufacturer, except for test 1, which should be conducted at not more than 77% of the manufacturer's recommended design density.

3.4.2.3 Quantity of aerosol agent

The quantity of aerosol agent to be used should be determined as follows:

$$W = V \times q \text{ (g)},$$

where:

W = agent mass (g);
V = volume of test enclosure (m^3);
q = fire-extinguishing aerosol density (g/m^3).

3.5 *Procedure*

3.5.1 Fuel levels in trays

The trays used in the test should be filled with at least 30 mm fuel on a water base. Freeboard should be 150 ± 10 mm.

3.5.2 Fuel flow and pressure measurements

For spray fires, the fuel flow and pressure should be measured before and during each test.

3.5.3 Ventilation

3.5.3.1 Pre-burn period

During the pre-burn period the test enclosure should be well ventilated. The oxygen concentration, as measured at mid-room height, should not be less than 20 volume per cent at the time of system discharge.

3.5.3.2 End of pre-burn period

Doors, ceiling hatches and other ventilation openings should be closed at the end of the pre-burn period.

3.5.4 Duration of test

3.5.4.1 Pre-burn time

Fires should be ignited such that the following burning times occur before the start of agent discharge:

.1 sprays - 5 to 15 s

.2 trays - 2 min

.3 crib - 6 min

3.5.4.2 Discharge time

Aerosol agents should be discharged at a rate sufficient to achieve 85% of the minimum design density in 120 s or less.

3.5.4.3 Hold time

After the end of agent discharge the test enclosure should be kept closed for 15 min.

3.5.5 Measurements and observations

3.5.5.1 Before test

.1 temperature of test enclosure, fuel and engine mock-up;

.2 initial weights of agent containers;

.3 verification of integrity agent distribution system and nozzles; and

.4 initial weight of wood crib.

3.5.5.2 During test

.1 start of the ignition procedure;

.2 start of the test (ignition);

.3 time when ventilating openings are closed;

.4 time when the extinguishing system is activated;

.5 time from end of agent discharge;

.6 time when the fuel flow for the spray fire is shut off;

.7 time when all fires are extinguished;

.8 time of re-ignition, if any, during hold time;

.9 time at end of hold time; and

.10 at the start of test initiate continuous monitoring as per 3.2.4.

3.5.6 Tolerances

Unless otherwise stated, the following tolerances should apply:

.1	length	±2% of value;
.2	volume	±5% of value;
.3	pressure	±3% of value;
.4	temperature	±5% of value; and
.5	concentration	±5% of value.

These tolerances are in accordance with ISO standard 6182/1, February 1994 edition 4.

4 Classification criteria

4.1 Class B fires should be extinguished within 30 s of the end of agent discharge. At the end of the hold period there should be no reignition upon opening the enclosure.

4.2 The fuel spray should be shut off 15 s after extinguishments. At the end of the hold time, the fuel spray should be restarted for 15 s prior to reopening the door and there should be no reignition.

4.3 The ends of the test fuel trays should contain sufficient fuel to cover the bottom of the tray.

4.4 Wood crib weight loss should be no more than 60%.

4.5 A reignition test should be conducted after the successful extinguishments of the tell tale fires in test 1 (Fire A) within 30 s after completion of agent discharge. The test should involve the attempted ignition of two of the tell-tale fire containers. One container should be at the floor level and the other at the ceiling level at the diagonally opposite corner. At 10 min after extinguishment of the fires, a remotely operated electrical ignition source should be energized for at least 10 s at each container. The test should be repeated at one min intervals four more times, the last at 14 min after extinguishment. Sustained burning for 30 s or longer of any of these ignition attempts constitutes a reignition test failure.

5 Test report

The test report should include the following information:

- .1 name and address of the test laboratory;
- .2 date and identification number of the test report;
- .3 name and address of client;

.4 purpose of the test;

.5 method of sampling system components;

.6 name and address of manufacturer or supplier of the product;

.7 name or other identification marks of the product;

.8 description of the tested product;

.1 drawings;

.2 descriptions;

.3 assembly instructions;

.4 specification of included materials; and

.5 detailed drawing of test set-up;

.9 date of supply of the product;

.10 date of test;

.11 test method;

.12 drawing of each test configuration;

.13 identification of the test equipment and used instruments;

.14 conclusions;

.15 deviations from the test method, if any;

.16 test results including measurements and observations during and after the test; and

.17 date and signature.

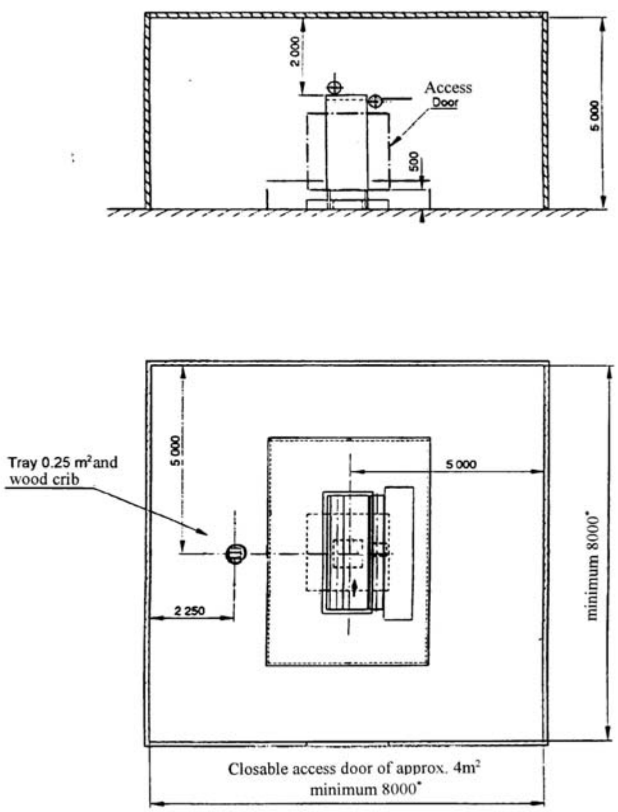

Figure 1

*The area should be 100m²

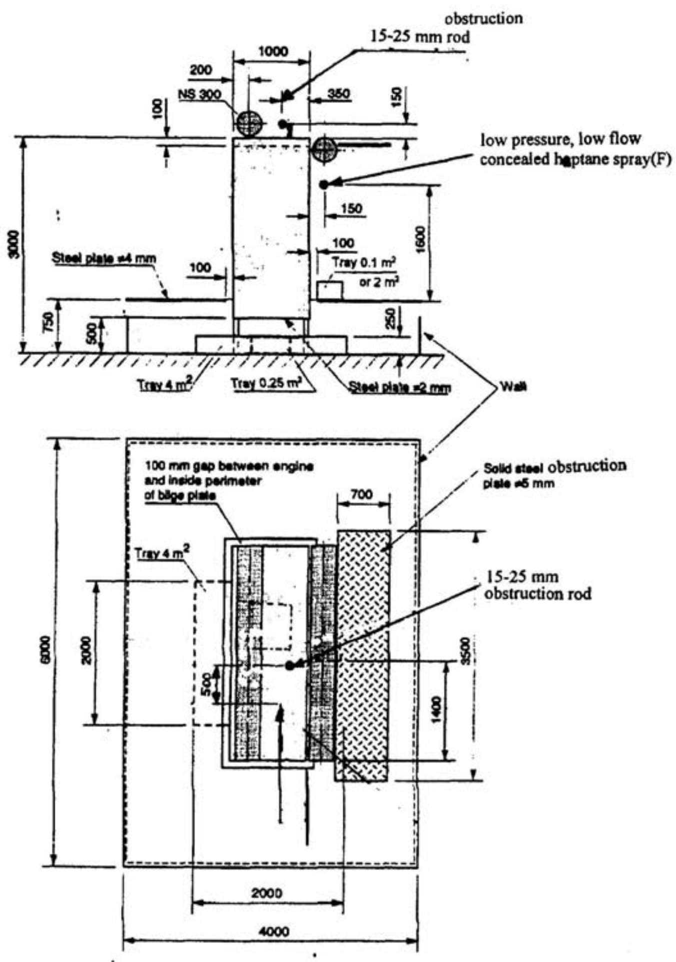
obstruction
15-25 mm rod
1000
200
NS 300
350
150
100
low pressure, low flow
concealed heptane spray(F)
150
100
1600
3000
Steel plate ≠4 mm
100
Tray 0.1 m²
or 2 m²
750
500
250
Tray 4 m²
Tray 0.25 m²
Steel plate ≠2 mm
Wall
100 mm gap between engine
and inside perimeter
of bilge plate
Solid steel obstruction
plate ≠5 mm
700
Tray 4 m²
15-25 mm
obstruction rod
6000
2000
500
3500
1400
2000
4000

Figure 2

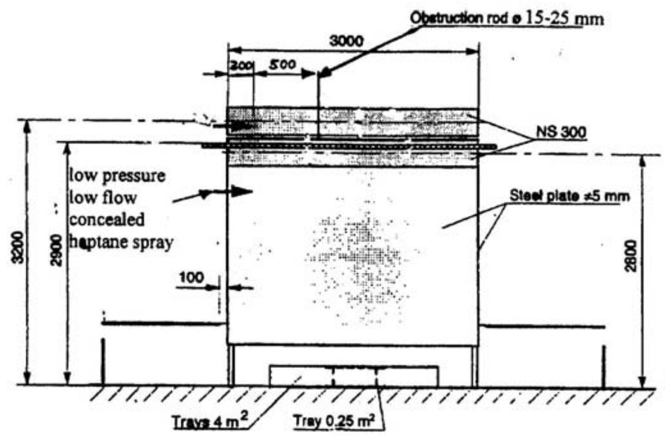
Obstruction rod ø 15-25 mm
3000
300
500
NS 300
low pressure
low flow
concealed
heptane spray
Steel plate ≥5 mm
3200
2900
2800
100
Trays 4 m²
Tray 0.25 m²

Figure 3

APPENDIX B – SYSTEM CONFIGURATIONS FOR EACH TEST

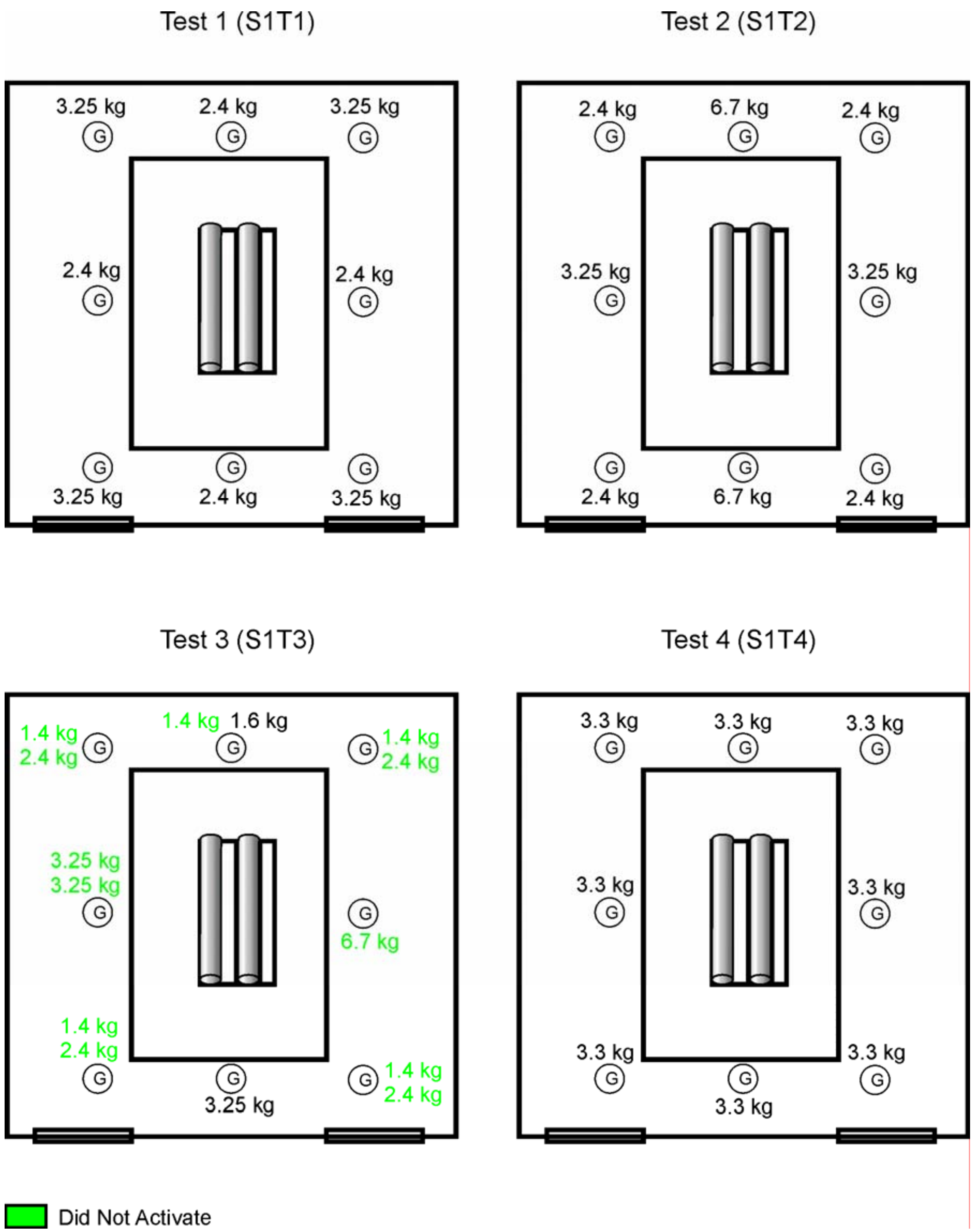

Figure B-1. System One Test Configurations.

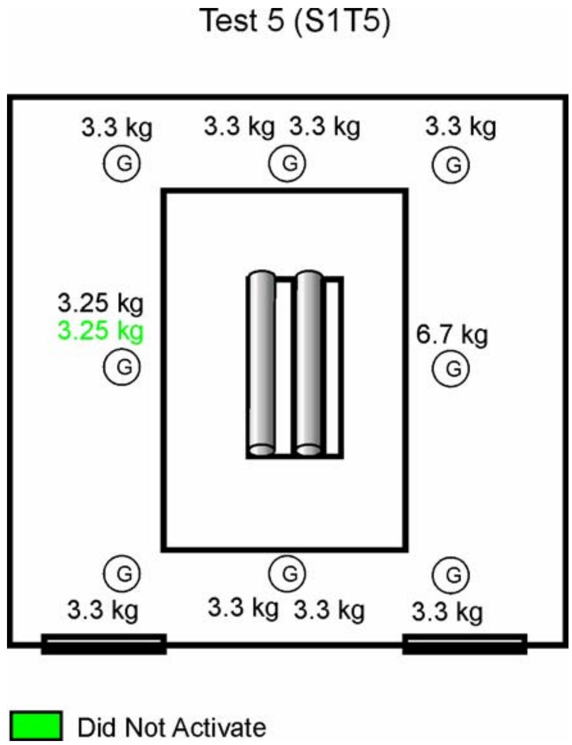

Figure B-1. System One Test Configurations (cont'd).

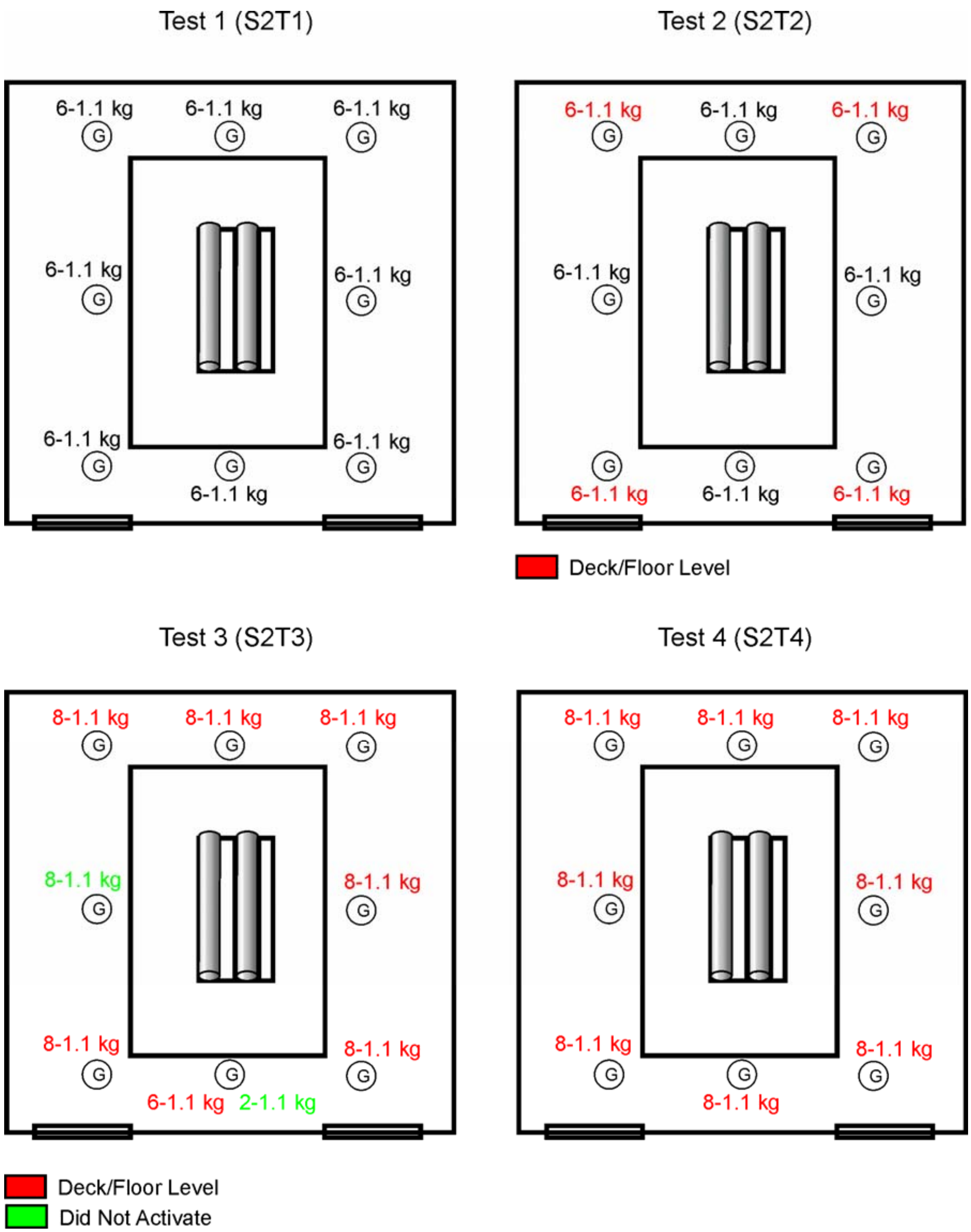

Figure B-2. System Two Test Configurations.

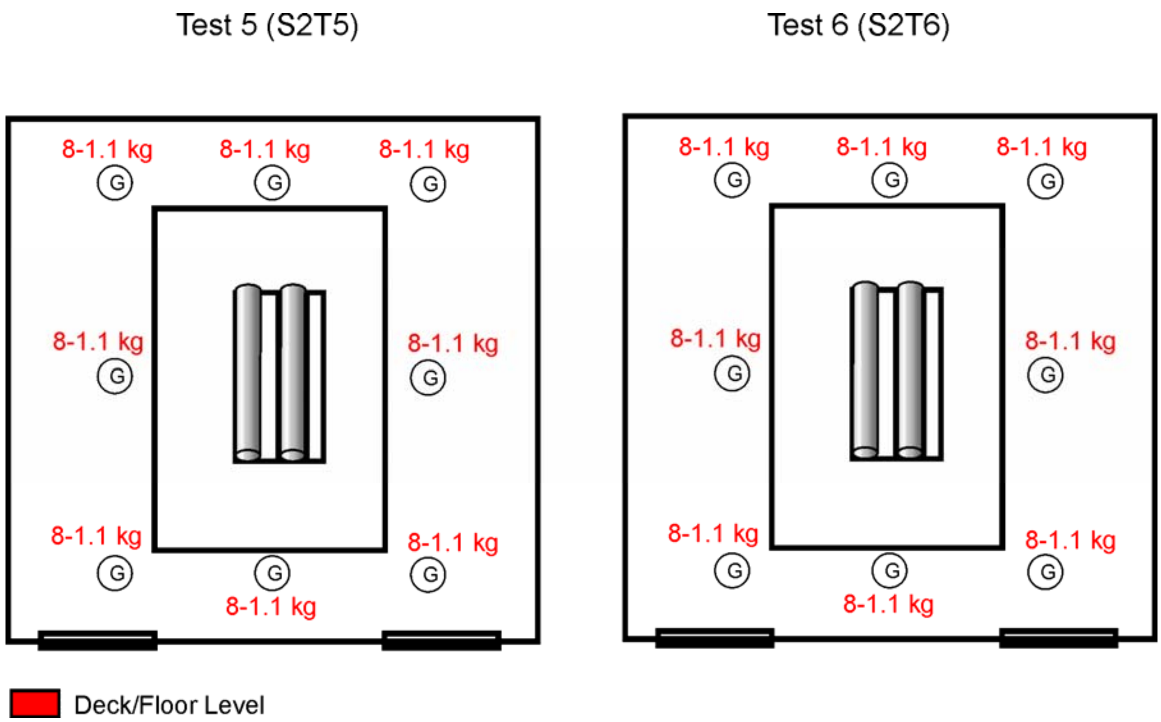

Figure B-2. System Two Test Configurations (cont'd).

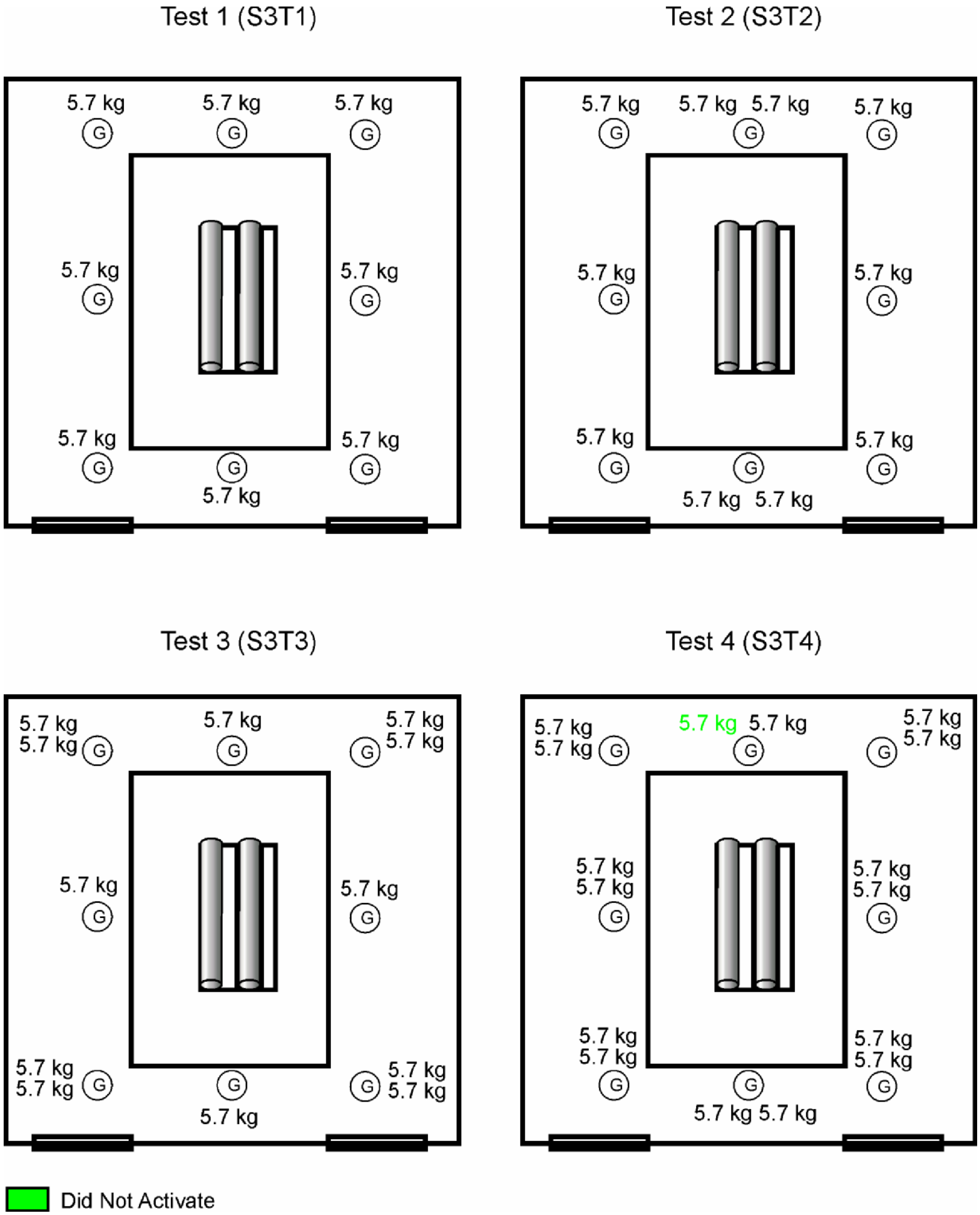

Figure B-3. System Three Test Configurations.

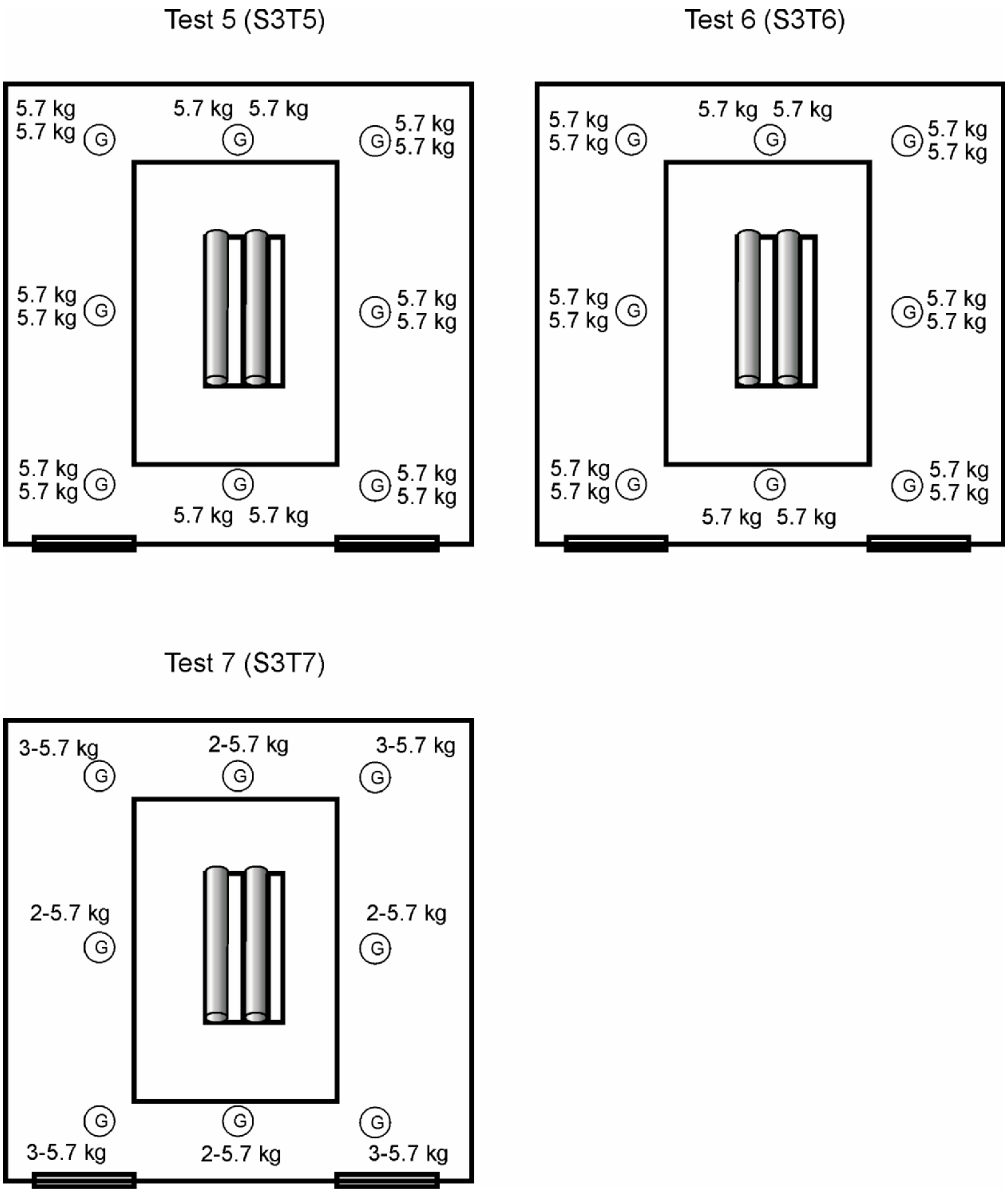

Figure B-3. System Three Test Configurations (cont'd).