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Report No. CG-D-02-07

An Evaluation of the Potential Failure Modes for Gaseous Agent Fire Extinguishing Systems Installed within the Protected Space

FINAL REPORT

February 2007

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United States Coast Guard
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N O T I C E

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1. Abstract (MAXIMUM 200 WORDS)

A full-scale fire performance evaluation was conducted to assist the USCG in developing a position on the practice of installing gaseous agent fire extinguishing system components (i.e., agent cylinders and control valves) within the space they are protecting (i.e., machinery spaces). Testing was carried out to identify the potential failure modes of the system and its components.

The evaluation assessed the survivability of a number of halocarbon and inert gas fire suppression system components against a range of exposures/conditions. The results suggest that a component containing plastic or rubber parts is likely to fail if the exposure exceeds 15 kW/m^2 and the energy dosage exceeds 9 MJ/m^2. An analytical assessment of agent storage cylinders (various extinguishing agents and cylinder sizes) conducted during this investigation suggests that the pressure relief valves in the cylinders would vent the extinguishing agent with approximately the same exposures/conditions that caused failures of plastic or rubber parts.

In addition, one test was conducted to determine if the loss of an agent cylinder in the space (implied in SOLAS as an acceptable consequence) would prevent the system from extinguishing the fire. The results show that the loss of an agent cylinder will render the system ineffective (not able to extinguish the fire). As a result, the system needs to be designed and installed in a manner to ensure that the design concentration of agent (1.3 times the minimum extinguishing concentration) is available at the time the system is activated.

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EXECUTIVE SUMMARY

A full-scale fire performance evaluation was conducted to assist the USCG in developing a position on the practice of installing gaseous agent fire extinguishing system components (i.e., agent cylinders and control valves) within the space they are protecting (i.e., machinery spaces). Testing was carried out to identify the potential failure modes of the system and its components.

The evaluation assessed the survivability of a number of halocarbon and inert gas fire suppression system components against a range of fire exposures/conditions. The results suggest that a component containing plastic or rubber parts is likely to fail in approximately ten minutes when exposed to the conditions produced during a fully developed compartment fire. An analytical assessment of agent storage cylinders (various extinguishing agents and cylinder sizes) conducted during this investigation suggests that the pressure relief valves in the cylinders would vent the extinguishing agent with approximately the same exposures/conditions that caused the failure of plastic or rubber parts.

A series of mapping tests were also conducted to identify the potential exposures to system components at various locations throughout the space for a range of fire sizes. The results of the mapping and component testing were analyzed to identify situations that could potentially render the system ineffective. The assessment identified a safe separation distance between cylinders as a function of compartment volume. The assessment also showed that unprotected cylinders high in the space would fail in about ten minutes for a majority of the likely fire scenarios (due to both component failures as well as due to the venting of the agent out the cylinder pressure relief valve).

In addition, one test was conducted to determine if the loss of an agent cylinder in the protected space would prevent the system from extinguishing a fire. The SOLAS design parameters imply that losing one cylinder (the factor of safety) would be an acceptable consequence. More specifically, SOLAS states that the system must still be capable of discharging the minimum extinguishing concentration of agent in the event that one agent cylinder is damaged. The test was conducted using an unbalanced system designed to discharge the agent at the minimum extinguishment concentration. The system, as tested, was unable to extinguish an obstructed heptane spray fire located on the side of a diesel engine mockup.

In summary, the results show that the loss of an agent cylinder could render the system ineffective (not able to extinguish the fire). As a result, the system needs to be designed and installed in a manner to ensure that the design concentration of agent (1.3 times the minimum extinguishing concentration) is available at the time the system is activated.

In conclusion, agent cylinders should only be installed in the space if no other option is available. If cylinders "must" be installed in the protected space, the following design parameters are highly recommended.

- Consideration should be given to house the cylinders in an A-30 rated steel enclosure.
- Agent cylinders should be located low in the space (preferably at/on the lowest deck level).

- Cylinders should be spaced such that a single fire/event can only damage one cylinder (reference minimum separation distance defined in this report).
- The system also needs to be activated within ten minutes to ensure that it will not be damaged/degraded by the conditions produced by the fire.

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LIST OF ACRONYMS, SYMBOLS AND ABBREVIATIONS

CaF_2	Calcium Fluoride
CO_2	Carbon dioxide
CO	Carbon monoxide
C	Celsius
cm	centimeter
CFR	Code of Federal Regulations
in^3	cubic inch
m^3	cubic meter
Cyl	cylinder
dia	diameter
FSS	Fire Safety Systems
ft	foot
GAFES	gaseous agent fire extinguishing system
HF	Hydrogen Fluoride
HFC	hydrogen fluorocarbon
in	inch
IG	Inergen
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
kg	kilogram
kg/L	kilogram per liter
kg/s	kilograms per second
KW	Kilowatt
KW/m^2	Kilowatt per square meter
L	Liter
LOAEL	lowest-observed-adverse-effect-level
MSC	Maritime Safety Committee
MSC/Cir	Maritime Safety Committee/Circular
MJ/m^2	MegaJoule per square meter
MW	Megawatt
m	meter
mm	millimeter
min	minute
NVIC	Navigation and Vessel Inspection Circular
N_2	Nitrogen
NOAEL	no-observed-adverse-effect-level
O_2	Oxygen
lb	pound
SOLAS	Safety of Life at Sea
m^2	square meter
mm^2	square millimeter
U.S.	United States
USCG	United States Coast Guard
W	watt
W/m^2	watt per square meter

1.0 INTRODUCTION

The physical and chemical properties of the halon alternative gases (halocarbons and inert gases) require that the agent cylinders be located as close to the protected space as possible. Longer pipe runs (i.e., long supply mains) can cause significant decreases in discharge nozzle pressure potentially reducing the capabilities of the system.

There is a movement in the maritime fire protection industry to allow gaseous agent fire extinguishing system (GAFES) components (i.e., agent cylinders and control valves) to be installed within the space they are protecting (i.e., machinery spaces). The current International Maritime Organization (IMO) test protocol MSC/Circ. 848 (FSS Code, 2001) has a provision to allow the agent cylinders to be installed in the protected space similar to the halon system requirements defined in SOLAS (SOLAS, 2001). These requirements are not based on the findings of a fire hazard type analysis and at a minimum, lack guidance on how the components should be installed within the space.

With respect to current U.S. Coast Guard (USCG) requirements, the Code of Federal Regulations Title 46: Shipping (CFR Title 46, 2005) and the Navigation and Vessel Inspection Circular 6-72 (NVIC 6-72, 1972) both prohibit the storage of the gaseous agent cylinders within the protected space. However, there are two manufacturers that have been recently given “type approvals” for systems with cylinders installed in the protected space based on a limited number of tests.

To evaluate the survivability of the two approved systems and to assist the USCG in developing a position on installing GAFES within the protected space, a full-scale fire performance evaluation was conducted to identify the potential failure modes of these systems. The focus was placed on systems and components currently considered acceptable by the USCG. In addition, one test was conducted to determine the capabilities of a system that only discharges the minimum agent extinguishing concentration alluded to in SOLAS.

2.0 OBJECTIVES

The objectives of this test program were to identify potential failure modes of GAFES installed within the protected space (i.e., machinery spaces). During these tests, typical system components were exposed to a range of potential fire conditions to assess their survivability and/or time to failure under representative conditions.

3.0 TECHNICAL DISCUSSION

3.1 Potential Exposures

The primary hazard in a shipboard machinery space is a fast growing Class B fire. These fires have been shown to produce untenable conditions within seconds and flashover within minutes of ignition. In addition, the temperatures in the overhead of the space (in the hot upper layer) can cause damage to equipment and wiring within minutes of ignition.

Localized heating of equipment resulting from direct flame impingement by a smaller fire can produce similar damage as the previously described fully developed compartment fire. This is based on the premise that localized heating can generate heat flux exposures which are equivalent to those produced during fully developed compartment fires. Heat flux exposures produced by fully developed compartment fires are typically within the range of 75 to 120 kW/m^2 (Back, 1991; Scheffey, 1990). Small fires (100 to 500 kW) impinging directly on an object have been shown to generate incident heat fluxes of almost the same magnitude (60 to 100 kW/m^2) (Back, 1994). These are the exposures/conditions that a system installed within the protected space must survive for an undetermined period of time prior to manual activation of the system by the crew.

These worst-case exposures (heat fluxes on the order of 100 kW/m^2) were originally selected as the basis of this evaluation. Since these exposures were expected to cause the component to quickly fail, the test exposures were reduced to 30-50 kW/m^2. This range was selected to allow the extrapolation of the area under the exposure/time curve (defined later as the energy dosage) to locations not intimate with the fire (a much wider range of application).

There is also the potential for an explosion to damage the components of a GAFES installed within the protected space. However, the conditions (over pressures and fragment damage) produced during such an event are unpredictable and can only be accounted for through durable/redundant components. The potential for explosion damage was outside the scope of this investigation.

3.2 System Information/Description

This evaluation focused on the systems and system components currently approved by the USCG for machinery space applications. These systems are listed in Table 1.

Table 1. GAFES Approved by the USCG.

Manufacturer	Approval Number	Agent	Agent Type
Ansul	162.161/0006/0	Novec 1230	Halocarbon
Ansul	162.162/0002/0	Inergen	Inert Gas
Chemetron	162.161/0005/0	FM 200	Halocarbon
Chemetron	162.161/0008/0	Novec 1230	Halocarbon
Fike	162.161/0002/0	FM 200	Halocarbon
Kidde-Fenwal	162.161/0007/0	FM 200	Halocarbon
Kidde-Fenwal	162.161/0009/0	Novec 1230	Halocarbon
Metal Craft	162.161/0004/0	FM 200	Halocarbon

The five manufacturers shown in Table 1 were contacted and asked to participate in this evaluation. Only one manufacturer volunteered to participate in this test series.

There are two general design classifications of GAFES installed within the protected space; consolidated and distributed. A consolidated system consists of a bank of agent cylinders (side-by-side) that are connected to a common manifold/distribution system. In a distributed system, the agent cylinders are spread throughout the protected space (or exist at more than one location in the space). The distributed systems can include either a common pipe network (i.e., agent distribution system) or separate pipe networks (i.e., one for each cylinder). Examples of these systems are shown in Figure 1. A distributed system was included in this evaluation.

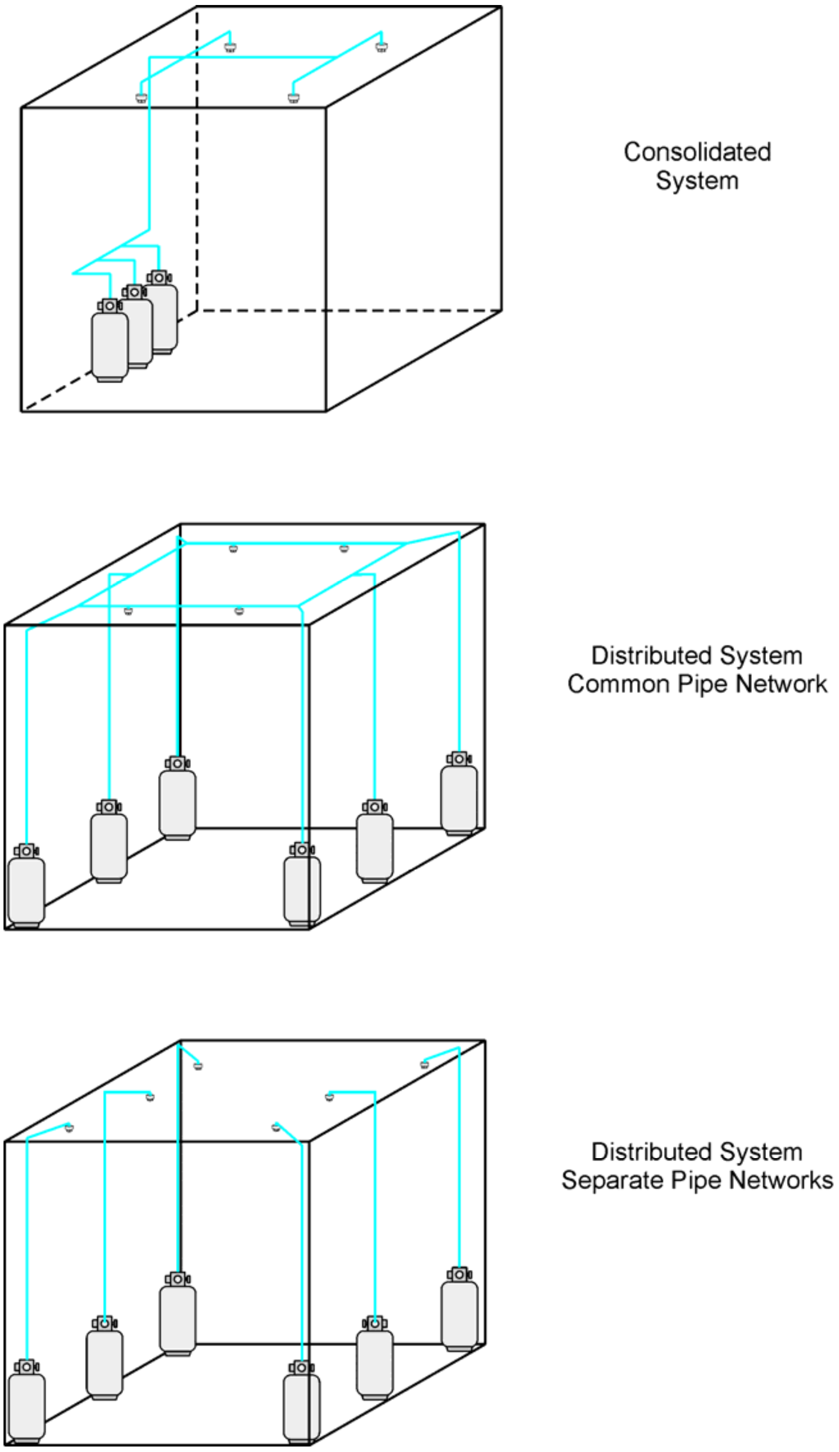


Figure 1. System Design Examples.

To be acceptable to the USCG, the distributed system must be designed such that the loss of the largest agent cylinder does not result in agent concentrations less than the cup burner number (minimum extinguishment concentration). The no-observed-adverse-effect-level and lowest-observed-adverse-effect-level requirements stated in MSC/Circ. 848 also still apply.

Only components currently approved by the USCG were included in this evaluation (i.e., no electrical activation systems or components that are allowed by IMO were evaluated).

During these tests, the survivability and the time to failure for a range of GAFES system components were quantified. These components included:

- Agent cylinders
- Cylinder valves
- Cylinder valve accessories
  - Connections
  - Gages
  - Safeties/rupture discs.
- Flexible hoses
- Activation systems/components
  - Mechanical
  - Pneumatic
- Check valves
- Control valves
- Pipe network connections
  - Threaded
  - Groove-Lock

The actual components tested are provided in Section 4.4.

3.3 System/Component Failure Criteria

The objectives of this test program were to identify potential failure modes of GAFES installed within the protected space. It is difficult to define failure on both a component level as well as a system level without fire testing of the system after the exposure. For example, components may fail by developing significant leaks but the system may still be capable of extinguishing the fire.

As a result, the following initial component level failure criteria were utilized. Additional consideration was given to determine the consequence of the component failure (i.e., degradation of the extinguishing capabilities of the system).

> Failure criteria for plumbing components (e.g., fittings, seals, hoses, etc): A 20 percent drop in system/component pressure in less than one minute.
>
> Failure criteria for control system components (e.g., activation system, control/cylinder valves, etc.): Loss of functionality during the test and/or a 20 percent drop in system/component pressure in less than one minute.

3.4 Current International Requirements

Although this study is focused on USCG approved systems and designs, the following sections summarize the international requirements for GAFES installed in the protected space and are provided for the reader's information. There are additional concerns associated with these requirements that needed to be identified.

3.4.1 Summary of IMO Requirements

IMO permits the agent cylinders to be stored within the protected space as long as they are distributed throughout the space and the following provisions are met (SOLAS, 2001; FSS, Code 2001).

1. A manually initiated power release, located outside the protected space, is provided. Duplicate sources of power are provided for this release and are located outside the protected space and can be immediately available.

2. Electric power circuits connecting the containers are monitored for fault conditions and loss of power. Visual and audible alarms are provided to indicate this.

3. Pneumatic, electric or hydraulic power circuits connecting the containers are duplicated and widely separated. The sources of pneumatic or hydraulic pressure are monitored for loss of pressure. Visual and audible alarms are provided to indicate this.

4. Within the protected space, electrical circuits essential for the release of the system are fire resistant according to IEC 60331 (1991) or other equivalent standards. Piping systems essential for the release of systems designed to be operated hydraulically or pneumatically are made of steel or other equivalent heat-resisting material to the satisfaction of the Administration.

5. Each pressure container is fitted with an automatic overpressure release device (safety/rupture disc) which, in the event of the container being exposed to the effects of fire and the system not being operated, will safely vent the contents of the container into the protected space.

6. The arrangement of containers and the electrical circuits and piping essential for the release of any system are such that in the event of damage to any one power release line or container valve through mechanical damage, fire or explosion in a protected space, i.e., a single fault concept, at least the amount of agent needed to achieve the minimum extinguishing concentration can still be discharged having regard to the requirement for uniform distribution of medium throughout the space.

7. The containers are monitored for decrease in pressure due to leakage and discharge. Visual and audible alarms in the protected area and on the navigation bridge or in space where the fire control equipment is centralized are provided to indicate this condition.

3.4.2 Discussion of the International Requirements

Many of the international requirements are vague in nature and/or need further discussion/consideration. Some of these issues are discussed in the following paragraphs.

The general requirement that the cylinders need to be distributed throughout the space needs additional detail. A minimum separation distance should be defined. In addition, the locations of the cylinders (e.g., low in the space) should also be defined.

The general requirement that control circuitry, pneumatic piping and/or pull cables must be duplicated also needs installation guidance. Duplicate controls can be as vulnerable as a single line if they are run at the same location. As a result, a minimum separation distance should be defined for these control lines. The location/route of travel of the control lines through the space should also be specified (e.g., low versus high in the space).

The current requirement that the overpressure device on each cylinder must vent the contents of the container into the protected space needs to be reconsidered. This may be problematic for the halocarbon agents. The halocarbon agents react with the fire/flame producing HF (hydrogen fluoride) gas as a decomposition product. At low agent concentrations, the HF production can be significant and produce hazardous conditions in the space.

With respect to system performance, IMO requires that after a single event within the protected space (explosion and/or fire), the system must still be capable of discharging enough agent to produce the minimum extinguishing concentration in the space. This allows the system to lose the factor of safety added to the minimum extinguishing concentration which was intended to account for fire size, leaks/openings in the space, cutter/obstructions, etc. The loss of this agent was shown during these tests to render the system ineffective.

On a separate note, the five-sixths rule was developed when the factor of safety was 20 percent and with the current safety factor of 30 percent, the five-sixths rule would preserve a modest safety factor of 8.3 percent.

4.0 TEST PROTOCOL

4.1 Component Survivability Tests

The component survivability tests were designed to determine the failure criteria/conditions for a set of typical GAFES components when exposed to a range of fire conditions. The tests were conducted in the standard IMO 500 m^3 machinery space. The components were mounted to the side of the engine mockup and pressurized with air to approximately five to seven bars during the test. A 0.5 MW heptane spray fire was used to produce the desired exposure to the component. The spray fire was located approximately 0.5 meters below and varying distances horizontally away from the component. The horizontal distance between the component and the spray nozzle was adjusted to produce the desired exposure. The spray fire was allowed to burn for a period of 15-minutes or until the component failed (which ever happened first). The exposure produced by this fire, the surface temperature of the component and the system pressures were monitored during the test. The pressure measurement was used to note the time the component failed.

To allow for extrapolation of the survivability results to a range of fire scenarios, the heat flux exposures were mapped throughout the space for three fire sizes (1.5 MW, 3 MW and 6 MW). The heat flux exposures in the space were measured as a function of elevation and radial distance away from the fire. The fire sizes were selected to bound the range of potential exposure durations (two to ten minutes) before the oxygen depletion in the space caused the fire to self extinguish (or began to).

4.2 Degraded System Test

A degraded system test was conducted to evaluate the extinguishing capabilities of a damaged system (one that is only capable of discharging the minimum extinguishing concentration of agent (cup burner concentration) into the space). The degraded system was tested against a 1.1 MW heptane spray fire located on the side of the diesel engine mockup under the obstruction plate (MSC/Circ. 848 Test Fire 3F). The degraded system consisted of two nozzles, offset from the centerline of the test enclosure by 2.5 m on the starboard side/half of the test enclosure (mid-way between the starboard wall and the centerline). This configuration was selected to represent a worst case-mixing scenario that would be representative of a highly obstructed machinery space.

4.3 Test Compartment

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the USCG 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 6 cargo hold. The compartment is constructed to meet the dimensional requirements of the IMO test protocol (MSC/Circ. 848 as well as others). The compartment volume is approximately 500 m^3 with nominal dimensions of 10 m × 10 m × 5 m as shown in Figure 2. The diesel engine mockup described in the test protocol is located on the fourth Deck in the center of the compartment as shown in Figure 3. Air to support combustion is provided naturally through two 2 m^2 vent openings located on the fourth deck forward in the compartment. These two vents are equipped with remotely activated retractable doors. Products of combustion are exhausted from the compartment through a 6 m^2 vertical stack located in the back of the compartment (aft). The exhaust stack is equipped with a remotely activated hydraulic damper. The supply vents and vertical stack were open during the exposure tests.

4.4 GAFES Components

The GAFES components that were tested during this program are listed in Table 2. The list includes a majority of components typically used in these types of systems. It should be noted that several of the components were tested more than once in order to evaluate their response to different heat flux exposures.

4.5 Degraded System Description

The degraded system consisted of two 142 L cylinders, each containing 263 kg of HFC-227 each, designed to produce a 6.7 percent volumetric concentration (cup burner concentration) in the test enclosure. The cylinders were arranged in an end manifold configuration on the main deck and actuated electrically from the control room. The supply main, constructed of 80 mm schedule 40-welded pipe, ran from the manifold into the test enclosure where it was divided into two branch lines, constructed of 50 mm schedule 40-welded pipe, which terminated at the two nozzles. The two 50 mm pendent nozzles each had an orifice area of 1355 mm^2 and a 360^o discharge pattern. Details of this system are given in Appendix A.

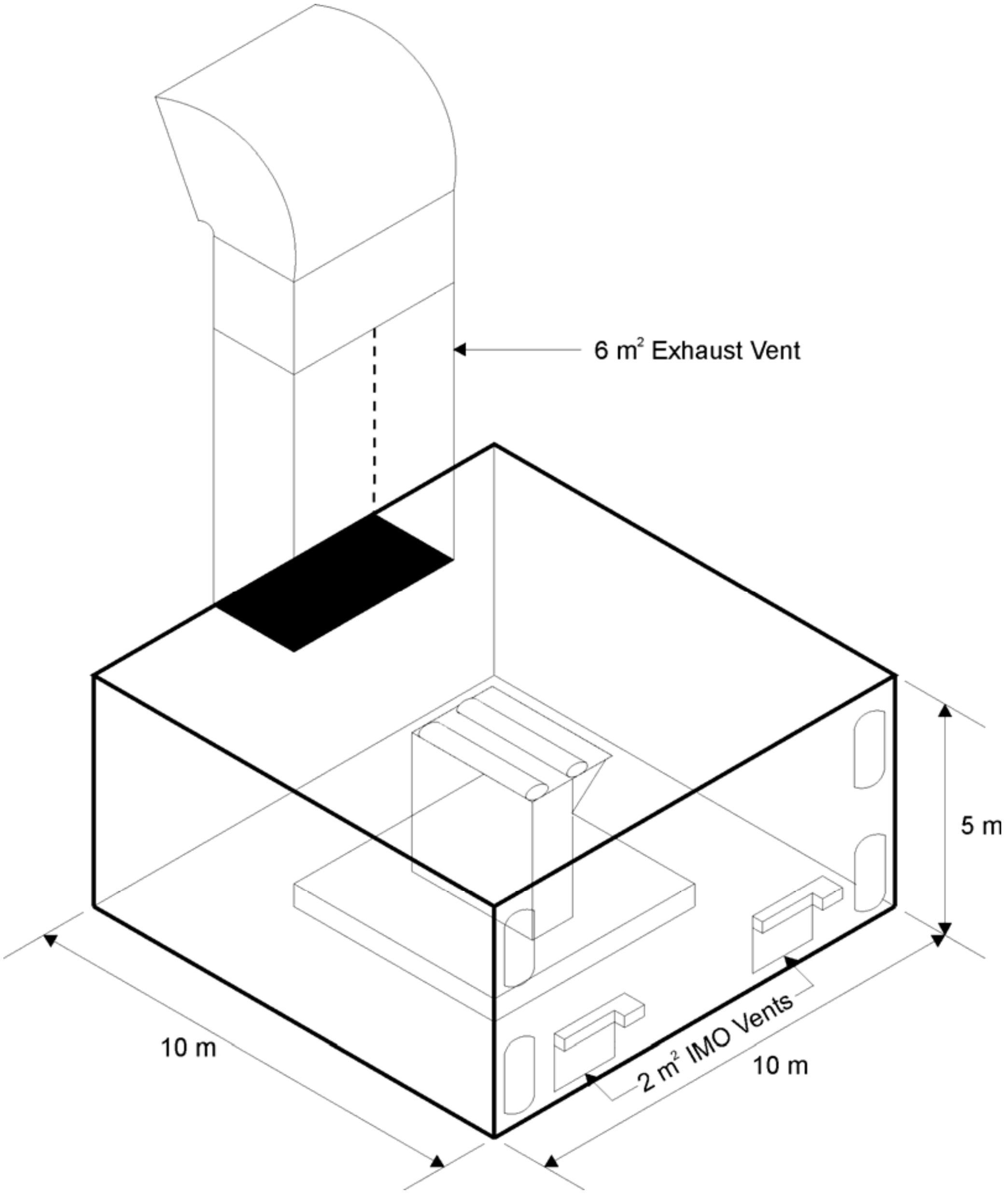
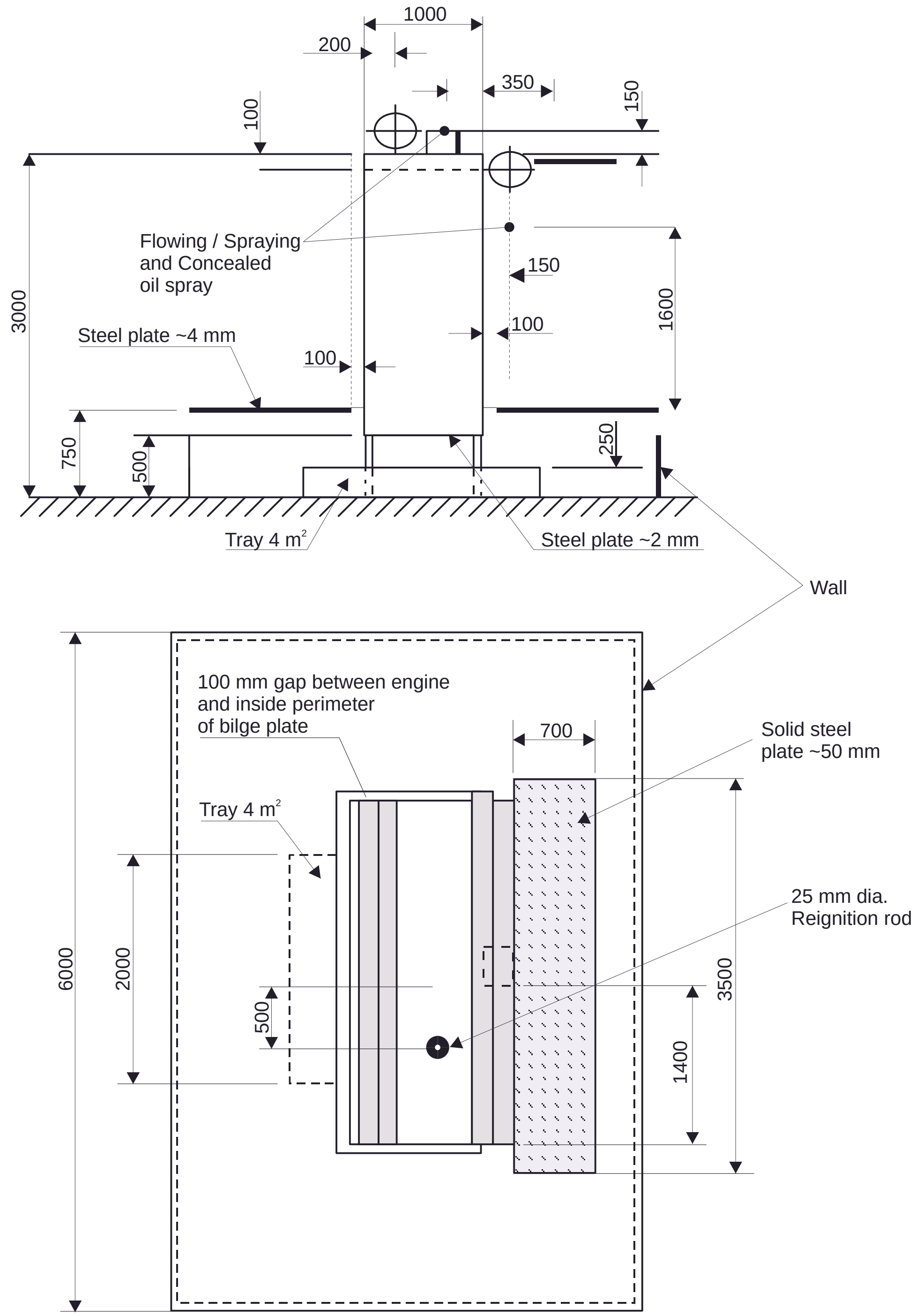


Figure 2. Machinery Space Configuration.



(All measurements are in mm, unless otherwise noted.)

Figure 3. Diesel Engine Mockup.

Table 2. Component Information.

Part Number	**Component Description**	**System Type**
Cylinder		
90-100601-100	272 kg (600 lb.) cylinder w/LLI	Halocarbon
90-100121-001	57 kg (125 lb.) cylinder w/LLI	Halocarbon
38-100667-001	66.7L cylinder assembly	Inert Gas
38-109802-001	Primary completer kit	Inert Gas
90-101040-001	N_2 pilot cylinder, 17L (1040 in^3)	Halocarbon
WK-877940-000	N_2 pilot cylinder, 1.8L (108 in^3)	Halocarbon
Discharge and Activation Hoses		
WK-264986-000	Actuation hose, 76 cm (30 in)	Halocarbon
06-236215-001	Actuation hose, 86 cm (34 in)	Halocarbon
06-118207-002	Flex hose	Halocarbon
WK-283899-000	50 mm (2 in.) discharge hose	Halocarbon
38-109802-001	Primary completer kit - discharge hose	Inert Gas
06-118225-001	75 mm (3 in.) Discharge hose	Halocarbon
Male straight		
Valves		
06-118058-001	75 mm (3 in.) Swing check valve	Halocarbon
WK-283888-000	Ball valve, 6 mm (1/4 in)	Halocarbon
81-870023-000	12mm (1/2 in.) Stop valve	Halocarbon
38-509833-001	Manifold check valve	Inert Gas
Misc.		
82-878737-000	Pressure operated head actuator	Halocarbon
82-878751-000	Lever/Pressure operated actuator	Halocarbon
WK-870652-000	Lever operated actuator	Halocarbon
90-981574-001	Siren, N_2	Halocarbon
WK-872450-000	Discharge head, plain nut	Halocarbon
WK-934208-000	Swivel adapter	Halocarbon
06-118262-001	Pressure switch	Halocarbon
06-118263-001	Pressure switch	Halocarbon
81-486536-000	Pressure switch	Halocarbon
81-981332-000	X-proof pressure switch	Halocarbon
81-871072-001	Discharge delay, N_2	Halocarbon
81-979469-000	Cable operated control head	Halocarbon
81-840098-000	Pull box	Halocarbon
WK-219649-000	152 m (500 ft.) pull cable	Halocarbon
81-803808-000	Corner pulley	Halocarbon
	63mm (2.5 in.) Victaulic coupling	

4.6 Fire Scenarios

4.6.1 Component Survivability Tests

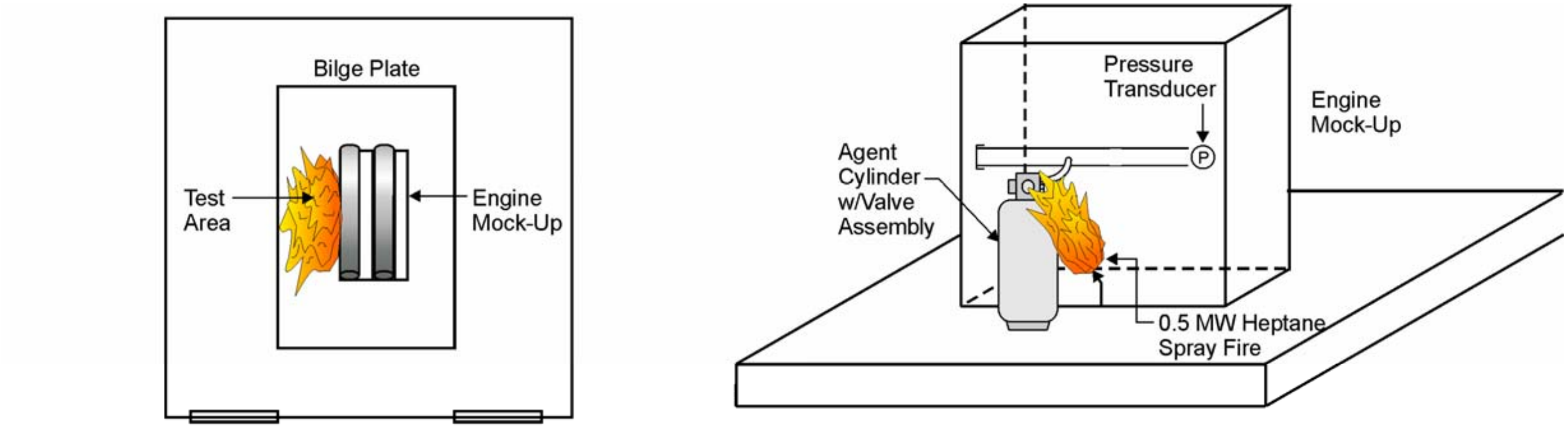
The exposures were produced using the 0.5 MW heptane spray fire. The parameters of this fire are described in Table 3. The spray nozzle was located 0.5 m below the component with the spray directed up at a 45-degree angle towards the object. Three horizontal distances between the spray nozzle and the component tested were utilized during these tests. The horizontal distance initially was 0.3 m which resulted in a heat flux exposure of 119.9 kW/m^2. Subsequent testing was performed with horizontal distances of 0.6 m and 0.9 m, resulting in heat flux exposures of 43.7 kW/m^2 and 15.5 kW/m^2, respectively. A majority of the tests were conducted with the 0.6 m horizontal distance (43.7 kW/m^2).

Table 3. Spray Fire Parameters.

Nominal Fire Size	**0.5 MW**	**1.1 MW**	**1.5 MW**	**3.0 MW**	**6.0 MW**
Spray nozzle	Wide spray angle (80) full cone type	Wide spray angle (80) full cone type	Wide spray angle (80) full cone type	Wide spray angle (80) full cone type	Wide spray angle (80) full cone type
Nozzle make and model	Bete Fog Nozzle P-32	Bete Fog Nozzle P-48	Bete Fog Nozzle P-54	Bete Fog Nozzle P-80	Bete Fog Nozzle P-120
Fuel flow	0.015 ± 0.005 kg/s	0.03 ± 0.005 kg/s	0.04 ± 0.005 kg/s	0.09 ± 0.005 kg/s	0.17 ± 0.005 kg/s
Fuel temperature	20 ± 5°C	20 ± 5°C	20 ± 5°C	20 ± 5°C	20 ± 5°C
Nominal heat release rate	0.5 ± 0.1 MW	1.1 ± 0.1 MW	1.5 ± 0.1 MW	3.0 ± 0.1 MW	6.0 ± 0.1 MW

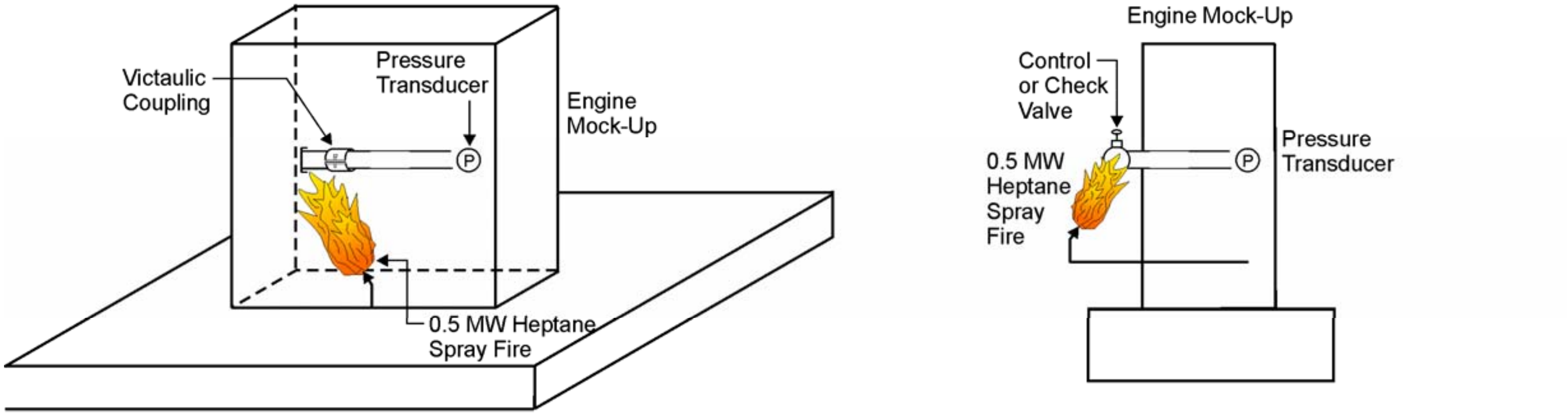
The GAFES component exposure tests were conducted on the unobstructed side of the diesel engine mock-up (starboard side). Several assembly/mounting devices were developed to hold the various components being tested approximately 1.0 m off the floor and 0.5 m away from the side of the mockup. Examples of the test configuration(s) are shown in Figure 4.

Each component was pressurized with air to approximately five to seven bars during these tests although some situations require the use of lower starting pressures. An air compressor located outside of the space was used to pressurize the GAFES components during these tests.



Test Location

Example 1 - Cylinder valve exposure configuration



Example 2 - Victaulic coupling exposure configuration

Example 3 - Valve exposure configuration

Figure 4 Test Configuration(s).

Steel tubing and fittings were used to connect the air compressor to the component being tested. The pressure in the system/component was monitored during the test to note when the component failed. Failure was defined as a drop of more than 20 percent in pressure in less than one minute for basic piping components. In addition, the component also had to be able to function properly at the end of the exposure.

4.6.2 Heat Flux Mapping Tests

The heat flux exposures were mapped for three fire sizes (1.5 MW, 3.0 MW and 6.0 MW). These scenarios were produced using heptane spray fires located on the starboard side of the engine mockup. The parameters of these fires were also described in Table 3.

4.6.3 Degraded System Test

The fire extinguishing capabilities of a damaged/degraded system were determined using an obstructed 1.1 MW heptane spray fire. The fire was located on the side of the diesel engine mockup under the obstruction plate in accordance with MSC/Circ. 848 Test Fire 3F. The parameters of this fire were also described in Table 3.

4.7 Instrumentation

The test compartment, the GAFES components and the degraded HFC-227ea system were instrumented for this test series. The instruments installed in the test compartment monitored the thermal conditions in the space and the exposure to the component (heat flux). The GAFES instrumentation was used to monitor the surface temperature and the pressure of the component (to note failure) during the test. The USCG's data acquisition system was used to collect the data during this evaluation. The data was collected at a rate of 1 scan per second (1 Hertz). The instrumentation scheme is shown in Figure 5. The details on these instruments are provided in the following sections.

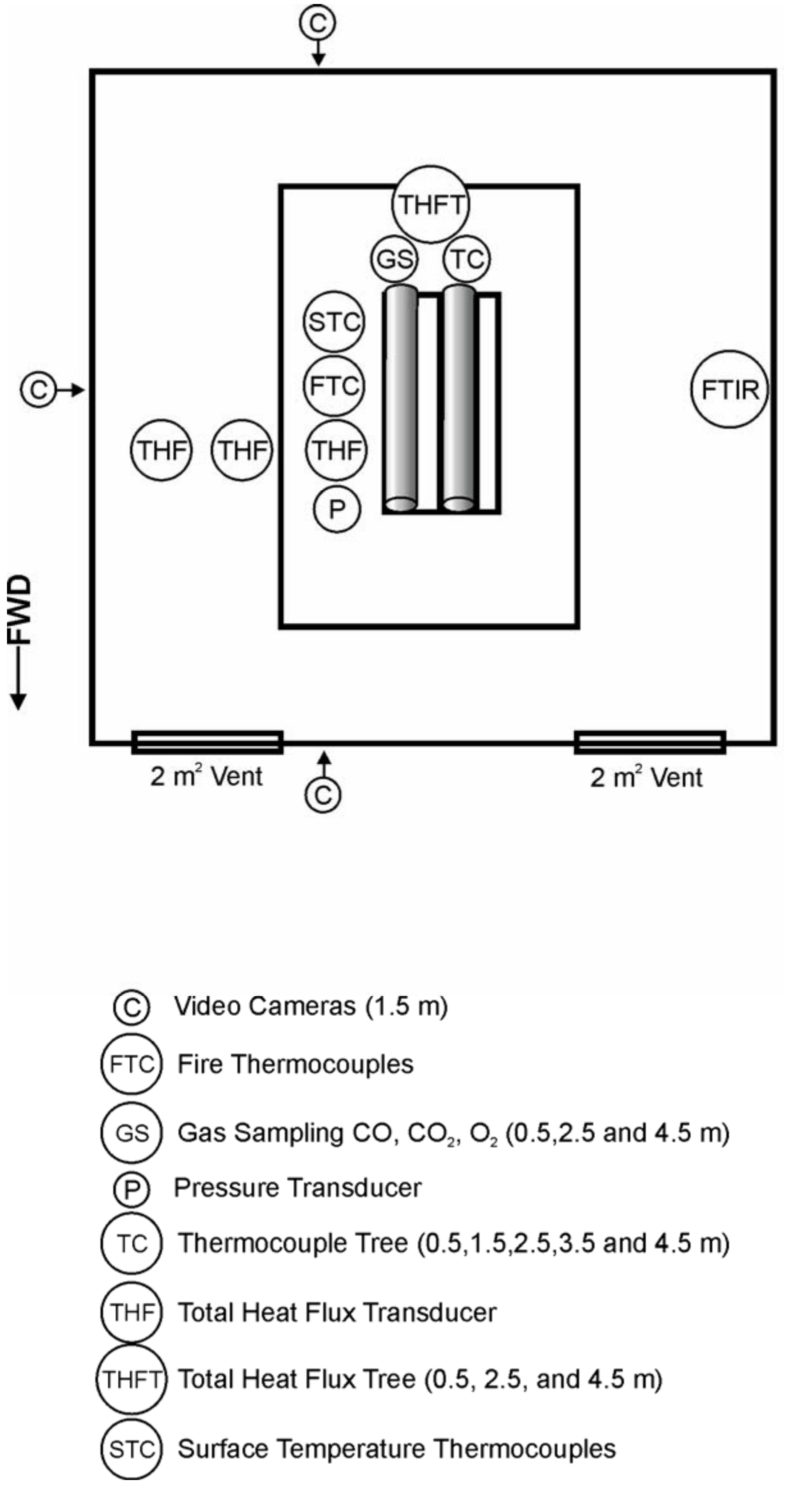


Figure 5. Instrumentation.

4.7.1 Machinery Space Instrumentation

The machinery space was instrumented to measure the air/gas temperatures and heat flux during and after the test. The fuel system pressure and the exposure to the GAFES components (heat flux) were also measured. During the heat flux mapping and fire extinguishing tests, the compartment CO, CO_2, and O_2 gas concentrations were also recorded. In addition, the agent concentration was measured during the fire-extinguishing test. A more detailed description of these instruments is listed in the following sections.

4.7.1.1 Air/Gas Temperature Measurements

One thermocouple tree was installed in the center of the compartment just aft of the diesel engine mockup. The tree consisted of five thermocouples positioned at the following heights above the deck (0.5, 1.5, 2.5, 3.5, and 4.5 m). Inconel sheathed Type K thermocouples (0.32 cm diameter Omega Model KMQIN-125G-600) were used for this application.

4.7.1.2 Gas Concentration Measurements

4.7.1.2.1 CO, CO_2, and O_2 Concentrations

Carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) concentrations (percent by volume) were measured near the center of the compartment (adjacent to the air/gas thermocouples) at three elevations 0.5, 2.5, and 4.5 m above the deck. MSA Lira 3000 Analyzers with a full-scale range of 10% were used to measure the carbon monoxide concentration, MSA Lira 303 Analyzers with a full-scale range of 25 percent 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.

The gas samples (CO, CO_2, and O_2) were pulled from the compartment through 0.95 cm stainless steel tubing using a vacuum sampling pump at a flow rate of 1 LPM resulting in a transport delay on the order of 10-20 seconds.

4.7.1.2.2 Extinguishing Agent and Hydrogen Fluoride (HF) Concentrations

The extinguishing agent (HFC-227each) and hydrogen fluoride (HF) concentrations were measured using a KVB/Analect Diamond 20 Fourier Transform Infrared Spectrometer (FTIR) configured with an open path for in situ measurements inside the space. This configuration included two flat 90^{o} mirrors (Analect Model OBE-100), two 91 cm light pipes (Axiom Model AOT-36), two 90^{o} parabolic mirrors with 20 cm focal lengths (Analect Model OBE-108), and two 3.8 cm diameter calcium fluoride, CaF_2, windows. A 40 cm active path length was used during these tests. Measurements were taken every 30 seconds.

Agent and HF concentrations were determined by comparison with spectra obtained using known concentrations. The specific agent concentrations were determined using the absorbencies at the wave numbers shown in Table 4.

Table 4. Component Specifications.

Agent / Compound	**Wave Number (cm^{-1})**
HFC-227ea	2034
Hydrogen Fluoride (HF)	4003, 4041, and 4077

The HF concentrations implied by the absorbencies at wave numbers 4003, 4041, and 4077 cm^{-1} were averaged together.

4.7.1.3 Fuel System Pressure Measurements

The spray fire fuel system pressure was monitored approximately six meters upstream of the nozzle where the fuel line entered the test chamber. The pressure was monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 17 bars. This transducer has an accuracy of 0.01 percent full-scale.

4.7.1.4 Total Heat Flux Exposures

The total heat flux exposure to the component was measured during each test. A Schmidt Boelter type total heat flux transducer manufactured by Medtherm Company with a full-scale range of 0-100 kW/m^2 was used for this application. The transducer was located horizontally adjacent to the GAFES component approximately 0.2 m away from the side of the mockup.

The total heat flux exposures were mapped throughout the space for a range of fire scenarios. Total heat flux was measured near the center of the compartment (adjacent to the air/gas thermocouples) at three elevations (0.5, 2.5, and 4.5 m) above the deck as shown in Figure 4. The total heat flux exposure was also measured at two distances (1.1 and 1.7 m) radically away from the centerline of the fire. Schmidt Boelter type total heat flux transducers manufactured by Medtherm Company having a full-scale range of 0-100 kW/m^2 were used for this application.

4.7.2 Component Instrumentation

The surface temperature and operating pressure of the GAFES components were measured during each test. A more detailed description of these instruments is listed in the following sections.

4.7.2.1 Surface Temperature Measurements

The surface temperature of the component was measured during the test. Inconel sheathed Type K thermocouples (0.32 cm diameter) Omega Model KMQIN-125G-600 were used for this application. The number of thermocouples and location varied between components (up to three thermocouples were used). The fastening technique was selected/developed on a component-by-component basis. Typically, the thermocouples were secured using metal wiring.

4.7.2.2 Component Pressure Measurements

The component pressure was monitored during the test to note the time of failure. Two pressure transducers were located away from the component to minimize their exposure during the test. The pressures were monitored using Setra Model 205-2 pressure transducers with a full-scale range of 17 bars. These instruments have an accuracy of 0.01 percent full-scale.

The transducers were positioned on the upstream (air compressor) and downstream side (component side) of an orifice plate assembly. The orifice plate provided a measure for the size of the leak that developed in the component during the test. For example, if a small leak (relative to the orifice size) was present, the system would be able to maintain a fixed pressure drop across the orifice plate. If the component were to fail, the leakage area would grow significantly, and the system would not be able to maintain pressure. A sharp drop in the system pressures would note the failure.

4.7.3 Degraded System Instrumentation

The discharge characteristics of the degraded system were measured using Inconel sheathed, type K thermocouples and pressure transducers (Setra Model 280E - full-scale range of 70 bars) installed in the system manifold and at the forward nozzle location.

4.7.4 Video Equipment

One video camera was used to visually document the heat flux mapping and component tests. This camera was located in the forward section of the compartment and was directed at the flame on the side of the mockup. During the fire-extinguishing test, three video cameras were used to monitor the test. Two of the three cameras were located on each end (forward and aft) of the compartment viewing the area around the diesel engine mockup. A third IR camera was located on the port side of the compartment looking at the flame. A microphone was also installed in the center of the space to provide the audio for the video camera(s).

4.8 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 telltale used to ignite the spray fire was fueled and the compartment ventilation condition was set. The two 2 m^2 lower vents and the 6 m^2 stack vent were open during the component exposure tests. The lower vents were open and stack vent was closed during the heat flux mapping tests. During the degraded system test, the lower vents and the stack vent were open during the preburn period and were closed just prior to system activation. 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 telltale was ignited and the compartment was cleared of test personnel. One minute later (two minutes after the start of video and data acquisition), the fuel spray system was activated. During the degraded system test, spray fire was allowed to burn for 30 seconds prior to system activation. The component survivability tests continued for 15 minutes after the fuel system was activated or until the component failed. The heat flux mapping tests continued until the fire became oxygen limited. The degraded system test continued for five minutes after the fuel system was activated or until the fire was extinguished (whichever happened first). On completion of the test, the space was ventilated using the installed forced ventilation system. During the exposure tests, the operability of the component was checked at the end of the test and any damage to the component was documented.

5.0 RESULTS AND DISCUSSION

Thirty-two tests were conducted during this investigation. These included 24 component survivability tests, 7 heat flux mapping tests and 1 degraded system fire extinguishing test. The results of these tests are discussed in detail in the following sections of this report.

5.1 System Survivability

5.1.1 Component Survivability Tests

The results of the component survivability tests are summarized in Tables 5A and 5B and are discussed as follows:

5.1.1.1 Agent Cylinders and Actuators

The 272 kg (600 lb) cylinder exposed to the 119.9 kW/m^2 heat flux during Test 5, held pressure for the duration of the 15-minute exposure. At the end of the exposure, smoke was noted coming from the 75 mm (3 in) Victaulic coupling at the exit to the cylinder. The pneumatic pressure actuator located on the cylinder valve was unable to actuate the cylinder after the exposure constituting a failure.

Table 5A. Component Test Results Summary (Part 1 - Cylinders).

Test No.	Part Number	Component Description	Heat Flux [kW/m^2]	Component Temperature [C]	Test Duration [min]	Energy Dosage [MJ/m^2]	Results/Comments
5	90-100601-100	272 kg (600 lb.) Cyl w/LLI	119.9	400.0	15.0	107.9	Pressure Actuator not Functional at End of Test - Cylinder Actuated while Removing Actuator - Smoke Coming from Victaulic - Valve Stuck in Place after Test
	82-878737-000	Pressure Op Actuator					
6	90-100121-001	67 kg (125 lb.) Cyl w/LLI	119.9	400.0	3.8	27.6	Pressure Switch burned/broken in half - Cylinder vented - Valve open when cylinder pressurized with switch capped
	82-878751-000	Lever Pressure Op Actuator					
	06-118263-001	Pressure Switch					
7	38-100667-001	66.7L Cylinder Assembly	119.9	250.0	1.8	12.6	Pressure switch melted and vented - Hoses burning when spray secured - Valve would not reseat after test
	38-109802-001	Primary Completer Kit					
9	WK-872450-000	Dischg Head, Plain Nut	15.5	130.0	15.0	14.0	Slight Melting of Pressure Gauge
	90-101040-001	N$_2$ Pilot Cyl, 17 L (1040 in.^{3})					
	WK-870652-000	Lever Op Actuator					
	WK-934208-000	Swivel Adapter					
10		Male Straight	15.5	140.0	15.0	14.0	Slight Melting of Pressure Gauge
	WK-870652-000	Lever Op Actuator					
	WK-877940-000	N$_2$ Pilot Cyl, 1.8L (108 in.^{3})					
11		Male Straight	43.7	150.0	15.0	39.3	Pressure Gauge Cover Melted Off - Slow Leak Prior to Test worsened over duration of test
	WK-870652-000	Lever Op Actuator					
	WK-877940-000	N$_2$ Pilot Cyl, 1.8L (108 in.^{3})					
13	WK-872450-000	Dischg Head, Plain Nut	43.7	150.0	15.0	39.3	Slight Melting of Pressure Gauge
	90-101040-001	N$_2$ Pilot Cyl, 17L (1040 in.^{3})					
	WK-870652-000	Lever Op Actuator					
	WK-934208-000	Swivel Adapter					
14	90-100121-001	67 L (125 lb.) Cyl w/LLI (New Valve)	43.7	250.0	15.0	39.3	Slight Melting of Pressure Gauge
	WK-870652-000	Lever Op Actuator					
	06-118263-001	Pressure Switch					

▨ Component failed during the test

Table 5B. Component Test Results Summary (Part 2- Valve, Hose, and Accessories).

Test No.	Part Number	Component Description	Heat Flux [kW/m^2]	Component Temperature [C]	Test Duration [min]	Heat Dosage [MJ/m^2]	Results/Comments
15	06-236215-001	Act'n Hose, 86 cm	43.7	300.0	15.0	39.3	Only Lightly Scorched
16	WK-264986-000	Act'n Hose, 76 cm	43.7	280.0	15.0	39.3	Only Lightly Scorched
17	06-118207-002	Flex Hose	43.7	425.0	3.5	9.2	Hose Ignited 1:00, Failed 3:30 after Start of Spray
18	WK-283899-000	50 mm Discharge Hose	43.7	400.0	5.0	13.1	Hose Ignited 0:45, Failed 5:00 after Start of Spray
19		62mm Victaulic Coupling	43.7	275.0	6.0	15.7	Vented 6:00 after Start of Spray
20	06-118058-001	75mm Swing Check Valve	43.7	275.0	15.0	39.3	Not Effected by Exposure
21	WK-283888-000	Ball Valve, 6 mm	43.7	250.0	5.5	14.4	Vented 5:30 after Start of Spray
22	38-109802-001	Primary Completer Kit - Discharge Hose	43.7	300.0	7.8	20.3	Vented 7:45 after Start of Spray
23	81-870023-000	12 mm Stop Valve	43.7	230.0	15.0	39.3	Successfully Cycled Valve after Exposure
	81-979469-000	Cable Operator					
	81-840098-000	Pull Box					
	WK-219649-000	152 m Cable					
	81-803808-000	Corner Pulley					
24	38-509833-001	Manifold Check Valve	43.7	250.0	4.0	10.5	Vented 4:00 after Start of Spray
25	90-981574-001	Siren, N_2	43.7	300.0	15.0	39.3	Successfully Operated after Exposure
26	06-118262-001	Pressure Switch	43.7	225.0	15.0	39.3	Held Pressure but Broke in Half Following Securing the Spray Fire
27	81-486536-000	Pressure Switch	43.7	400.0	15.0	39.3	Successfully Cycled Switch After Exposure but not Electronically Functional
28	81-981332-000	X-Proof Pressure Switch	43.7	350.0	15.0	39.3	Successfully Cycled Switch After Exposure but not Electronically Functional
29	06-118225-001	75mm Discharge Hose	43.7		15.0	39.3	Not Effected by Exposure
30	81-871072-001	Discharge Delay, N_2	43.7	250.0	15.0	39.3	Failed to Function after Exposure - Held Pressure Throughout but No Delay in Pressure Rise at Outlet after Exposure

▨ Component failed during the test

The 57 kg (125 lb) cylinder was exposed to the 119.9 kW/m^2 heat flux in Test 6 and to the 43.7 kW/m^2 heat flux during Test 14 (cylinder valve replaced prior to test). During Test 6, a pressure switch installed on the valve melted away early in the test and the cylinder failed by venting pressure shortly thereafter. It is not clear whether the cylinder vented through the valve or through the pressure switch. The cylinder valve was operational after the test when using the manual lever but would not operate when pneumatically activated (the plunger would move but would not generate sufficient force to cause activation).

No damage was observed when the cylinder was exposed to the lower heat flux (43.7 kW/m^2) during Test 14.

The 66.7 L inert gas cylinder failed by venting through the pressure switch installed as part of the primary completer kit during the 119.9 kW/m^2 exposure. The rubber or elastomer-coated hoses that were also part of the kit were observed to have ignited during the exposure. The main cylinder valve would not reseat after the exposure.

5.1.1.2 Nitrogen Pilot Cylinders

The nitrogen pilot cylinders are utilized to provide the pneumatic pressure required to cause activation of the agent cylinder, to trip pressure switches used to shutdown ventilation and to drive warning sirens. Two sizes of these cylinders, 17 L (1040 in^3) and 1.8 L (108 in^3) were exposed to two heat flux exposures of 15.5 kW/m^2 and 43.7 kW/m^2 without any significant damage during Tests 9 through 13.

5.1.1.3 Discharge and Actuation Hoses

The discharge and actuation hoses were exposed to 43.7 kW/m^2 during Tests 15, 16, 17, 19, 20, 22 and Test 29. The flexible metal hoses without rubber or elastomer coatings were unaffected by the exposure (Tests 15, 16, and 29). The hoses that had rubber or elastomer coatings ignited during the test and failed (vented pressure) shortly there-after.

5.1.1.4 Victaulic Coupling

A 62 mm (2.5 in) Victaulic coupling was exposed to 43.7 kW/m^2 during Test 19 and failed (vented pressure) six minutes into the test. Victaulic couplings can be utilized throughout the gaseous agent system, but are most commonly used near the agent cylinders.

5.1.1.5 Check, Ball and Stop Valves

Check, ball and stop valves were exposed to 43.7 kW/m^2 during Tests 20, 21, 23, and 24. The 6 mm (0.25 in.) ball valve and the manifold check valves failed (vented pressure) during the exposure, likely due to failures associated with the elastomers utilized to seal the valve in the closed position. The large 75mm (3 in.) swing check valve survived the exposure with no significant damage largely due to the mass of the valve body protecting the sealing material on the valve seat. The 12 mm (0.5 in.) stop valve was also unaffected by the exposure.

5.1.1.6 Nitrogen Time Delay Tank and Fittings

The N_2 delay tank (P/N 81-871072-001) held pressure throughout the 15-minute test period. However, the tank failed to delay the pneumatic actuation after the exposure. The tank is designed to receive N_2 from the actuation line and delay its progression for a preset period of time. The tank was outfitted with a pressure tap before the inlet (upstream) and after the outlet (downstream). Prior to the exposure, the seven bar test pressure was not recorded downstream of the tank for 1 minute after the upstream pressure rose. After the exposure, the seven bars test pressure was recorded downstream of the tank at the same time as the upstream pressure.

5.1.1.7 Pressure Switches

Both cylinder pressure switches (P/N 06-118262-001 and 06-118263-001) suffered severe damage during these tests. In Test 6, pressure switch 06-118263-001 melted away several minutes after the start of the spray fire. In Test 26, pressure switch 06-118262-001 melted away toward the end of the 15-minute exposure.

The inline pressure switch (P/N 81-486536-000) and inline explosion proof pressure switch (P/N 81-981332-000) held pressure during the test and mechanically functioned properly after the test. However, the internal electronics were damaged. The inline switches are used to energize or de-energize electronically operated equipment (i.e., shut down ventilation or machinery). With the electronics damaged, the functionality of the switches was lost.

5.1.2 Cylinder Safety Relief Venting

Agent cylinders are equipped with safety relief valves to prevent a catastrophic failure from occurring if the cylinder is heated. These valves take the form of burst discs which allow the cylinder to vent its contents at pressures that are above normal values but below that which would result in structural failure of the hardware. For agents that are stored at pressures on the order of 24.8 bar (low-pressure cylinders), the relief valves are nominally designed to operate at approximately 51.7 bar. For agents that are stored at pressures ranging from 41.8 bar to 151.8 bar (high-pressure cylinders), the relief valves are nominally designed to operate at approximately 200 bar.

For agent cylinders stored within the protected space, the operation of a safety relief valve could result in lower than desired agent concentration when the system is discharged. Even though the agent is discharged into the space, the contents of the single cylinder would not be sufficient to cause extinguishment and would most likely be exhausted by the ventilation system in the space prior to the activation of the remaining agent cylinders. For some agents, the release of the agent through the safety relief valve could also result in excessive thermal decomposition product formation (namely HF gas).

The temperatures of the agent cylinders corresponding to the operation of the safety relief valve are a function of the agent, cylinder fill density, and the degree of nitrogen pressurization (where applicable). Figures 6 and 7 give the pressure curves calculated utilizing the Peng Robinson Equation of State with Geometric Mixing Rules [Reid 1987, Henley 1981] for agents HFC-227each (FM-200 and FE-227), HFC-125 (FE-25), FK-5-1-12 (Novec-1230), carbon dioxide (IG-001) and IG-541 (Inergen) superimposed over the approximate safety relief valve operating pressures. As can be seen from these figures, the temperature at which the safety relief valve would be expected to operate ranges from a low of 63 °C to a point where the 93 °C maximum temperature included in these figures is not close to causing the relief valve to operate.

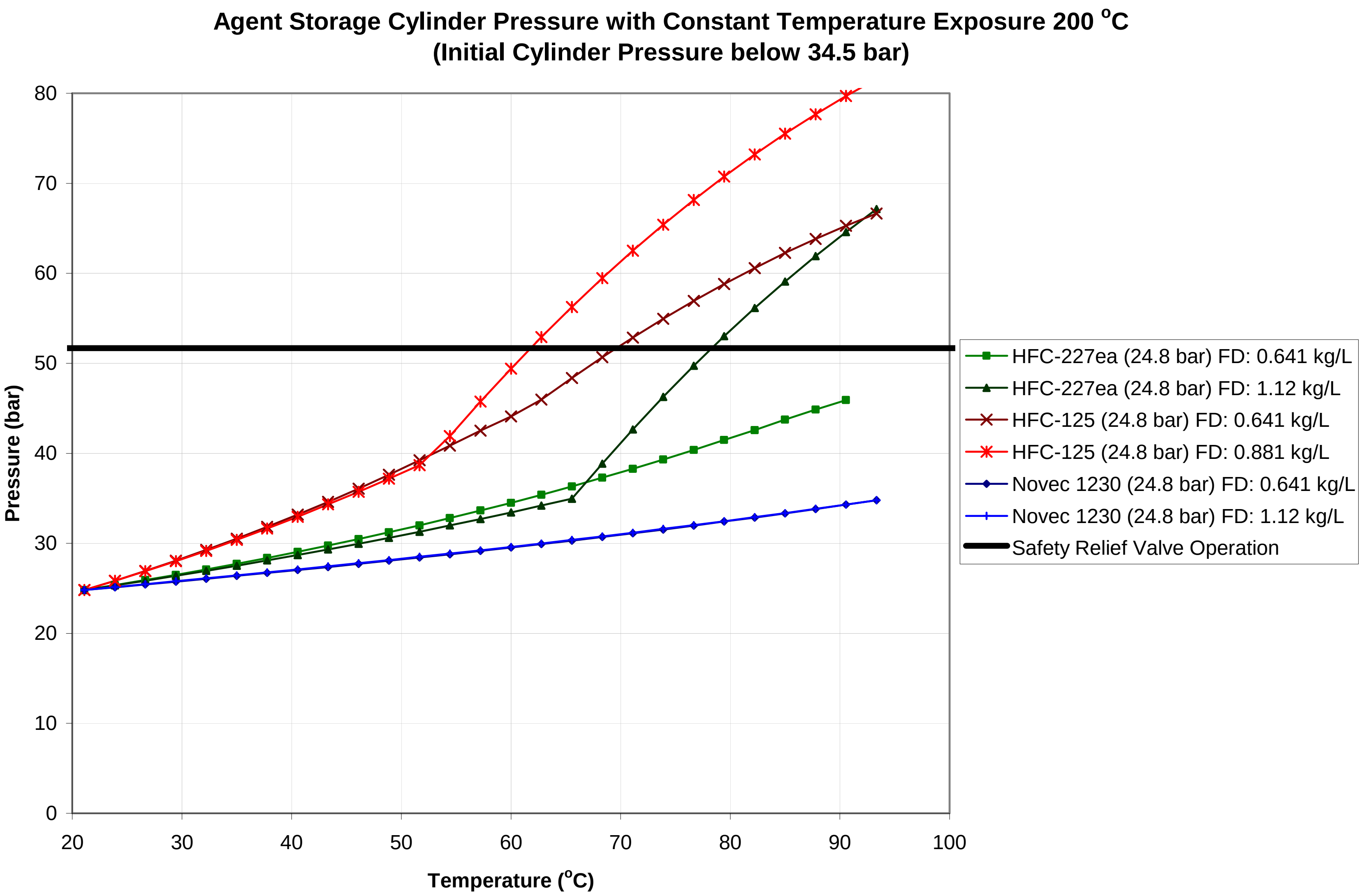


Figure 6. Agent Cylinder Pressure versus Temperature (Low Pressure Cylinders).

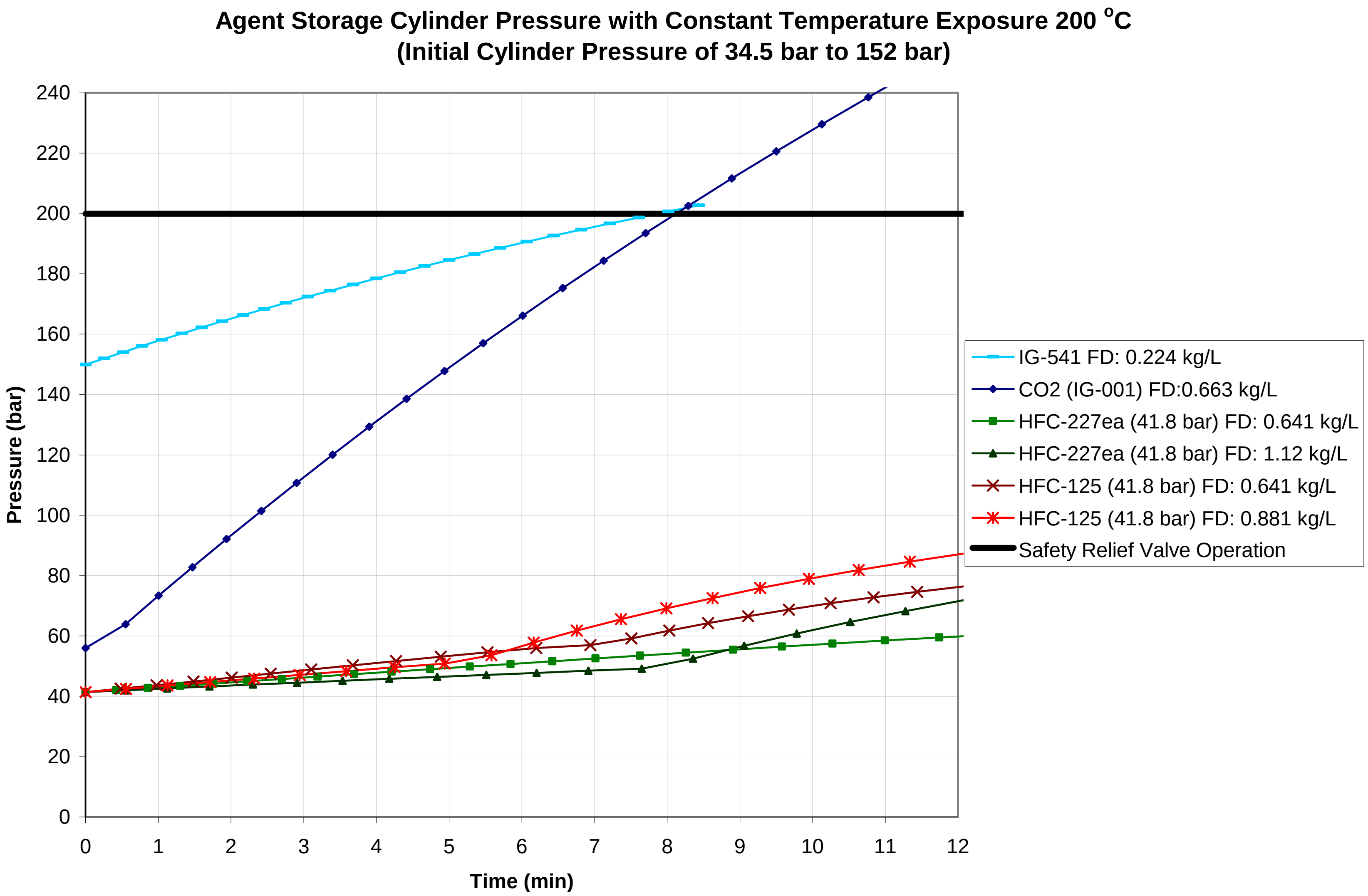


Figure 7. Agent Cylinder Pressure versus Temperature (High Pressure Cylinders).

In order to estimate the exposure time to the fire environment before the operation of the safety relief valve, two simplistic heat transfer models were utilized. The first model utilizes a constant uniform heat flux to half of the surface area of the cylinder and neglects any developed temperature gradient through the cylinder (lumped heat capacity). This simulates the radiant heating of the cylinder from a fire. The estimated time to safety relief valve operation with an imposed heat flux of 15 kW/m^2 is given in Figures 8 and 9 for the low and high-pressure cylinders respectively. As can be seen from these figures, the agent cylinders are able to withstand this exposure for at least 18 minutes prior to relief valve operation.

The second heat transfer model utilizes a constant temperature exposure and estimates the cylinder response if immersed in the hot smoke layer formed within the space. This simplistic model utilizes a constant temperature exposure of 200 ^{o}C and a convective heat transfer coefficient of 59.6 $W/m^2\ ^{o}C$. The estimated times for safety relief valve operation under this scenario are given Figures 10 and 11. As can be seen from these figures, the time to failure is much lower in this analysis with the first cylinder burst disk rupturing at approximately 7.5 minutes.

5.1.3 Survivabilty Discussion and Summary

5.1.3.1 Component Tests

In a majority of the cases, the breakdown of the system was caused by the failure of a plastic or rubber component or subcomponent. For example, the O-rings in the halocarbon cylinder valves, the gasket in the Victaulic coupling and the outer shell of the flex hoses were vulnerable to these types of exposures. Smaller parts with less mass to distribute the heat and parts with exposed rubber tended to fail the quickest. Rubber flex hoses were particularly susceptible to failure due to the large area of rubber exposed to the heat source and the ignition of the outer jacket during the test.

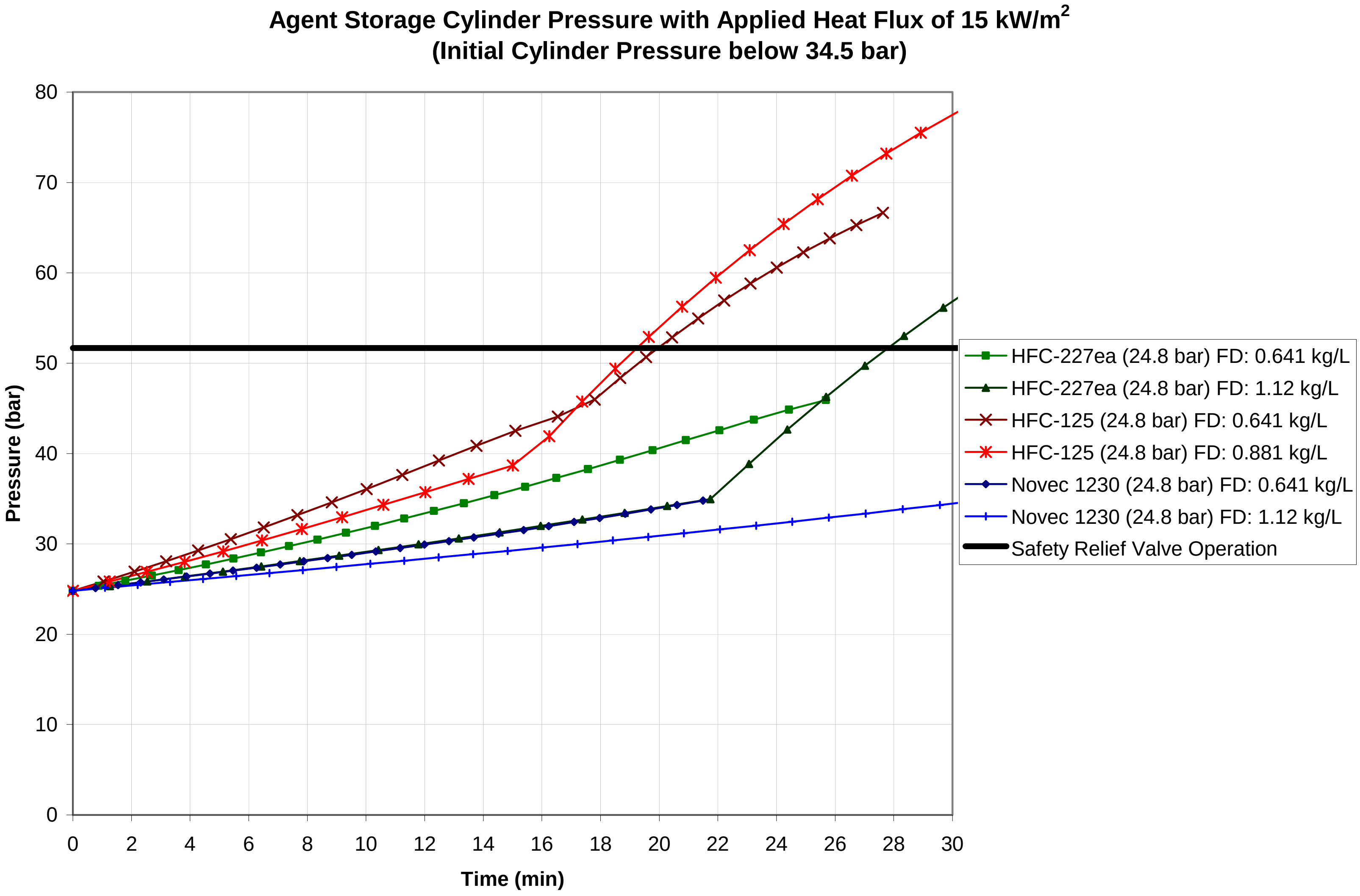


Figure 8. Agent Cylinder Pressure versus Time (Low Pressure Cylinders).

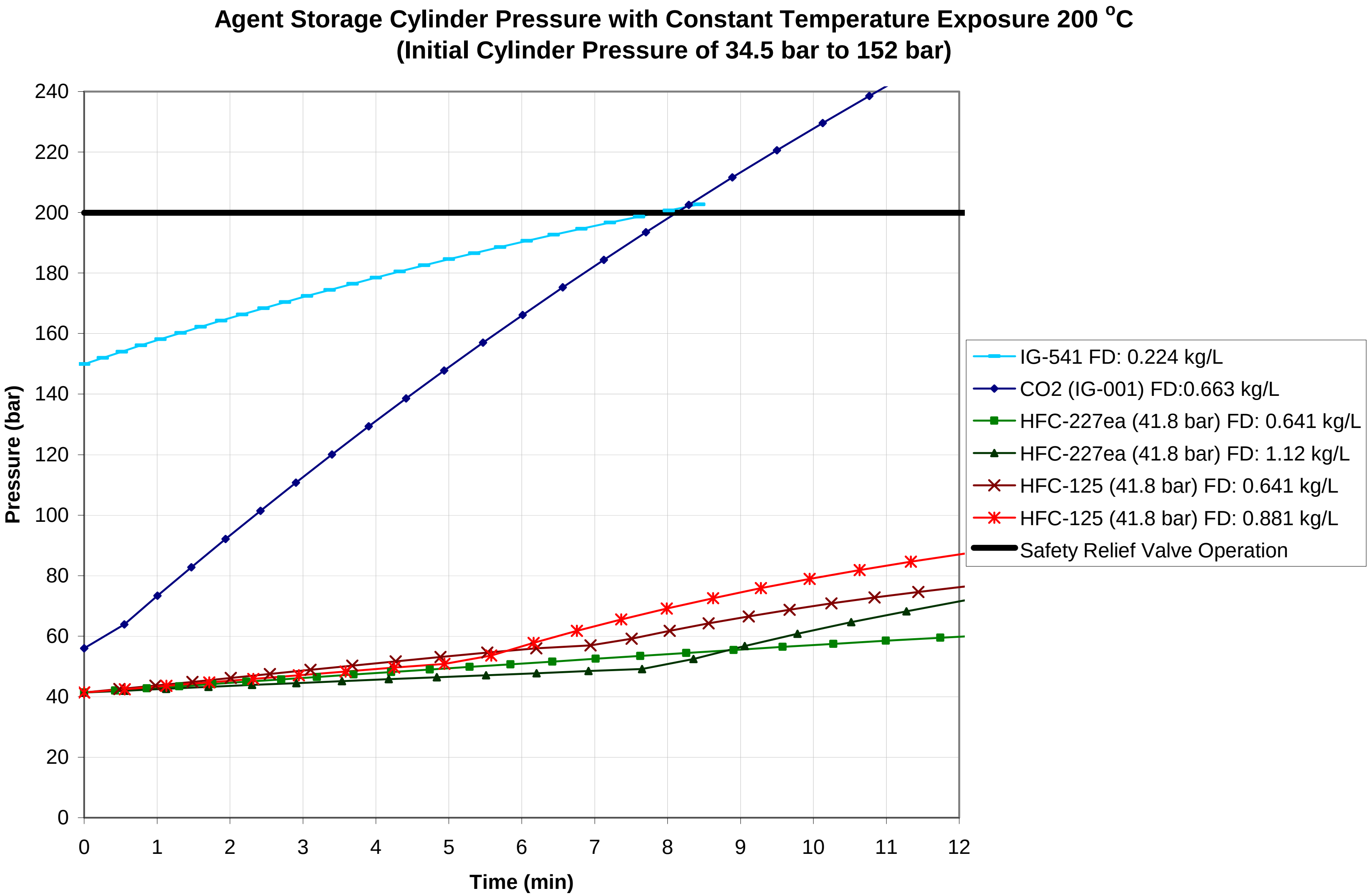


Figure 9. Agent Cylinder Pressure versus Time (High Pressure Cylinders).

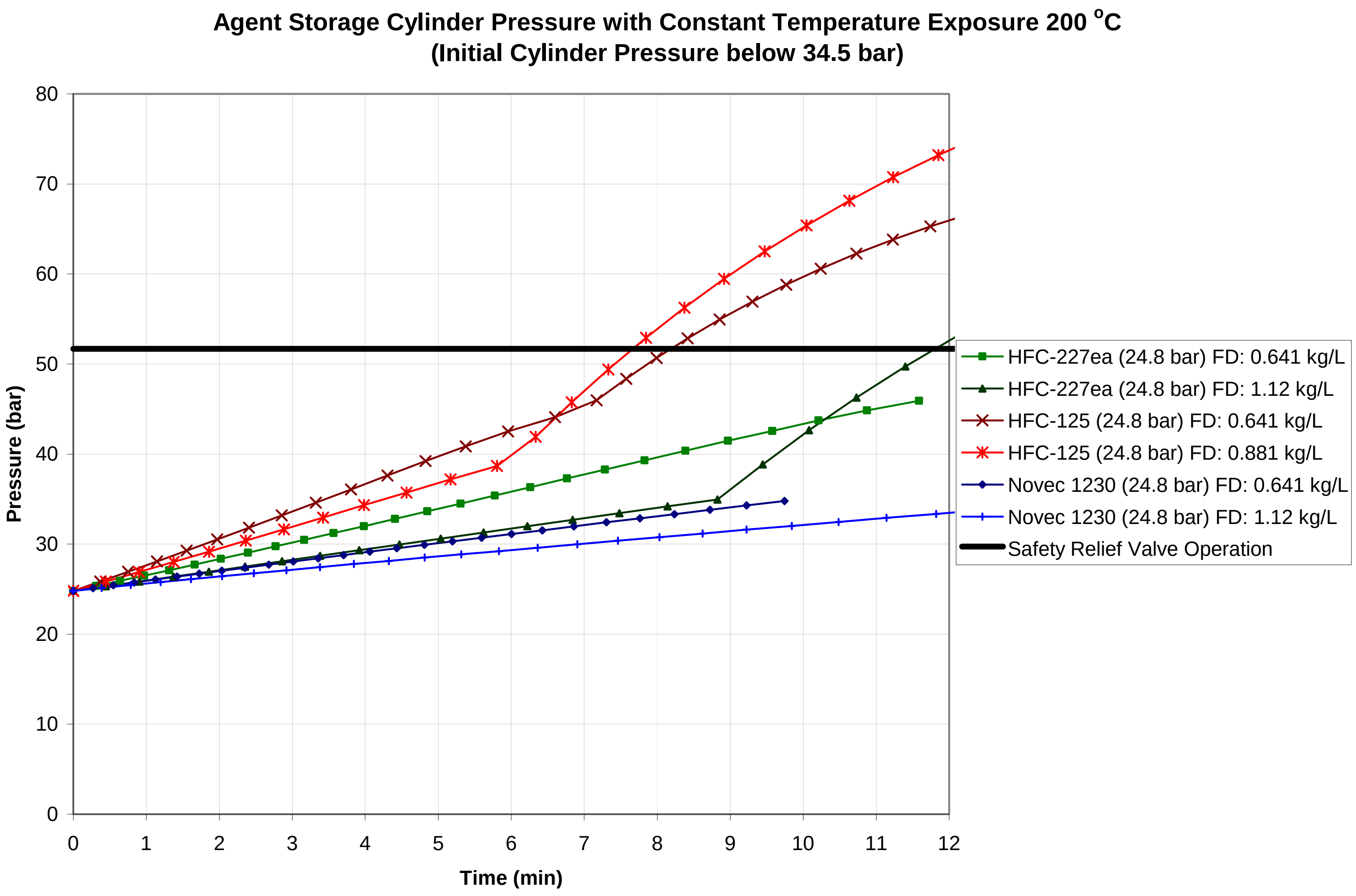


Figure 10. Cylinder Pressure with Constant Temperature Exposure of 200 °C (Low Pressure Cylinders).

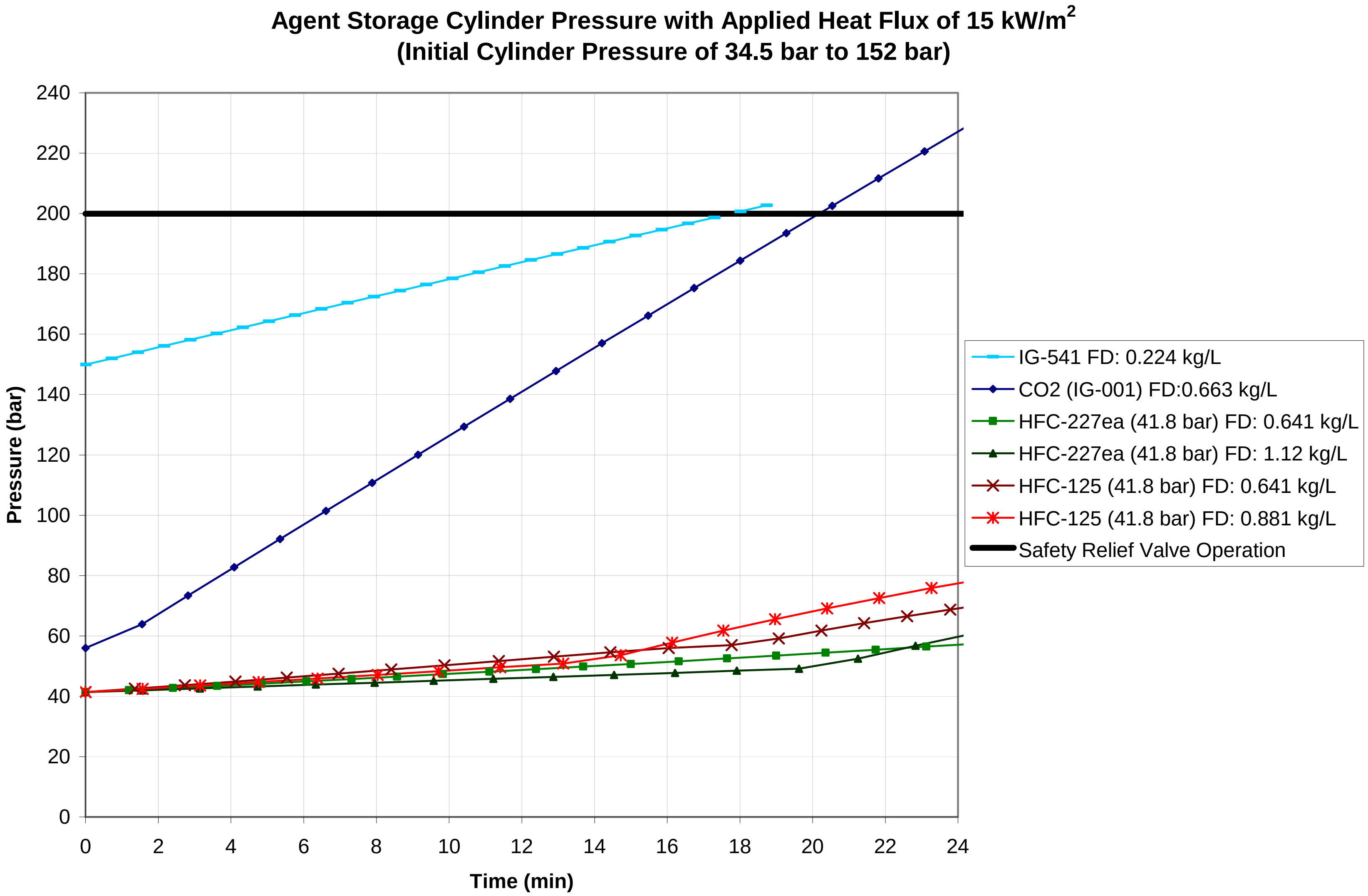


Figure 11. Cylinder Pressure with Constant Temperature Exposure of 200°C (High Pressure Cylinders).

Since the rubber components and/or subcomponents were observed to be the weakest link in the suppression system, the heat fluxes capable of damaging rubber materials were researched. Since the type of rubber used in the various components is unknown and probably varies from component to component and/or from manufacturer to manufacturer, the critical flux for several types of rubber (ethylene propylene, styrene-butadiene and chloroprene) were averaged to develop a "generic" critical value of 15 kW/m^2 [Tewarson, 2002].

In order to extrapolate these test results to a range of fire scenarios, a critical energy dosage was first determined. This critical energy dosage represents the point at which the combination of the exposure and duration was adequate to cause the component to fail. A first order approximation of the energy dosage is the product of the exposure and the duration (for exposures above the critical 15 kW/m^2 value). The exposures and energy dosages that resulted in component failure for these tests are shown in Figures 12 and 13. As shown in this figure, the critical energy dosage appears to fall in the range from 9-15 MJ/m^2 independent of exposure. More specifically, many components failed at this dosage for both the 43.4 and 119.9 kW/m^2 exposures. It should be noted that there is little if any data on Figures 12 and 13 at or near the critical exposure of 15 kW/m^2

5.1.3.2 Cylinder Venting Analysis

The cylinder venting analysis suggests that the critical energy dosage for a radiant exposure is on the order of 16.2 MJ/m^2 but only about 6.8 MJ/m^2 for the convective (hot gas) exposure. As a result, the rubber components would fail prior to the venting of the cylinder when the exposure is caused by a radiant flux. However, for the hot gas exposure (immersion of the agent cylinder in the hot gas layer), the critical energy dosage required to cause the cylinder to vent its contents would be less than the critical value for the rubber components.

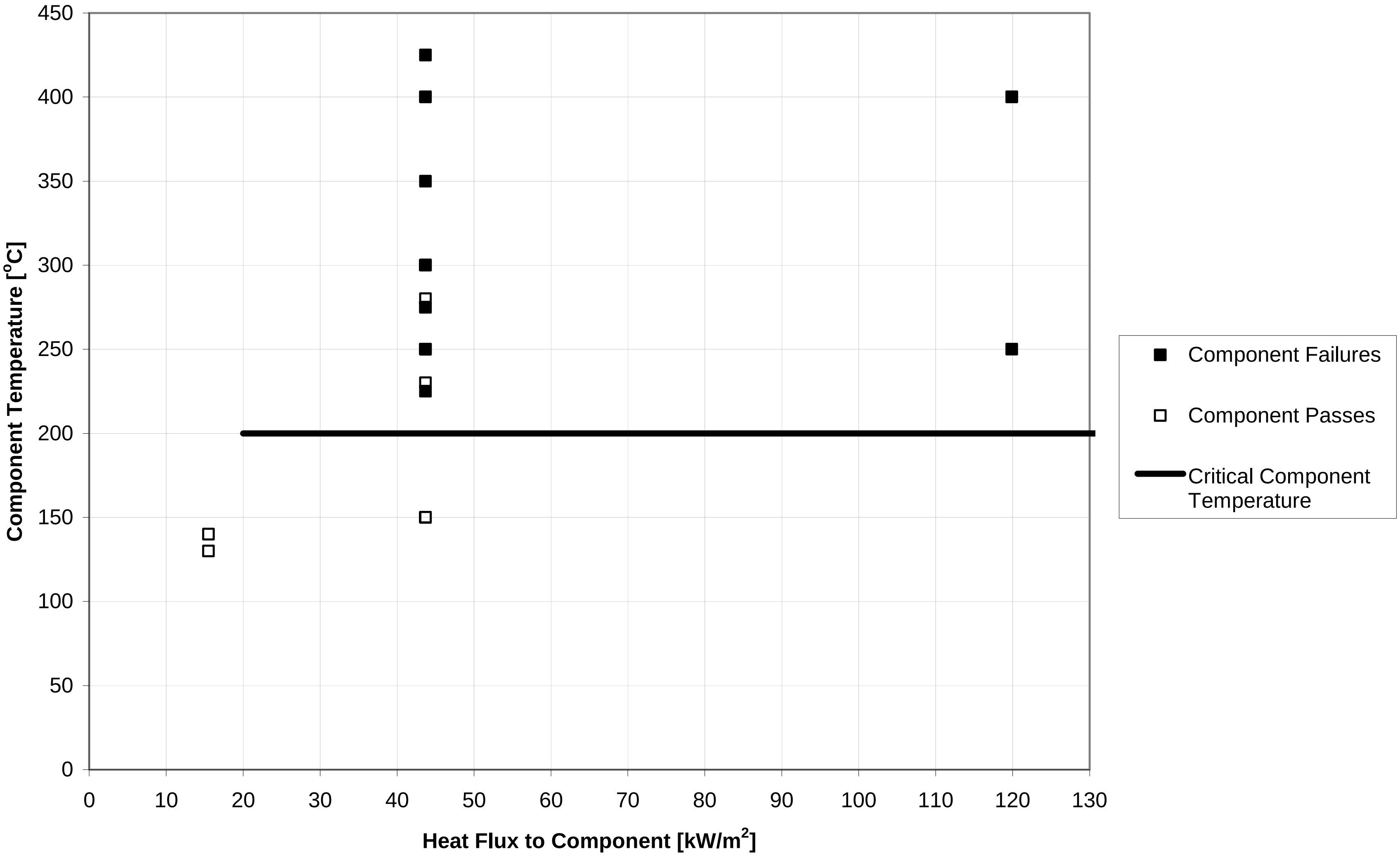


Figure 12. Critical Component Temperature.

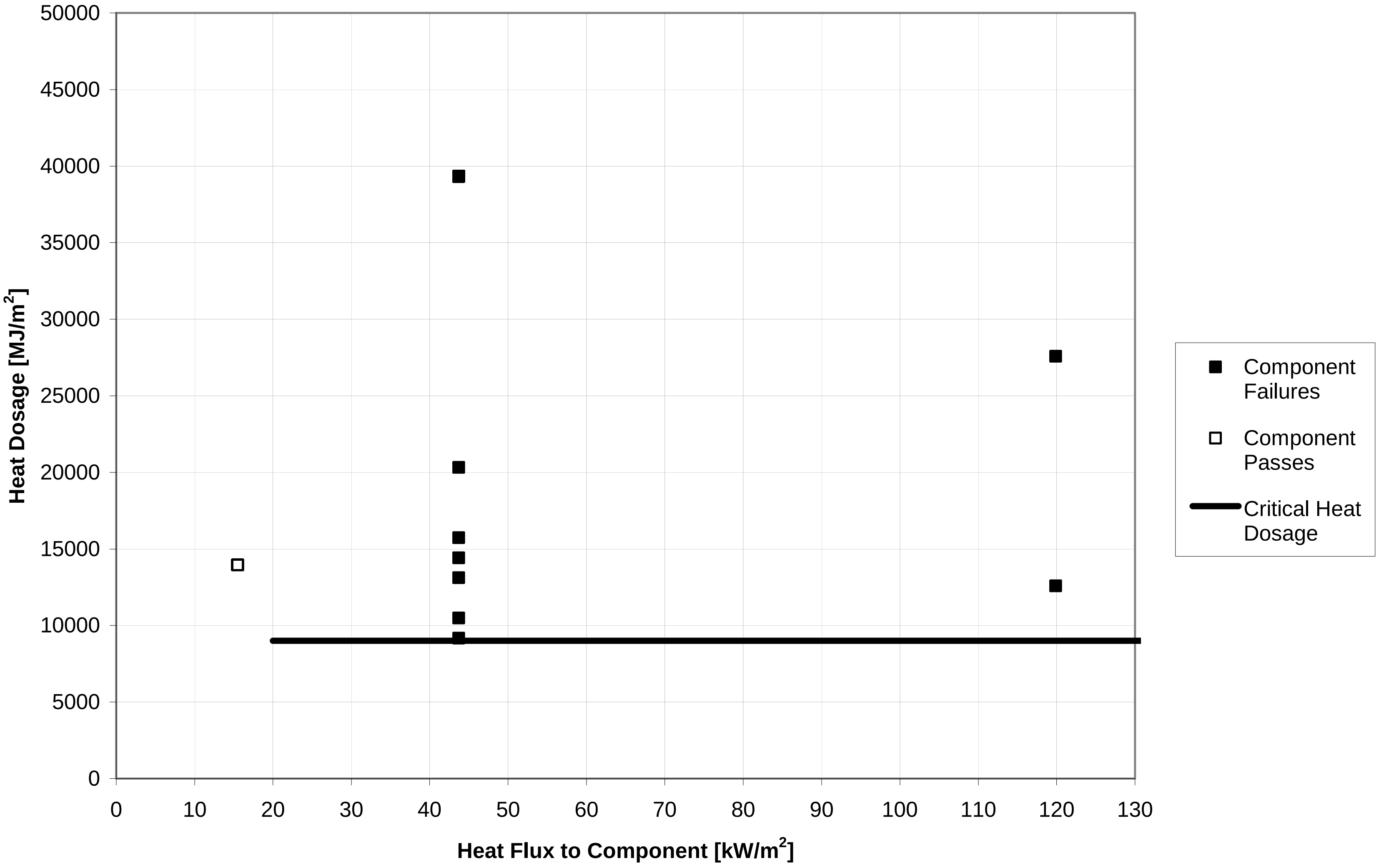


Figure 13. Critical Energy Dosage.

5.2 Heat Flux Mapping Tests

5.2.1 Heat Flux Mapping Test Results

The heat flux exposures were mapped throughout the compartment for the following heptane spray fire sizes: 0.5, 1.5, 3.0 and 6.0 MW. The average heat flux measured at each location is listed in Table 6.

Table 6. Mapping Test Results - Heat Flux Exposures.

Fire Size	**Fire** kW/m^2	**Radial 1.1 m** kW/m^2	**Radial 1.7 m** kW/m^2	**Tree HF, lower** kW/m^2	**Tree HF, middle** kW/m^2	**Tree HF, upper** kW/m^2
0.5	65.3	9.3	3.9	0.1	0.1	1.4
1.5	105.3	20.3	8.8	0.2	0.6	5.0
3	137.3	30.0	13.8	0.7	2.9	13.0
6	125.1	38.3	20.9	2.8	8.5	30.7

For the 0.5 MW spray fire, the heat fluxes were averaged using the measurements recorded 15 seconds after the start of the spray to 15 seconds prior to securing the spray. The 15-second time periods on either side of the averaged points were eliminated to avoid any effects of starting and stopping the fuel spray.

For the 1.5 MW spray fire, the average heat fluxes were calculated using the measurements made 15 seconds after spray fire actuation for a period of approximately 10 minutes.

The test conducted with the 3.0 MW spray fire was terminated seven minutes after ignition. Despite limiting the test to seven minutes, the heat fluxes measurements indicate that the diminished oxygen concentration in the space had a significant affect on the fire prior to securing the spray. To ensure that the average heat fluxes were calculated during the time period when the fire was at maximum capacity, the oxygen concentration measured at the same approximate elevation as the spray was analyzed. The time when the middle oxygen analyzer showed a significant drop in concentration was used as the final point in the heat flux average calculation. For the 3.0 MW spray fire, the middle oxygen concentration dropped off 1.5 minutes into the spray fire. The drop in concentration and the associated heat flux are shown in Figure 14.

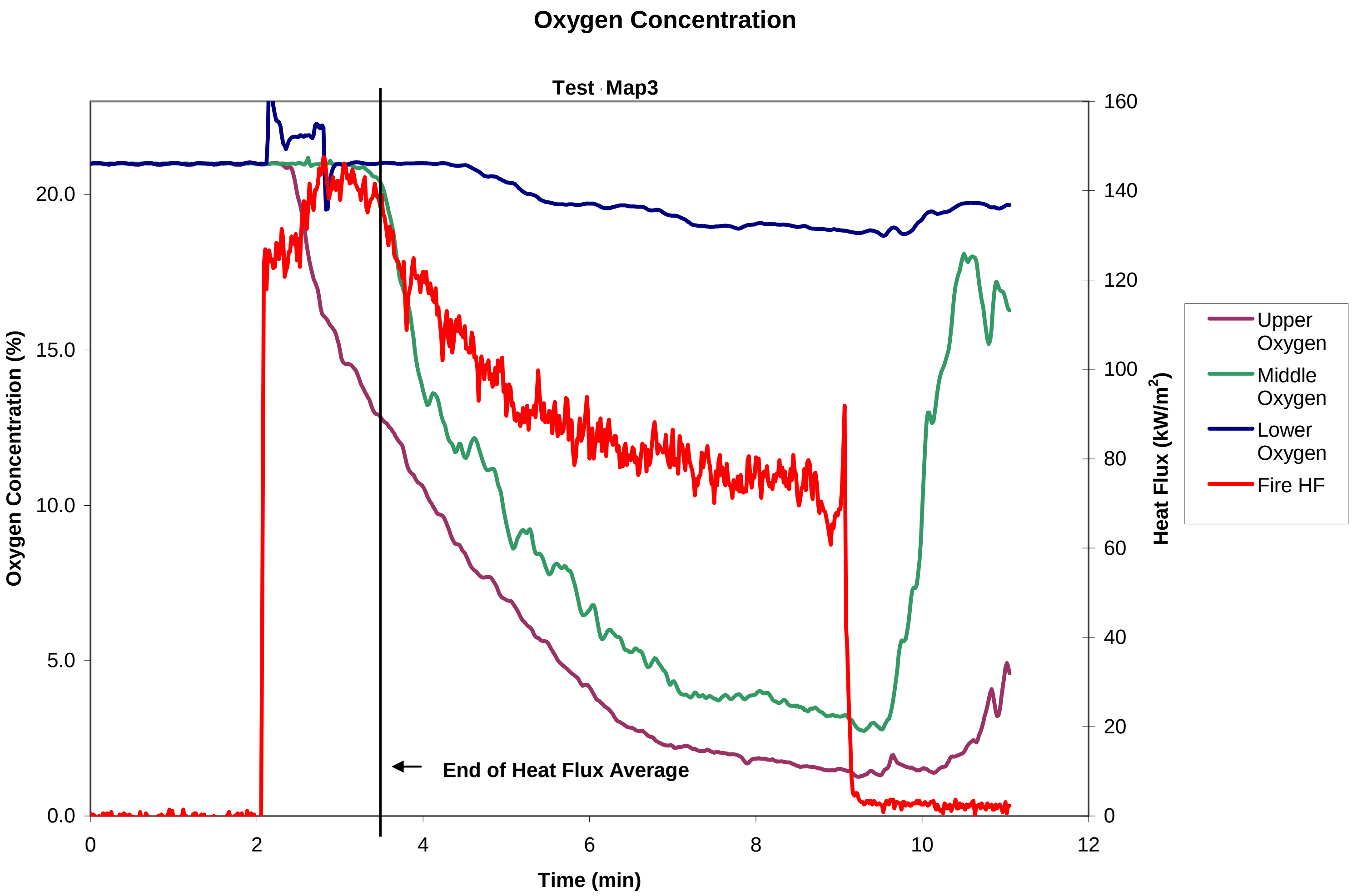


Figure 14. Oxygen Concentration and Heat Flux Plot for the 3.0 MW Fire.

The test conducted with the 6.0 MW spray fire had similar issues with the diminishing oxygen concentration as the 3.0 MW fire. The 6.0 MW spray fire was secured four minutes into the test. Once again, the middle oxygen concentration was used to determine the time period for calculating the average heat fluxes. For the 6.0 MW fire, the data was averaged starting 15 seconds after ignition for a period of 35 seconds (ending 50 seconds after the start of the spray fire). A graph of the oxygen concentration and heat flux is shown in Figure 15.

5.2.2 Heat Flux Mapping Discussion

The heat flux exposures measured in the spray fire flaming region ranged from 65–137 kW/m^2 and increase as a function of fire size (with the exception of the 6.0 MW which the transducer was not exactly in the center of the flame).

The exposures measured horizontally away from the fire were produced primarily by radiation and as a result, the values generally decay as a function of one over the distance squared. The radiant exposures measured 1.1 m away from the fire ranged from 9–38 kW/m^2 and increased as a function of fire size. However, the exposures at a given location did not increase proportional to the increase in fire size as one would expect. This may be a function of the location of the center of the flame moving away form the heat flux transducers for the larger fire sizes.

The heat fluxes measured in the hot layer only exceeded the critical value of 15 kW/m^2 (the flux required to melt most plastic materials) for very large fires (greater than 6 kW/m^3). However, the temperatures in the hot layer exceeded 200^{o}C for most of the fires which would be adequate to cause an agent cylinder to vent its contents.

The conditions measured in the hot layer during these tests are less than what would be expected in an actual machinery space. These tests were conducted in an uninsulated steel box with no forced ventilation. Actual machinery spaces are insulated to an A-60 rating and are well ventilated. The insulation would reduce the wall losses resulting in high temperatures and heat fluxes. Forced ventilation will allow the fire to burn longer by providing additional oxygen to the fire.

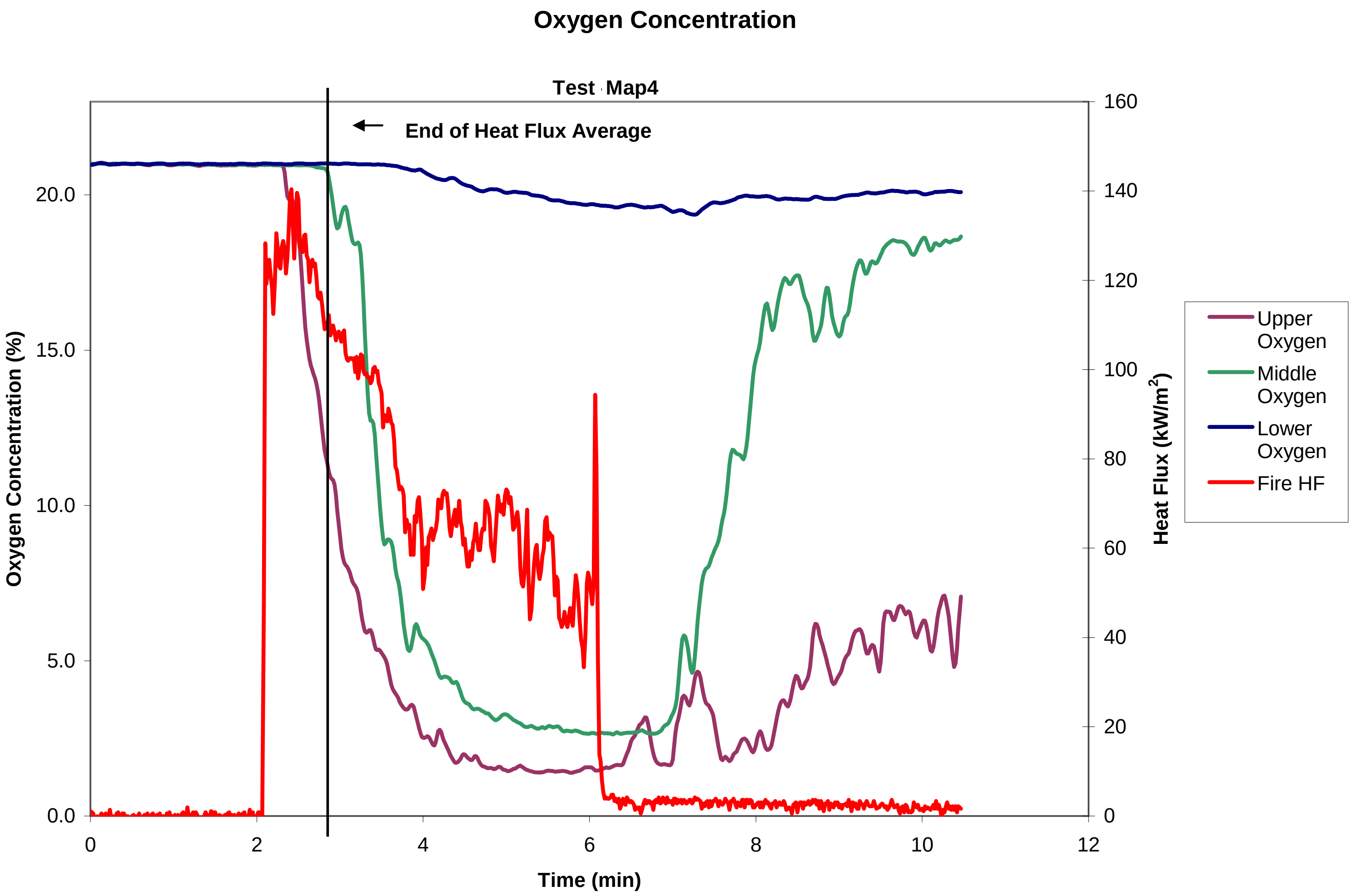


Figure 15. Oxygen Concentration and Heat Flux Plot for the 6.0 MW Fire.

5.3 System Survivability (Application of Results)

The survivability of a gaseous agent system installed in the protected space depends on its ability to withstand both the radiant heat emitted by the fire and the elevated temperatures inside the compartment. These will be discussed in detail in the following sections of this report.

5.3.1 Separation Distance

The minimum separation distance was determined to ensure that a fire located anywhere in the space could not damage more than a single cylinder. The minimum separation distance was determined based on the critical energy dosage resulting in component failure (9 MJ/m^2 was the minimum value identified during the component tests) and the exposures measured during the heat flux mapping tests. Assuming that the cylinders are located low in the space, the primary exposure to the cylinder would be produced by the radiation released by the fire. Assuming a critical energy dosage of 9 MJ/m^2, a typical component could only survive for a period of ten minutes at the critical exposure of 15 kW/m^2. These values served as the basis for this analysis.

The following analysis was conducted as a function of compartment volume to expand the applicability of the results/data. The physics used in the analysis scales proportionally as a function of compartment volume assuming that the compartment ventilation system is designed based on the volume of the space (i.e., based on air changes per hour).

The first step in the process to identify the minimum separation distance was to determine the maximum fire size that would sustain burning in a typical machinery space for a period of ten minutes. Assuming a ventilation rate of ten air changes per hour combined with the amount of air in the space, the maximum fire size that could be sustained for a period of ten minutes is approximately 6 kW/m^3.

The second step was to determine the radiation released by the fire and the radiant exposure as a function of distance away from the fire. The radiant energy output ($\dot{Q}_R$) is given by the radiative fraction, χ_R, multiplied by the total heat release rate of the fire ($\dot{Q}$):

$$\dot{Q}_R = \chi_R \ \dot{Q} \tag{1}$$

The radiative fraction, χ_R, is typically in the range from 0.05 to 0.2 and decreases with increased burning area. For the fire sizes evaluated during these tests, the radiative fraction should be roughly 0.2.

A point source model was then used to predict the radiant exposure as a function of distance away from the fire. A point source model is the simplest configuration model used to predict radiation to a target. More realistic fire shapes give rise to more complex equations and require additional assumptions. The incident radiative heat flux, $\dot{q}''$, predicted by a point source model is given by the following equation:

$$\dot{q}'' = \frac{\dot{Q}_R \cos\theta}{4\ \pi\ R^2} \tag{2}$$

The variable $\dot{Q}_R$ is the total radiative energy output of the fire, θ is the angle between the vector normal to the target and the line of sight from the target to the point source location, and R is the distance from the point source to the target.

Equation 2 was used to define the minimum safe distance between the fire and the cylinder (not the minimum separation distance), by setting $\dot{q}''$ equal to 15 kW/m^2 (the critical exposure for most components containing plastic materials) and solving for distance, R, as a function of compartment volume. The results of these calculations are shown graphically in Figure 16.

As shown in Figure 16, the minimum safe distance between the fire and the cylinder increases with compartmental volume (as one would expect). This increase is related to the increased amount of oxygen available for combustion in the larger machinery spaces (i.e., the size of the fire required to consume the oxygen in ten minutes is larger for the larger spaces).

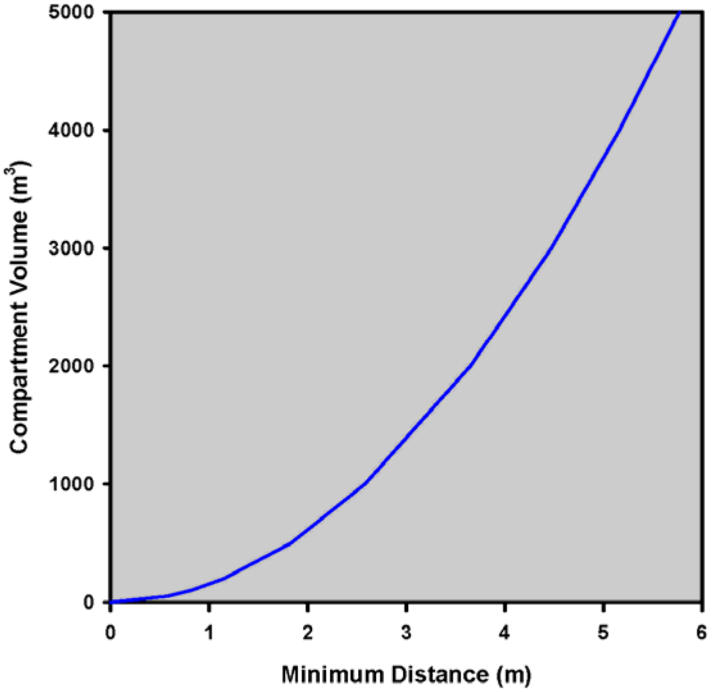


Figure 16. Minimum Safe Distance Between a Gaseous Agent Cylinder and a Fire as a Function of Compartment Volume.

The minimum separation distance between cylinders is determined by multiplying the minimum safe distance by two. More specifically, the cylinders need to be spaced such that a fire located between two cylinders can only damage one of the cylinders.

5.3.2 Elevation

A fire in a compartment will generate a temperature gradient as a function of elevation that can be simply represented by two zones/layers: a hot zone/layer high in the space and a cold zone/layer low in the space. The cold zone/layer remains at near ambient temperature and supplies air (oxygen) to fire to support combustion. The temperature of the hot layer and the portion of the compartment occupied by the hot layer (referred to as the layer depth) is dependant on the ventilation configuration in the compartment, size and aspect ratio of the compartment, the thermal conductivity of the compartment boundaries and the size and location of the fire.

During the heat flux mapping tests performed with the larger fire sizes (3 MW and 6 MW), the temperatures in the upper region of the compartment were greater than 200 °C. These temperatures were limited during these tests by the lack of oxygen to support combustion and the high heat loses through the boundaries (uninsulated steel boundaries). In a shipboard machinery space, the ventilation system would provide additional oxygen to support the fire and would not be secured until the gaseous agent system has been actuated. The affects of these variations (variations between the test conditions and an actual machinery space) can be accounted for using first-order approximations. Utilizing a simplistic analytical model and assuming the space is equipped with a forced ventilation system that provides ten air changes per hour, the hot layer is expected to extend down below the mid-height point with an average temperature exceeding 250 °C for even moderate size fires (3 kW/m^3 or greater). As a result, unprotected (uninsulated) cylinders located high in the space will begin to fail (vent through the safety relief valve) about ten minutes into the event for the majority of the potential/representative fire scenarios. Locating the cylinders low in the space to avoid the hot layer dramatically increases the time the system can survive in the space during a fire.

5.4 Degraded System Capabilities

A degraded system test was conducted to evaluate the extinguishing capabilities of a damaged system (one that is only capable of discharging the minimum extinguishing concentration of agent (cup burner concentration) into the space). The degraded system was tested against a 1.1 MW heptane spray fire located on the side of the diesel engine mockup under the obstruction plate (MSC/Circ. 848 Test Fire 3F). The system was unable to extinguish the fire during this test.

The spray fire temperature, the system operating pressures and the HFC-227ea concentration are shown in Figures 17 through 19. As shown in Figure 17, the system was able to quickly knockdown the fire but was unable to completely extinguish it. The system discharge time of 10.8 seconds and average nozzle pressure of 6.2 bars shown in Figure 18 are within the approved system design limits. The measured agent concentration, given in Figure 19, shows an initial peak near the cup burner value followed by a steady decline in concentration as the agent was consumed by the fire.

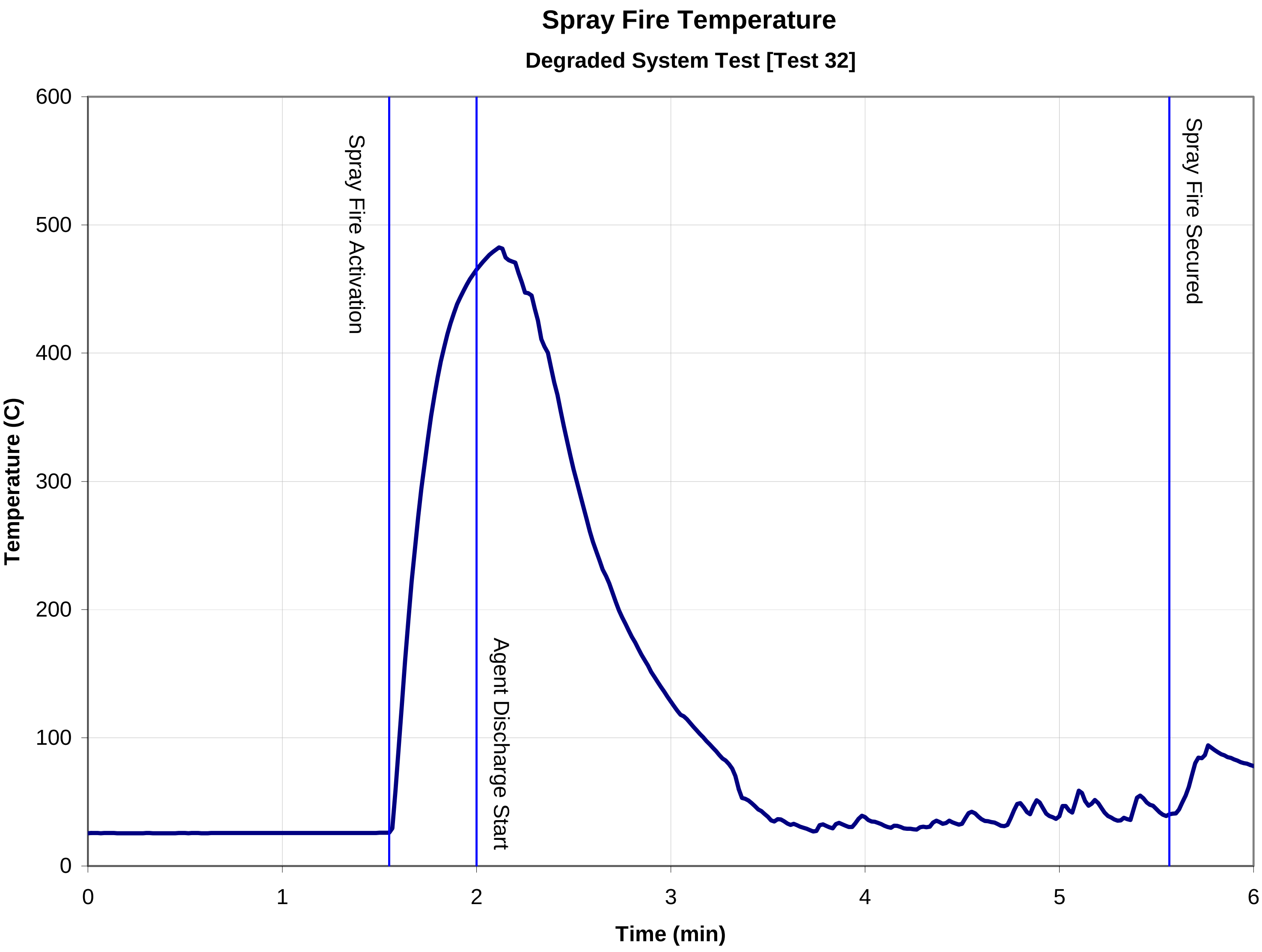


Figure 17. Degraded System Test Fire Temperature Measurements.

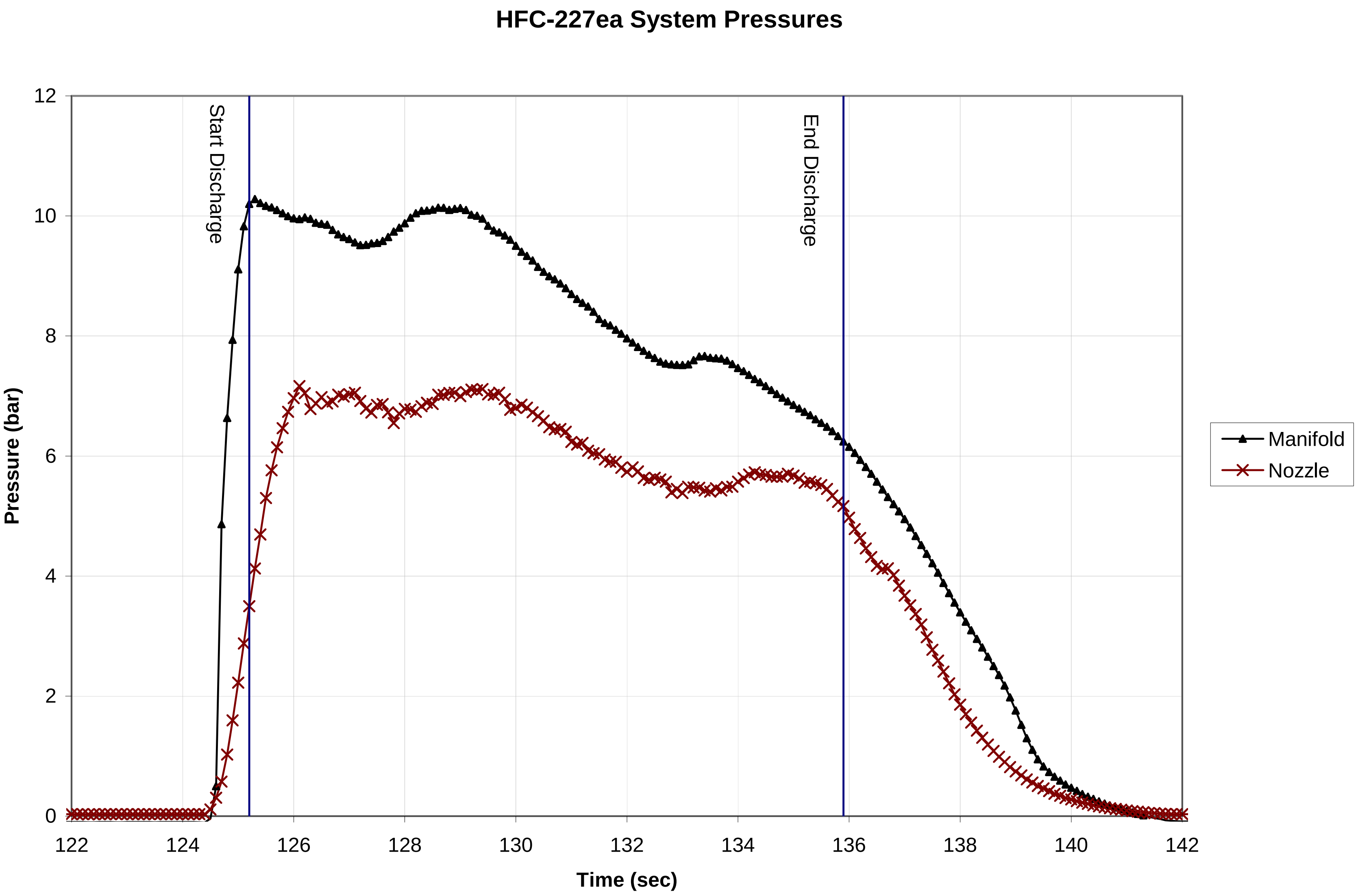


Figure 18. Degraded System Operating Pressure.

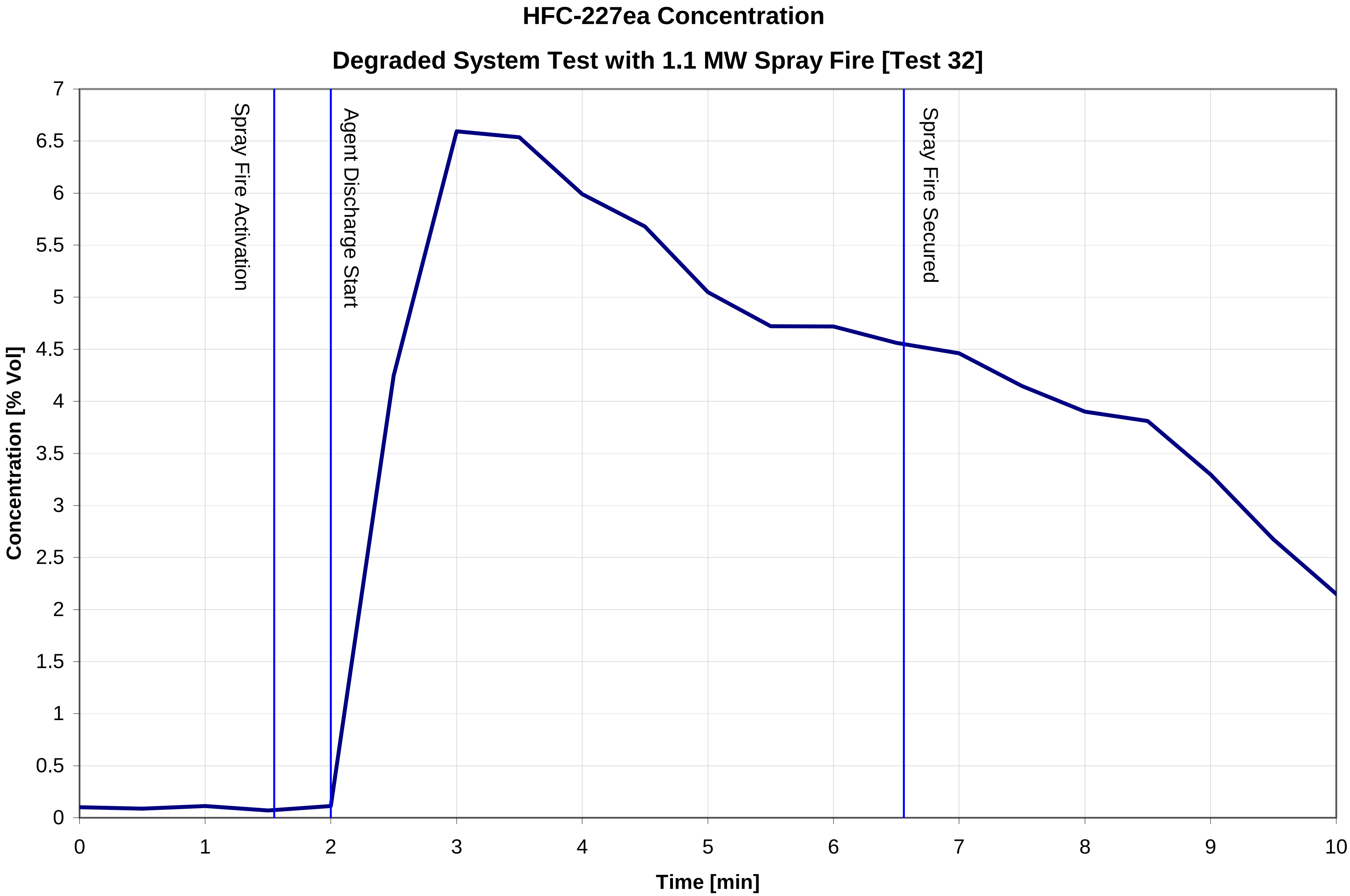


Figure 19. Degraded System Agent Concentration Measurements.

These results of this test demonstrate that the loss of an agent cylinder could render the system ineffective (not able to extinguish the fire). As a result, the system needs to be designed and installed in a manner to ensure that the design concentration of agent (1.3 times the minimum extinguishing concentration) is available at the time the system is activated.

6.0 CONCLUSIONS

A full-scale fire performance evaluation was conducted to assist the USCG in developing a position on the practice of installing a gaseous agent fire extinguishing system within the space it's protecting (machinery space applications). Testing was carried out to identify the potential failure modes of the system and its components.

The evaluation assessed the survivability of a number of halocarbon and inert gas fire suppression system components against a range of potential exposures/conditions. The results suggest that a component containing plastic or rubber parts is likely to fail if the exposure exceeds 15 kW/m^2 and the energy dosage exceeds 9 MJ/m^2. The energy dosage is determined by multiplying the exposure by the duration of the exposure. An analytical assessment of typical agent storage cylinders (various extinguishing agents and cylinder sizes) conducted during this investigation suggests that the pressure relief valves in the cylinders would vent the extinguishing agent with approximately the same exposures/conditions that caused the failure of plastic or rubber parts.

Heat flux mapping tests were also conducted to identify the potential exposures to system components at various locations throughout the space for a range of fire sizes. The results of the mapping and component tests were analyzed to identify situations that could potentially rendered the system ineffective. The assessment identified a safe separation distance between cylinders as a function of compartment volume. The assessment also showed that unprotected cylinders high in the space would begin to fail (plastic parts will melt and pressure relief valves will vent) about ten minutes into the event for a majority of the likely machinery space fire scenarios.

The SOLAS design parameters imply that losing one agent cylinder (the factor of safety) would be acceptable for systems installed in the protected space. More specifically, SOLAS states that the system must still be capable of discharging the minimum extinguishing concentration of agent in the event that one agent cylinder is damaged during the event.

To assess this requirement, an additional test was conducted to determine if a degraded system (one that only discharges the minimum extinguishing concentration of agent) could extinguish a representative machinery space fire. The test was conducted using an unbalanced system designed to discharge the minimum extinguishment concentration of HFC 227each. The system, as tested, was unable to extinguish an obstructed 1.1 MW heptane spray fire on the side of a diesel engine mockup. These results demonstrate that the loss of an agent cylinder will render the system ineffective (not able to extinguish the fire). As a result, the system needs to be designed and installed in a manner to ensure that the design concentration of agent (1.3 times the minimum extinguishing concentration) is available at the time the system is activated.

In conclusion, agent cylinders should only be installed in the space if no other option is available. If cylinders "must" be installed in the protected space, the following design parameters are highly recommended.

- The system needs to be designed and installed in a manner to ensure that the design concentration of agent (1.3 times the minimum extinguishing concentration) is available at the time the system is activated.
- The cylinders should be housed in an A-30 rated steel enclosure within the space.
- System activation lines should be duplicated and run at different locations through the space (reference minimum separation distance defined in this report).

If the cylinders cannot be housed in an A-30 enclosure, the following design parameters are also recommended (in addition to the ones mentioned above).

- Agent cylinders should be located low in the space (preferably at/on the lowest deck level).
- Cylinders should be spaced such that a single fire/event can only damage one cylinder (reference the minimum separation distance defined in this report).
- The system also needs to be activated within ten minutes to ensure that it will not be damaged/degraded by the conditions produced by the fire.

7.0 REFERENCES

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APPENDIX A — DEGRADED HFC-227EA SYSTEM DETAILS

AgentCalcs for HFC-227ea
File Name: C:\Program Files\Hughes Associates\AgentCalcs for HFC-227ea
Calculation Date/Time: Friday, October 13, 2006, 11:03:39 AM

Consolidated Report

Customer Information

Company Name:
Address:

Phone:
Contact:
Title:

Project Data

Project Name:
Designer:
Number:
Account:
Location:
Description: USCG GAFES Degraded HFC-227ea System

Consolidated Report
Enclosure Information

Elevation: 0 m (relative to sea level)
Atmospheric Correction Factor: 1

Enclosure Number: 1
Name: IMO Chamber State of Maine
Enclosure Temperature...
Minimum: 20.0 C
Maximum: 20.0 C
Maximum Concentration: 6.717 %
Design Concentration...
Adjusted: 6.717 %
Minimum: 6.700 %
Minimum Agent Required: 262.3 kg

Width: 10.00 m
Length: 10.00 m
Height: 5.00 m

Volume: 500.00 cubic m
Non-permeable: 0.00 cubic m

Total Volume: 500.00 cubic m

Adjusted Agent Required: 263.0 kg
Number of Nozzles: 2

Consolidated Report
Agent Information

Agent:	HFC-227ea / Propellant N2
Adjusted Agent Required:	263.0 kg
Container Name:	142 L Cylinder
Container Part Number:	90-100350-001
Number of Main Containers:	2
Number of Reserve Containers:	0
Manifold:	Baseline End, 2 Cyls, Horizontal
Pipe Take Off Direction:	Horizontal
Agent Per Container:	131.5 kg
Fill Density:	0.926 kg / l
Container Empty Weight:	91.0 kg
Weight, All Containers + Agent:	445.0 kg
Floor Area Per Container:	0.13 square m
Floor Loading Per Container:	1712 kg /square m

Pipe Network

Part 1 - Pipe

			Pipe			
Description	Start	End	Type	Diameter	Length	Elevation
Main Cyl. X 2	0	1		50 mm	1.30 m	1.30 m
Manifold X 2	1	2	40T	50 mm	0.61 m	0.48 m
Manifold X 1	2	3	40T	80 mm	1.28 m	0.00 m
Pipe	3	4	US40B WS	80 mm	1.00 m	0.00 m
Pipe	4	5	US40B WS	80 mm	1.00 m	-1.00 m
Pipe	5	6	US40B WS	80 mm	0.50 m	0.00 m
Pipe	6	7	US40B WS	80 mm	3.30 m	-3.30 m
Pipe	7	8	US40B WS	80 mm	1.04 m	0.00 m

Consolidated Report

Part 1 - Pipe

Description	Start	End	Type	Diameter	Pipe Length	Pipe Elevation
Pipe	8	9	US40B WS	80 mm	1.50 m	0.00 m
Pipe	9	10	US40B WS	80 mm	5.00 m	0.00 m
Pipe	10	11	US40B WS	80 mm	2.50 m	0.00 m
Pipe	11	12	US40B WS	50 mm	2.50 m	0.00 m
Pipe/E1-N1	12	13	US40B WS	50 mm	0.10 m	-0.10 m
Pipe	11	14	US40B WS	50 mm	2.50 m	0.00 m
Pipe/E1-N2	14	15	US40B WS	50 mm	0.10 m	-0.10 m

Part 2 - Equivalent Length

Start	End	90	45	Thru	Side	Union	Other	Added	Total
0	1	0	0	0	0	0		0.00 m	15.24 m
1	2	0	0	0	0	0	nd FLex Hose...	9.08 m	9.08 m
2	3	0	0	0	2	0		0.00 m	11.40 m
3	4	0	0	0	0	0		0.00 m	1.01 m
4	5	1	0	0	0	0		0.00 m	2.26 m
5	6	1	0	0	0	0		0.00 m	1.74 m
6	7	1	0	0	0	0		0.00 m	4.54 m
7	8	1	0	0	0	0		0.00 m	2.29 m
8	9	1	0	0	0	0		0.00 m	2.74 m
9	10	1	0	0	0	0		0.00 m	6.25 m
10	11	1	0	0	0	0		0.00 m	3.75 m
11	12	0	0	0	1	0		0.00 m	4.60 m
12	13	1	0	0	0	0		0.00 m	0.94 m
11	14	0	0	0	1	0		0.00 m	4.60 m
14	15	1	0	0	0	0		0.00 m	0.94 m

Part 3 - Nozzles

Start	End	Flow	Name	Size	Type	Nozzle Area
0	1	131.5 kg				

Consolidated Report

Part 3 - Nozzles

Start	End	Flow	Name	Size	Type	Nozzle Area
1	2	131.5 kg				
2	3	263.0 kg				
3	4	263.0 kg				
4	5	263.0 kg				
5	6	263.0 kg				
6	7	263.0 kg				
7	8	263.0 kg				
8	9	263.0 kg				
9	10	263.0 kg				
10	11	263.0 kg				
11	12	131.5 kg				
12	13	131.5 kg	E1-N1	50 mm	Metric	1354.84 square mm
11	14	131.5 kg				
14	15	131.5 kg	E1-N2	50 mm	Metric	1354.84 square mm

Parts Information

Total Agent Required: 263.0 kg
Container Name: 142 L Cylinder (Part: 90-100350-001)
Number Of Containers: 2
Manifold: Baseline End, 2 Cyls, Horizontal

Nozzle	Type	Diameter	Nozzle Area	Part Number
E1-N1	Metric	50 mm	1354.84 square mm	
E1-N2	Metric	50 mm	1354.84 square mm	

Nozzle	Drill Diameter	Drill Size
E1-N1	Drill Data Not Found	
E1-N2	Drill Data Not Found	

Pipe:	Type	Diameter	Length
	US40BWS	50 mm	5.20 m

Consolidated Report

Pipe:	Type	Diameter	Length
	US40BWS	80 mm	15.84 m
	40T	80 mm	1.28 m

1 - EL Check and FLex Hose

List of 90 degree elbows:
2 - 50 mm
7 - 80 mm

List of Tees:
1 - 80 mm

System Acceptance

System Discharge Time: 10.0 seconds
Percent Agent In Pipe: 51.0%
Percent Agent Before First Tee: 45.0%

Enclosure Number: 1
Enclosure Name: IMO Chamber State of Maine

Minimum Design Concentration: 6.700%
Adjusted Design Concentration: 6.717%
Predicted Concentration: 6.717%
Maximum Expected Agent Concentration: 6.717% (At 20.0 C)

Nozzle	Minimum Agent Required	Adjusted Agent Required	Predicted Agent Delivered	Nozzle Pressure (Average)
E1-N1	131.2 kg	131.5 kg	131.5 kg	6.515 bar
E1-N2	131.2 kg	131.5 kg	131.5 kg	6.515 bar

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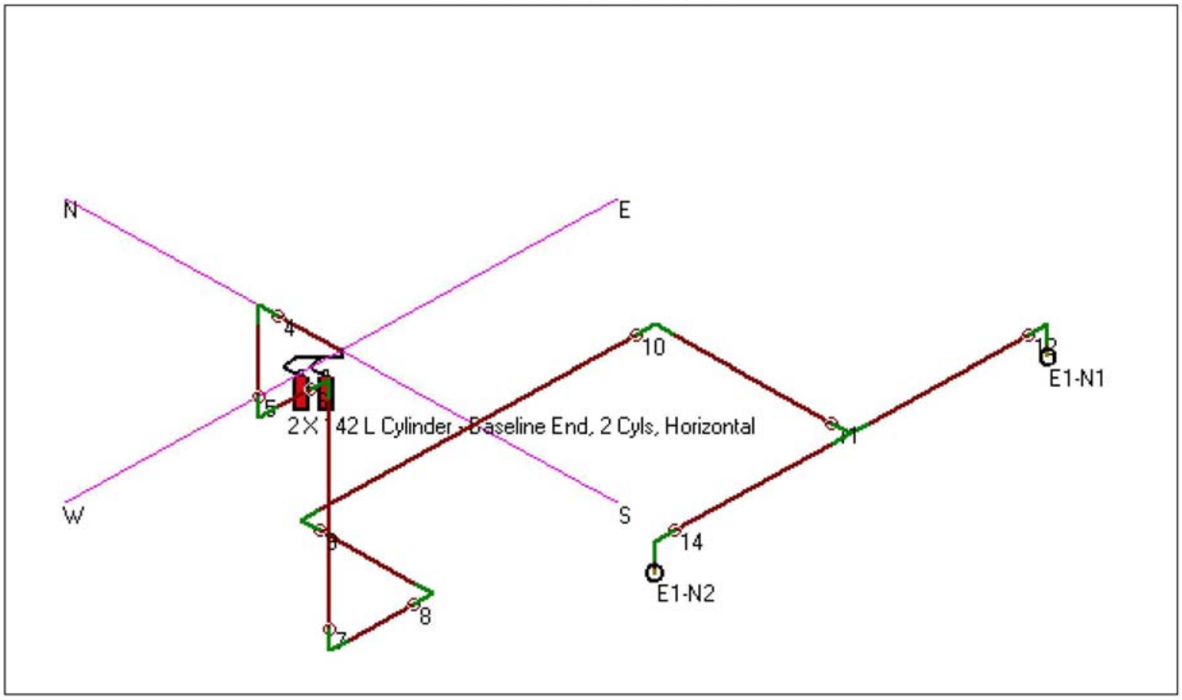
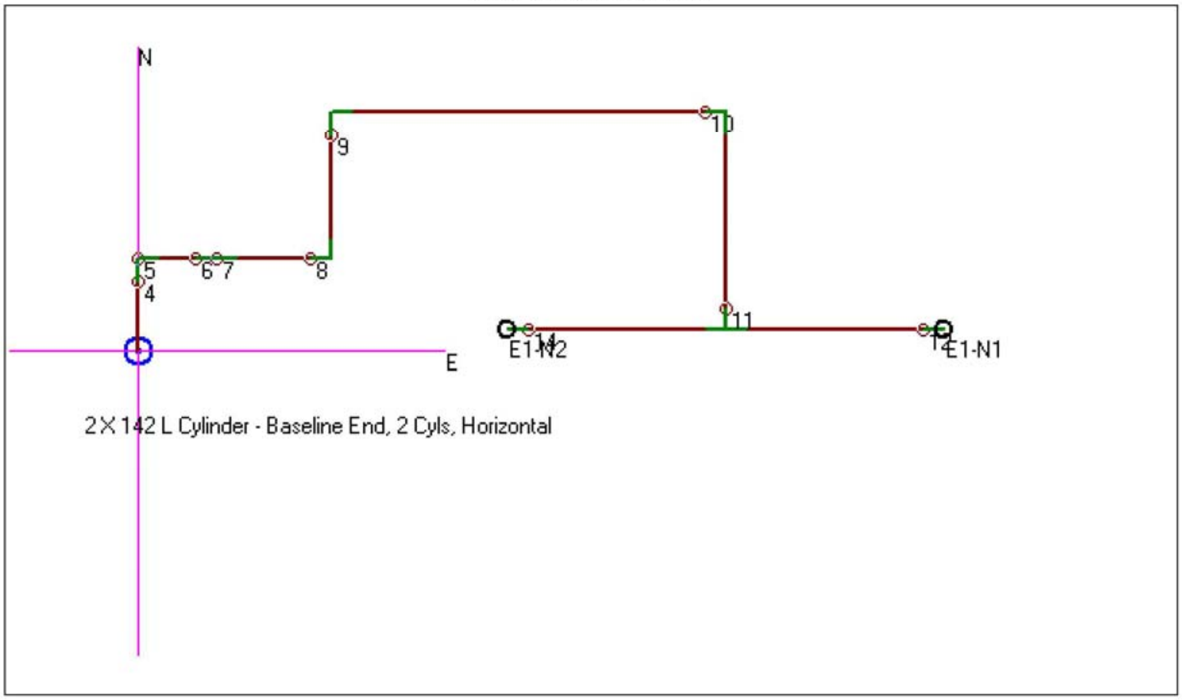
Standard Isometric View



Standard Plan View



Consolidated Report

Standard Elevation View