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HANGAR FIRE SUPPRESSION UTILIZING NOVEC 1230

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14. ABSTRACT
This report describes an investigation of Novec 1230, a total flood agent, for smaller-volume applications to suppress ground-level petroleum fuel fires in aircraft hangars. A 30×30×8-ft concrete-and-steel test structure was constructed for this test series. Four discharge assemblies consisting of a 20-ft manifold with four fan nozzles and a pressurized composite vessel containing the agent were installed, on the sides of the test structure. System discharge parameters---discharge time, discharge rate, and quantity of agent discharged---were adjusted to produce the desired Novec 1230 concentration and retention time in the test structure. Novec 1230 vapor concentrations were monitored using two 3-channel gas analyzers, which verified that agent concentration in the test structure exceeded the required extinguishing concentration for at least 5 min after discharge.

Two fire suppression tests were conducted with the discharge system. The first test involved suppression of an array of 36 cups filled with Jet-A fuel. The second involved suppression of a 4.6-gal, approximately 5-ft diameter, Jet-A pool fire. Both fires were successfully extinguished by the Novec 1230 discharge system. Air measurements during extinguishment showed concentrations of hydrogen fluoride in excess of immediately dangerous to life and health (IDLH) values, indicating incompatibility with Novec's use in occupied spaces. Calculations predict that Novec 1230 may generate ~3x the concentrations of hydrogen fluoride produced from halon agents. Peripheral effects of hydrogen fluoride in the post fire environment were not considered.

15. SUBJECT TERMS
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1. SUMMARY

This report describes an investigation into the potential use of the firefighting agent Novec 1230 in suppressing ground-level petroleum fuel fires in aircraft hangars. Novec 1230 is often employed as a total flood agent, whereby Novec 1230 vapor is discharged into the entire interior space of a structure. In this effort, where the goal was to suppress fuel fires on the floor and prevent reignition until first responders arrive, a system was designed to discharge Novec 1230 vapor at ground level to generate a suppressive layer of Novec 1230 vapor above the floor of a test structure.

A concrete-and-steel test structure measuring 30×30-ft with a height of 8 ft was constructed for this test series. Four discharge assemblies were installed, one on each side of the test structure, each one consisting of a 20-ft manifold with four fan nozzles and a pressurized composite vessel containing the agent. System discharge parameters, such as discharge time, discharge rate, and quantity of agent discharged, were optimized to produce the desired Novec 1230 concentration and retention time in the test structure. Novec 1230 vapor concentrations were monitored using two three-channel gas analyzers, which verified that the Novec 1230 concentration in the test structure exceeded the required extinguishing concentration for at least 5 min after discharge.

Two fire suppression tests were conducted with the Novec 1230 discharge system. The first test involved suppression of an array of 36 small cups filled with Jet-A fuel. The second test involved suppression of a 4.6-gal, approximately 5-ft diameter, Jet-A pool fire. Both fires were successfully extinguished by the Novec 1230 discharge system. Air measurements during extinguishment showed concentrations of hydrogen fluoride in excess of immediately dangerous to life and health (IDLH) values, indicating incompatibility with Novec's use in occupied spaces. Calculations predict that Novec 1230 may generate ~3x the concentrations of hydrogen fluoride produced from halon agents. Peripheral effects of hydrogen fluoride in the post fire environment were not considered.

The results of this project will aid Air Force Civil Engineer Center (AFCEC) personnel in selecting and designing fire protection systems for current and future Air Force hangar facilities.

All tests were carried out at AFCEC Test Range II at Tyndall Air Force Base.

2. INTRODUCTION

Historically, United States Air Force (USAF) hangar facilities have utilized fire protection systems employing aqueous film-forming foam (AFFF) agent. Although effective at extinguishing petroleum-based flammable liquids, AFFF systems have several disadvantages. After discharge, AFFF leaves a residue of salts and surfactant compounds on exposed surfaces. This residue must be removed from aircraft and other equipment before these assets can be brought back into service, which is often a time-consuming and expensive process. In addition, the fluorinated compounds present in AFFF have been the subject of increased regulation due to their environmental impact [1]. In some cases AFFF residue must be collected and disposed of as hazardous waste after a discharge. Also, high-expansion-foam systems generate several feet of thick foam product. This can limit visibility and hinder the movement of first responders into, or of bystanders out of, the affected facility.

A potential alternative to AFFF for fire suppression in an aircraft hangar is Novec 1230 fire protection fluid (hereafter referred to as "Novec"), manufactured by 3M. Although liquid at room temperature, Novec has a low boiling point and a very high vapor pressure and low heat of vaporization. After discharge through the nozzle of a typical fire protection system, Novec rapidly vaporizes and forms a gaseous mixture with air. This mixture of air and Novec has a much higher heat capacity than air alone. At sufficient concentrations, Novec is able to extinguish fires by removing sufficient heat to disrupt the combustion process. As a primary gaseous agent, Novec leaves no residue that would require cleanup, removal, or disposal. Novec has an ozone depletion potential (ODP) of zero and a global warming potential (GWP) of one [2].

Recently, the USAF began replacing halon fire protection systems in its jet engine noise suppressor systems (commonly known as hush houses) with systems employing Novec [3]. All USAF hush houses are scheduled to be refitted with such systems by 2018. These particular systems discharge Novec through overhead nozzles to flood the entire hush house volume with agent. A system recently installed in an 81×65×24-ft high model AF37T-10 hush house discharges 8,210 lb of agent [4]. This quantity of agent costs $145,399.10 at the current GSA Advantage pricing of $17.71/lb. A similar total flood system in an aircraft hangar that contains several times the volume of a hush house would require considerably more Novec.

It was hypothesized an entire hangar may not need to be totally flooded with agent if the primary goal of the fire protection system was to protect against petroleum liquid fires located on the facility floor. As an alternative, the agent could be discharged through nozzles mounted in or in close proximity to the facility floor. Because Novec is significantly denser than air, it would readily spread horizontally over the floor surface but have less tendency to diffuse vertically. The protected space would then extend from the floor to one or a few feet above the floor, depending on application parameters such as nozzle design, quantity, and rate of Novec discharge. This report describes the design of such as system and evaluation in a simulated hangar environment.

The objective of this test series was to determine the effectiveness of Novec at extinguishing floor level Jet-A petroleum fuel fires when discharged through nozzles located near the floor in a localized ground-level application. A small 30×30-ft open-topped steel and concrete test structure was constructed for this test series to simulate a hangar environment.

Novec discharge system performance estimation and test structure design were based on the results of multidimensional modeling and simulation (M&S) using AFT Fathom for one-dimensional (1-D) computational hydraulic fluid systems modeling and ANSYS Fluent for three-dimensional (3-D) computational fluid dynamics (CFD) modeling of the complex non-adiabatic, multiphase, multispecies test environment. The discharge apparatus was designed to entrain a gaseous mixture of Novec with air to achieve a desired Novec concentration and distribution within the 30×30-ft test structure.

The discharge apparatus employed in this test series was designed as a proof of concept and is not meant to be representative of a system that would be installed in a full-sized hangar. In an actual hangar, the quantity and design of nozzles along with their respective application parameters would be optimized for the larger environment. Also, if the hangar doors were open it is likely that the gaseous Novec 1230 agent would be less effective, as the Novec would be only partially contained and able to diffuse out of the protected space. A mechanism to automatically close the hangar doors before discharge of Novec may be essential for optimal agent performance. However, such a mechanism to automatically close hangar doors may be hazardous to personnel and equipment, so the final solution will need to balance risks.

Overall, the results of this project will aid Air Force Civil Engineer Center (AFCEC) personnel in selecting and designing fire protection systems for current and future Air Force hangar facilities.

All tests were carried out at AFCEC Test Range II at Tyndall Air Force Base.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1. Definitions

The following terms are commonly used when describing gaseous firefighting systems and agents. For purposes of this report these terms will be defined as follows:

- **Protected Space**: The region of space in which flame is suppressed by the suppression system and agent. Because the Novec system is tasked with suppressing ground level jet fuel fires, the protected space in the test structure was defined as the volume of space from floor level to 1-ft height in the entire 30×30-ft test structure.
- **Extinguishing Concentration**: The minimum concentration of a gaseous agent required to extinguish a particular solid or liquid fuel. Common jet fuels including JP-4, JP-8, and Jet-A have an extinguishing concentration of 4.15 percent Novec [4], as determined by cup burner experiments.

3.2. Performance Criteria

USAF aircraft hangars are typically protected by fire protection systems employing the AFFF agent. The primary performance criteria for the Novec discharge system described in this report is to meet or exceed the performance of these AFFF discharge systems. A recent evaluation of Air National Guard fire protection listed the following concerning AFFF hangar systems:

- **Discharge Time**: Once flow begins, it takes high-expansion-foam systems approximately 1 min for AFFF to cover the floor space occupied by aircraft. A further, unspecified time is required to cover the entire hangar floor space.
- **Suppression Duration**: A hangar fire protection system must limit or prevent damage to the aircraft for a minimum of 4 min, the expected response time of firefighting personnel.

The prototype Novec discharge system described in this report is therefore expected to meet or exceed these requirements, specifically coverage of the protected space in 1 minute and suppression of fire in the protected space for at least 4 min.

Novec is most commonly used in a total-flood extinguisher system. The established standard for design of such a system is the National Fire Protection Association (NFPA) *2001 Standard on Clean Agent Fire Extinguishing Systems*. NFPA 2001 provides the following requirements for the protected space in a total flood system:

- **Design Concentration**: For class B fires, the agent must reach a concentration in the protected space (termed the "design concentration") equal to 1.3 times the extinguishing concentration. (Common jet fuels including JP-4, JP-8, and Jet-A have a cup burner extinguishing concentration of 4.15 percent Novec; consequently, the resulting design concentration for Novec is 5.40 percent).

- **Discharge Time**: The protected space must reach 95 percent of the design concentration (5.13 percent) within 10 s.
- **Retention Time**: The concentration of agent in the protected space must not fall below 85 percent of the design concentration (4.59 percent) for at least 10 min to prevent re-ignition of the fire.

Although Novec is not being used as a total flood agent in this application, these requirements were used as additional guidelines during development of the Novec discharge system, specifically that Novec must reach a design concentration of 5.40 percent, and not fall below 4.59 percent for the 4-min suppression period. Note that the NFPA discharge time (10 s) and retention time (10 min) requirements exceed the primary performance criteria goals for this effort (1 min and 4 min, respectively).

3.3. Quantity of Novec Required

The minimum quantity of Novec required to achieve the design concentration of 5.40 percent in the 30×30×1-ft protected space can be estimated using the method provided in NFPA 2001 section A.5.5.1:

$$W = (V / S) \times (C / (100 - C))$$

And

$$S = 0.0664 + 0.0002741 \times T$$

Where:

W = weight of Novec required (kg)
V = volume of protected space (m^3)
S = specific vapor volume of Novec (m^3/kg)
C = design concentration (%)
T = temperature in protected space (ºC)

Using the above method and assuming a temperature of 20 ºC results in a requirement of 20.24 kg (44.61 lb) of Novec. While this method can accurately estimate the quantity of Novec required to protect an enclosed space in a total flood application, it should be considered a lower limit on the quantity required in a "limited flood" application. Although Novec is a heavier-than-air gaseous agent, over time the Novec will diffuse vertically in the structure, due to momentum imparted by the discharge process and natural diffusion from regions of higher to lower concentration. Novec that diffuses vertically above the height of the test structure walls can flow over the walls and out of the test area. This would result in a concentration gradient of Novec, high at the floor level, approaching zero above the test structure, and which would drop over time as Novec was lost from the test structure.

An upper limit design goal of one-third or less of the Novec required for an equivalent total flood application was pursued for this effort to demonstrate the potential for significant cost savings. Assuming a conservatively low average hangar ceiling height of 30 ft at a temperature of 20 ºC similarly to lower limit conditions, a *de facto* upper-limit Novec mass requirement of 202.4 kg (446.1 lb) for the test structure was established.

3.4. CFD Modeling

Computational fluid dynamic (CFD) modeling & simulation (M&S) of the test environment was conducted prior to experimentation. M&S was performed to determine if Novec could be discharged within the established mass limits to reach and maintain the design concentration within the protected space for the retention time desired.

A 3-D Novec spray-evaporation CFD model was developed using ANSYS Fluent, a commercial CFD software product capable of modeling complex thermal and fluid dynamics. The model was used to simulate the Novec discharge spray pattern and the conversion of Novec liquid droplets into the gaseous phase while mixing with the atmosphere. These simulations were first used to determine if the proposed limited flood application was plausible. Once confirmed, the CFD modeling approach was used to optimize Novec discharge settings by maximizing Novec phase conversion efficiency while minimizing Novec mass loss beyond the protected space.

The Novec spray-evaporation CFD model was based on a multiphase, Euler–Lagrange frame-work. The atmosphere was treated as a primary, continuous gas phase (Eulerian field) by solving the unsteady Reynolds-averaged Navier–Stokes equations throughout the 3-D fluid domain. The Novec spray was treated as a secondary, dispersed (Lagrangian) liquid droplet phase traveling through the Eulerian field. The primary and secondary phases were physically coupled in terms of mass, momentum, and energy exchange. The evaporation rate of liquid Novec was governed by the localized thermal and fluidic state of Novec and air. This modeling strategy is common when the primary phase is composed of a gas species mixture and the secondary dispersed phase occupies approximately 10 percent or less of the volume of the fluid domain. Large droplet-to-air mass ratios are acceptable and still allow for numerically robust simulations. Accurate Novec material properties were critical to achieve reliable and relevant simulation results. Novec properties were taken from the NIST Reference Properties Database (REFPROP) v9.1 and confirmed via private communication with 3M personnel. Key Novec properties at 25 °C are listed in Table 1. Properties that exhibited a strong dependence on temperature at or near atmospheric conditions were defined as polynomial or piecewise-polynomial functions of temperature.

Table 1. Summary of Key Novec Thermofluidic Properties @ 25 ºC

Property	Value
Molecular Weight	316.05 kg/mol
Boiling Point	49.2 °C
Critical Temperature	168.66 °C
Critical Pressure	1865 kPa
Liquid Density	1605 kg/m^3
Liquid Specific Heat @ 25 ºC	1.103 kJ/(kg-K)
Liquid Thermal Conductivity @ 25 ºC	0.0588 W/(m-K)
Liquid Surface Tension @ 25 ºC	10.8 dyne/cm
Liquid Viscosity @ 25 ºC	0.524 cp
Vapor Specific Heat @ 25 ºC	0.891 kJ/(kg-K)
Vapor Thermal Conductivity @ 25 ºC	0.0049 W/(m-K)
Vapor Viscosity @ 25 ºC	1.16e-5 kg/(m-s)
Vapor Pressure @ 25 ºC	40.36 kPa
Liquid Surface Tension @ 25 ºC	10.8 dyne/cm

A 30×30-ft floor space enclosed by a 4-ft high retention wall was proposed as the test structure. This 900-ft^2 floor area was chosen to maintain the order of fluid space and time scale magnitudes associated with a real hangar environment, while attempting to conserve agent cost. The 4-ft wall height was proposed to reduce fabrication challenges by using standard 8×4-ft carbon steel sheet metal for most of the construction. Initial simulations were executed employing four- and eight- nozzle spray configurations to study general Novec discharge performance and to predict the overall flow behavior and Novec gas retention patterns. These layouts are illustrated in Figure 1. A range of Novec discharge flow rates, pressures, and initial nozzle exit droplet diameters were examined to optimize spray conditions. These parameters were also guided by the performance envelopes of existing Novec total flood fire suppression systems.

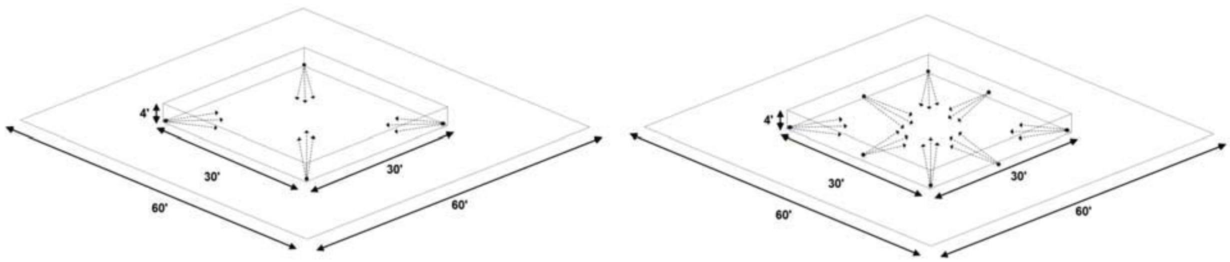

Figure 1. Four Nozzle Discharge Configuration (Left) and Eight Nozzle Discharge Configuration (Right)

Figure 2 illustrates Novec gas concentration simulation results viewed from the vertical plane of an upper mass limit discharge using an eight-nozzle configuration to dispense approximately

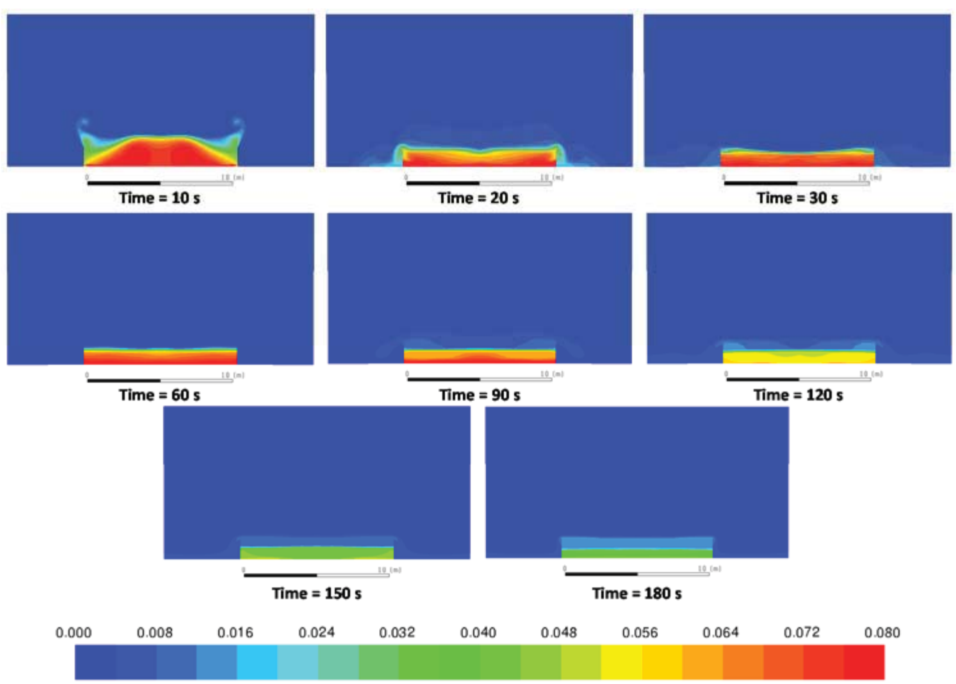

Figure 2. Predicted CFD Vertical-Plane Novec Gas Concentration Contours [Mol/Mol] Over Time for Upper Limit Novec Discharge Conditions

200 kg (440 lb) of Novec over a 10-s period. Figure 3 shows similar contour data as Figure 2, but from the view of the spray plane with Novec liquid spray droplets overlaid at the end of discharge.
Figure **4** and
Figure **5** illustrate velocity magnitude and Novec gas density also at the end of discharge. Figure 6 shows the predicted maximum, average, and minimum Novec concentration within the protected space as a function of time. Peak Novec concentration was approximately 10 percent (0.1 mol/mol), and remained over the NFPA minimum discharge requirement for nearly 3 min.

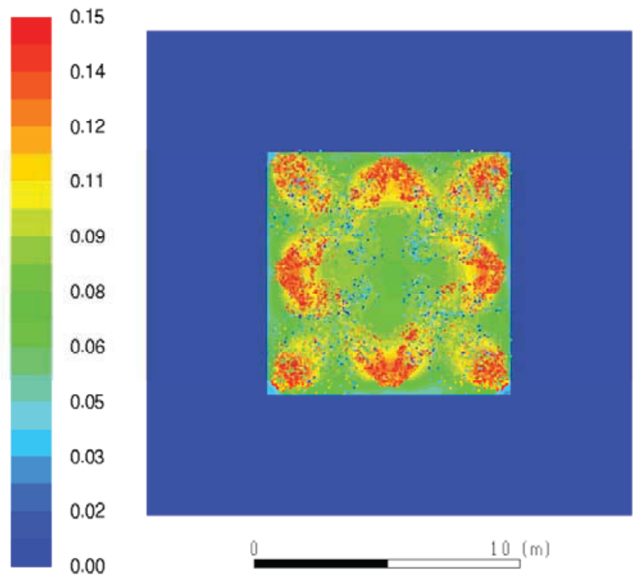

Figure 3. Predicted CFD Spray-Plane Novec Gas Concentration Contours [mol/mol] Overlaid with Novec Liquid Spray Droplets, Color in Relative Descending Size at *t*=10 s

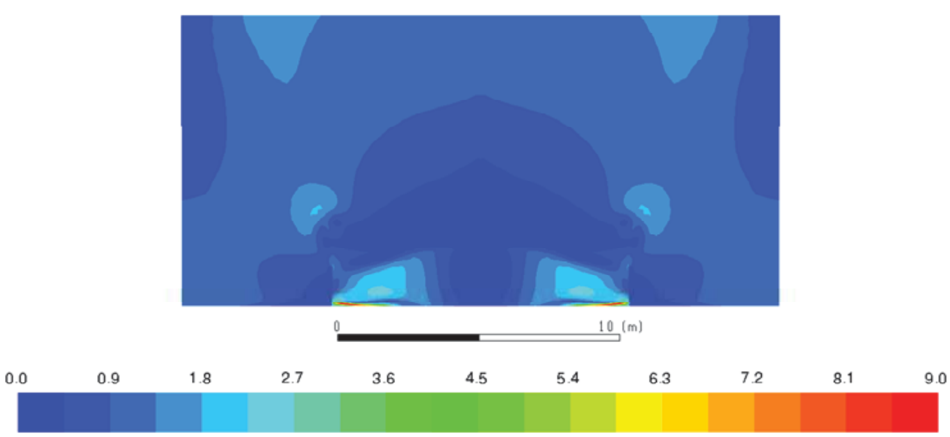

Figure 4. Predicted CFD Vertical-Plane Velocity Magnitude Contours [m/s] at *t*=10 s

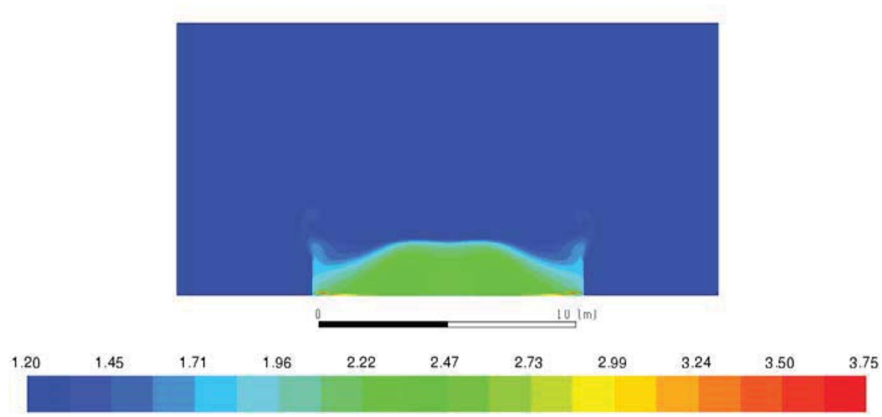

Figure 5. Predicted CFD Vertical-Plane Gaseous Density Contours [m/s] at *t*=10 s

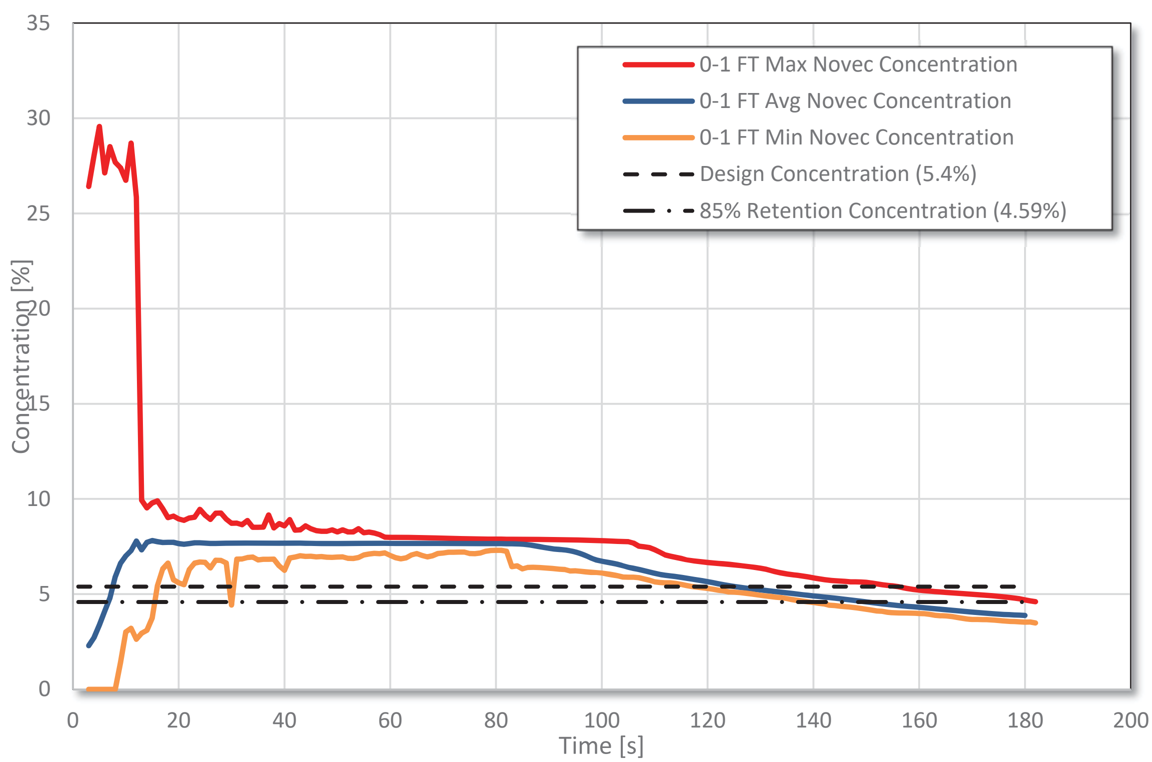

Figure 6. Predicted CFD Novec Gas Concentration over Time for Upper Limit Novec Discharge Conditions in the Protected Space Region

The following design guidelines for the Novec discharge system were determined based on CFD M&S results:

- **Jet Momentum:** The quantity of Novec discharge nozzles should be practically maximized to minimize individual nozzle flow rate, jet momentum, vertical turbulent gaseous diffusion into the atmosphere, and Novec gas spillage over the retention wall. The presence of the Coanda effect between the spray and test floor causing jet attachment was confirmed by M&S for relatively high-momentum sprays in very close proximity to the floor. Thus, a minimum jet momentum and height above the floor should be established to minimize Novec loss due to floor wetting. M&S determined a nozzle pressure range of 75 to 125 psi and a floor stand-off distance of 8 in or greater to achieve this compromise.

- **Jet Droplet Size:** M&S confirmed an average arithmetic Novec liquid droplet diameter between approximately 100 and 250 μm provided the best balance of droplet surface area to achieve an acceptable evaporation rate versus droplet mass to reach the trajectory magnitudes of interest for the present test structure.
- **Nozzle Shape:** M&S demonstrated flat fan spray nozzles versus conical spray nozzles minimized floor-spray wetting and 3-D flow interaction by comparison, particularly in adjacent spray regions. It was shown that the wider the flat fan spray angle, the greater Novec gas concentration uniformity was achieved, specifically near retention walls.

3.5. Test Structure

All tests were carried out at AFCEC Test Range II in building 9500E at Tyndall Air Force Base. This building measures approximately 80×80-ft. Due to the high cost of Novec and structural features of this facility, it was not practical to discharge sufficient Novec to flood the entire floor space to reach the desired concentration of Novec. Instead, a test structure was constructed within the building. An illustration of this structure is presented in Figure 7.

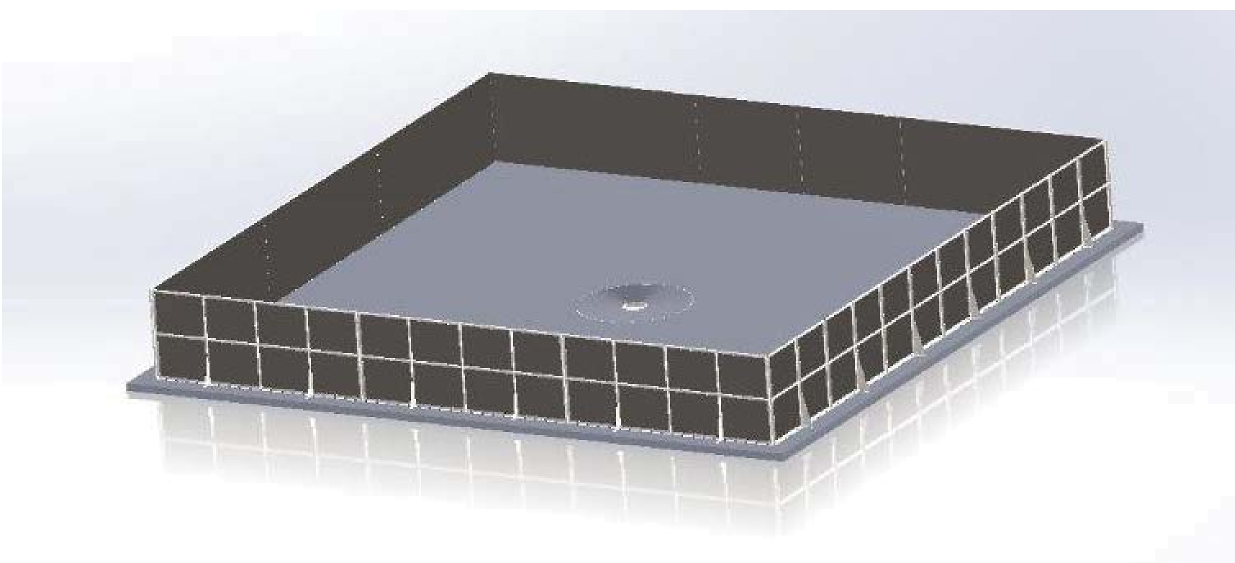

Figure 7. Illustration of the Test Structure

The base of the test structure consists of a 32×32-ft × 3.75-in concrete pad. The pad served as a barrier between the fuel spills and the facility floor, and to protect the floor from any damage caused by fires conducted during the test series. The concrete used to form the pad was blended with the protective polymer product BarChip structural synthetic fiber manufactured by Elasto Plastic Concrete. This polymer additive is used to help protect the concrete from cracking and spalling when exposed to heat from the jet fuel fires.

The concrete pad included a 5-ft diameter by 1.9-in deep conical depression in the center of the pad, a feature commonly described as a birdbath. This conical depression was used to contain the Jet-A fuel in the pool fires performed during this test series. This depression could accommodate pool fires up to 5-ft in diameter. The approximate quantity of fuel required to produce a given size pool fire is presented in Table 2.

Table 2. Volume of Fuel Required to Produce a Pool Fire of a Given Diameter

Pool Fire Diameter (ft)	Volume of Fuel (gal)
2	0.5
3	1.7
4	4.0
5	7.7

A 30×30×4-ft wall was constructed around the perimeter of the concrete pad to contain the Novec discharged into the test structure. This wall was constructed using 16-gauge (approximately 0.06-in thick) steel plates mounted on a frame composed of 1.5×1.5×0.125-in thick steel angle beams. Duct tape was used to seal any openings or gaps between the steel plates, and along the floor between the plates and concrete pad, to minimize Novec leakage out of the structure during testing. Figure 8 is a photograph of the test structure.

Figure 8. Initial Version of the Test Structure

After several Novec discharges were performed near the lower to middle discharge range as defined in section 3.3. , it was noted that peak Novec concentration and retention time were not reaching design goals. It was theorized that more Novec was being lost over the 4-ft walls than was expected based upon the simulation results. To test this theory, an extension consisting of plastic sheeting suspended from a wood frame was added to the test structure walls, which extended the wall from 4-ft to 8-ft height. Subsequent tests indicated that this extension significantly improved the retention time of Novec in the test structure at the 1-ft level. Although it was originally intended to be temporary, trial fires within the structure revealed that the plastic sheeting was not damaged by fires of the size scheduled to be performed later in the test series. It was therefore decided to leave the wall extensions in place for the remainder of the test series. Figure 9 shows a photograph of the final version of the test structure.

Figure 9. Final Version of the Test Structure with Extended Walls

3.6. Small Fire Test Cups

The conical depression at the center of the concrete pad could accommodate up to 5-ft diameter jet fuel pool fires. It was also of interest to conduct tests using smaller fires, or fires in locations other than the center of the concrete pad. Smaller fires would demonstrate the ability of Novec to extinguish fires in their infancy, while alternate locations would demonstrate the ability of Novec to diffuse throughout the protected space. 36 cylindrical steel cups, measuring approximately 4-in diameter by 2-in height, were used for small fire testing. The cups were arranged in a six by six grid, equally spaced within the test structure. During testing, each cup was filled with 150 mL of water and 120 mL of Jet-A fuel. Control fires under these conditions burned in excess of 10-min when allowed to burn to completion. Photos of a cup before and during a fire test are shown in Figure 10.

Figure 10. A Cup before (Left) and during (Right) a Fire Test

3.7. Discharge Apparatus

Novec was discharged into the test structure through four identical discharge apparati, one located on each side of the structure. Each system consisted of a 45-gal composite pressure vessel (Pentair structural composite pressure vessel model CH31573) positioned outside of the test area that contained the liquid Novec agent and nitrogen gas at a pressure of up to 150 psi. Photographs of one composite pressure vessel appear in Figure 11.

Figure 11. A Composite Tank Positioned on a Platform Scale (Left) and Detail of Top of Tank Displaying (From Left to Right) Nitrogen Inlet Hose, Bleed Valve, Pressure Transducer, Pressure Gauge, and Novec Inlet Tube (Right)

Each pressure vessel was connected to a manifold equipped with multiple flat fan spray nozzles that penetrated the walls of the test structure. An electric ball valve was installed at each nozzle to enable controlled initiation and termination of the flow of Novec. Each Novec reservoir was placed on a platform scale (Arlyn Scales platform scale model 320M-48) to monitor the flow of Novec during tests. Omega engineering pressure transducers (Omega model PX605-300GI) and flow meters (Siemens Coriolis flow meter model SITRANS-FC430) were placed at several points in the system to monitor discharge performance. All ball valves, pressure transducers, and scales were connected to a central data acquisition and control computer. Figure 12 shows an illustration of the test structure and four discharge apparatus.

Design optimization of the discharge manifold was performed using the AFT Fathom Pipe Flow Analysis and System Modeling Software Package. This permitted evaluation of the anticipated pressure drops in the manifold based on the discharge flow rate to ensure that the desired spray characteristics obtained from CFD modeling could be achieved. An example analysis of one iteration of the manifold design is presented in Figure 13.

The final design consisted of a 22.5-ft long by 1.25-in diameter manifold connected to the composite tank by a 1.5-in diameter flexible tube. Four nozzle assemblies were positioned at 7.5-ft intervals along the manifold. Each nozzle assembly consisted of a 0.5-in pipe equipped with an electric ball valve, pressure gauge, and nozzle. Photographs of one manifold are shown in Figure 15, and Figure 14 is an illustration of one manifold.

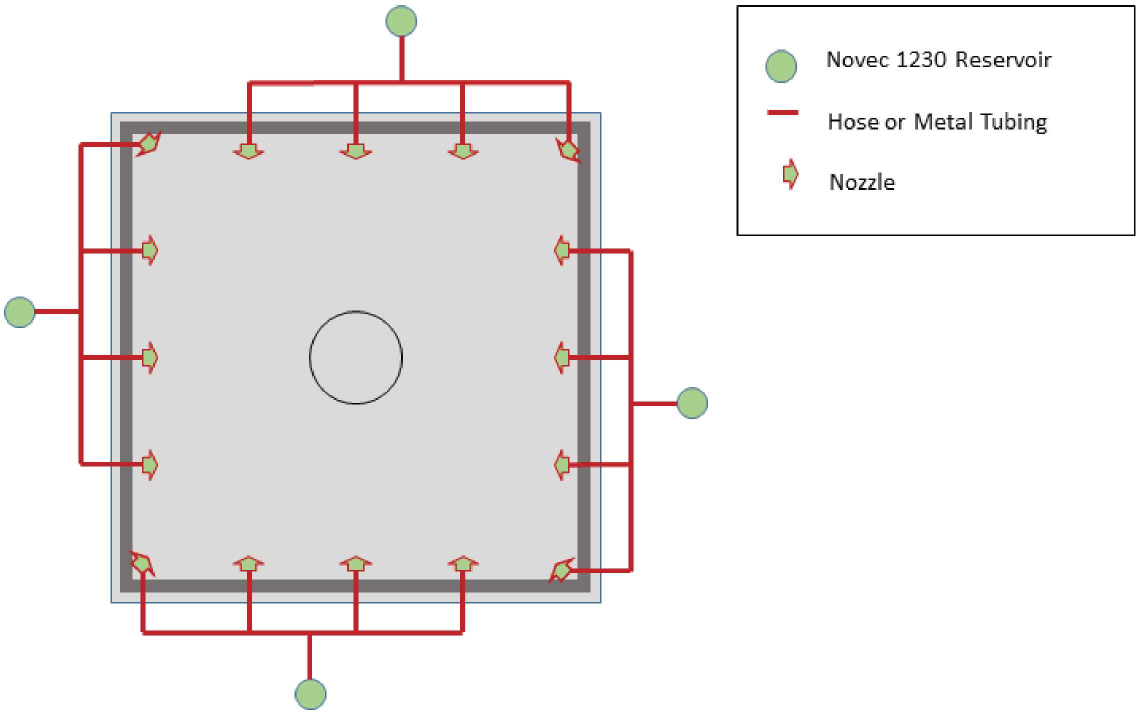

Figure 12. Overhead Illustration of the Novec Discharge System

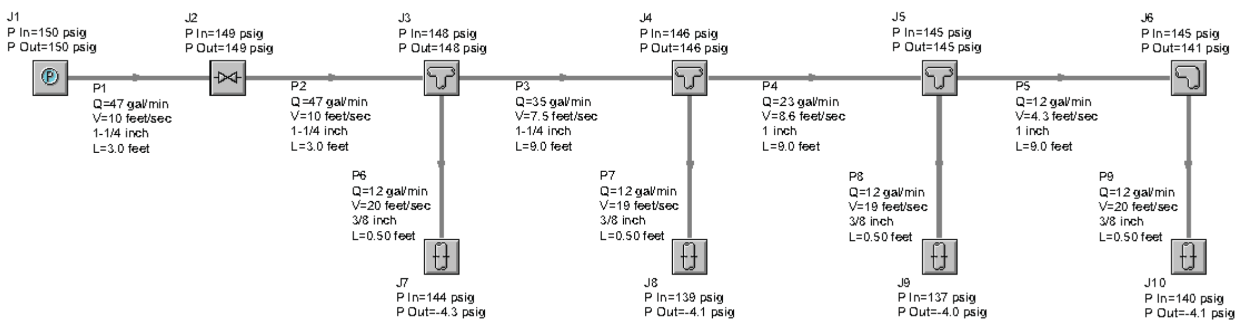

Figure 13. Example of Analysis of One Manifold of the Novec Discharge System Using the AFT Fathom Pipe Flow Analysis and System Modeling Software Package

Figure 14. One Discharge Manifold Viewed from Two Angles

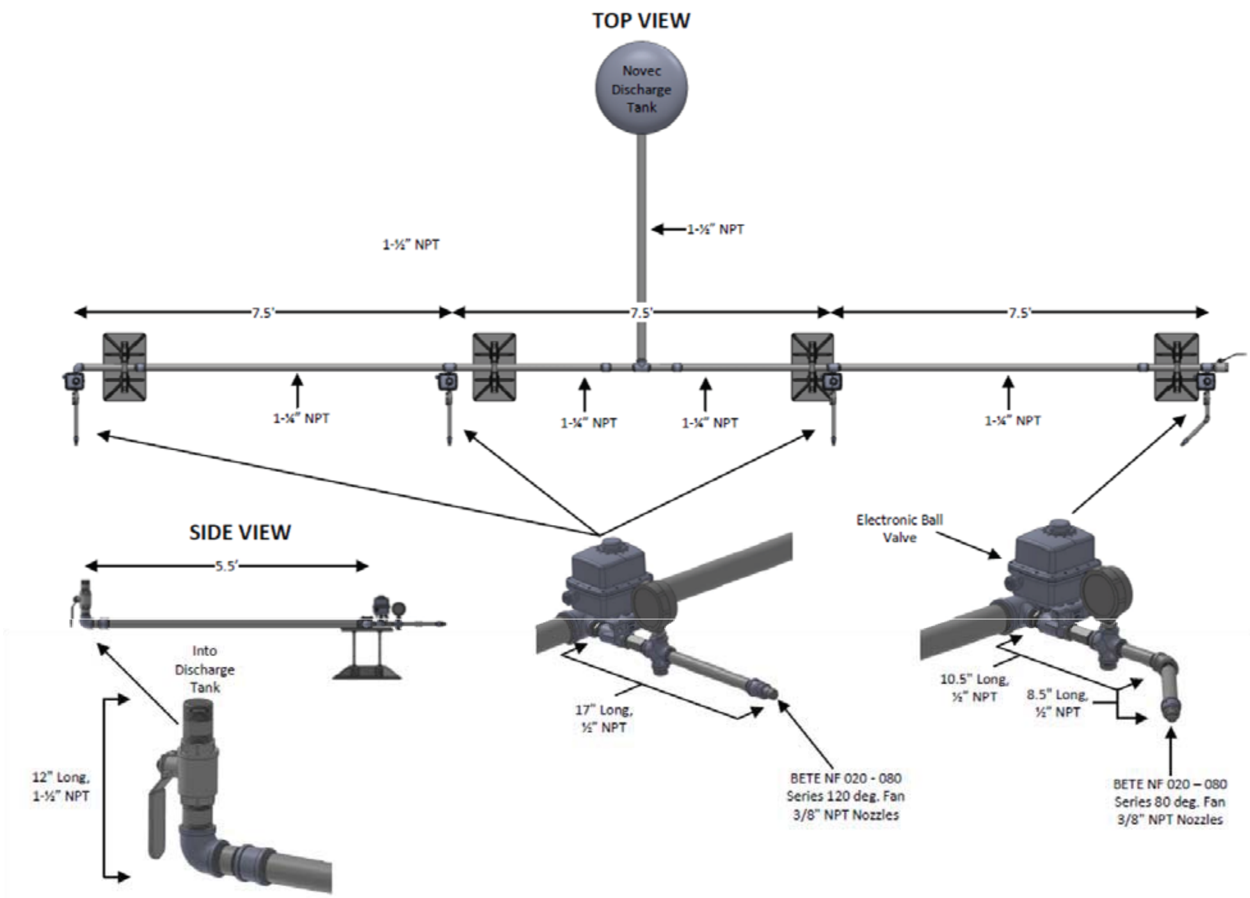

Figure 15. Illustration of One Manifold of the Novec 1230 Discharge System

3.8. Nozzles

A number of BETE brand name type NF standard fan nozzles were obtained for evaluation. Pictures of a BETE nozzle and a nozzle mounted in a discharge manifold in the test structure are shown in Figure 16.These were chosen because they were available in a wide range of orifice sizes and spray angles which allowed flexibility in flow rate and discharge pattern. In total, NF20, NF40, NF50, NF80, NF90, NF100, and NF120 size nozzles in 65-, 80- and 120-degree spray patterns were obtained for evaluation. Note that the nozzle size number is only relative and does not represent any physical dimension.

Figure 16. BETE Fan Nozzle (Left). BETE Fan Nozzle Installed in the Test Structure (Right)

After initial trial discharges with water, it was determined that 80-degree nozzles in the four corner positons and 120-degree nozzles in the twelve wall positions produced the desired spray pattern. These nozzles were then used to optimize Novec discharge conditions in later tests.

3.9. Measurement of Novec Gas Concentration

Two Tripoint Instruments brand model 123 dual gas analyzers were used to measure Novec concentrations in the test structure during discharge. Gas analysis was performed to determine if concentration objectives were met, to verify that Novec was diffusing to all areas of the structure, and to validate results from the CFD modeling. These analyzers were factory calibrated for two gasses, Novec and carbon dioxide (which was not measured during this project) in air. The presence of additional gasses, including combustion products from burning jet fuel, would cause the instruments to read incorrectly and could damage the instrument. Therefore, they were used only during discharge tests that did not involve a fire. A photograph of the two Tripoint gas analyzers is presented in Figure 17.

Figure 17. Two Tripoint Gas Analyzers

Each of the two gas analyzers had three input channels affording a total of six simultaneous measurements within the test structure. Two poles were placed within the test structure, one in the center of the structure and one adjacent to one wall between two nozzle positions. Three gas sampling points were located on each pole, at a height of 1-, 3-, and 5-ft. Figure 18 shows the locations of the six sampling points for gas analysis. Gas analysis was initiated several minutes before agent discharge and continued for at least 10 minutes after discharge.

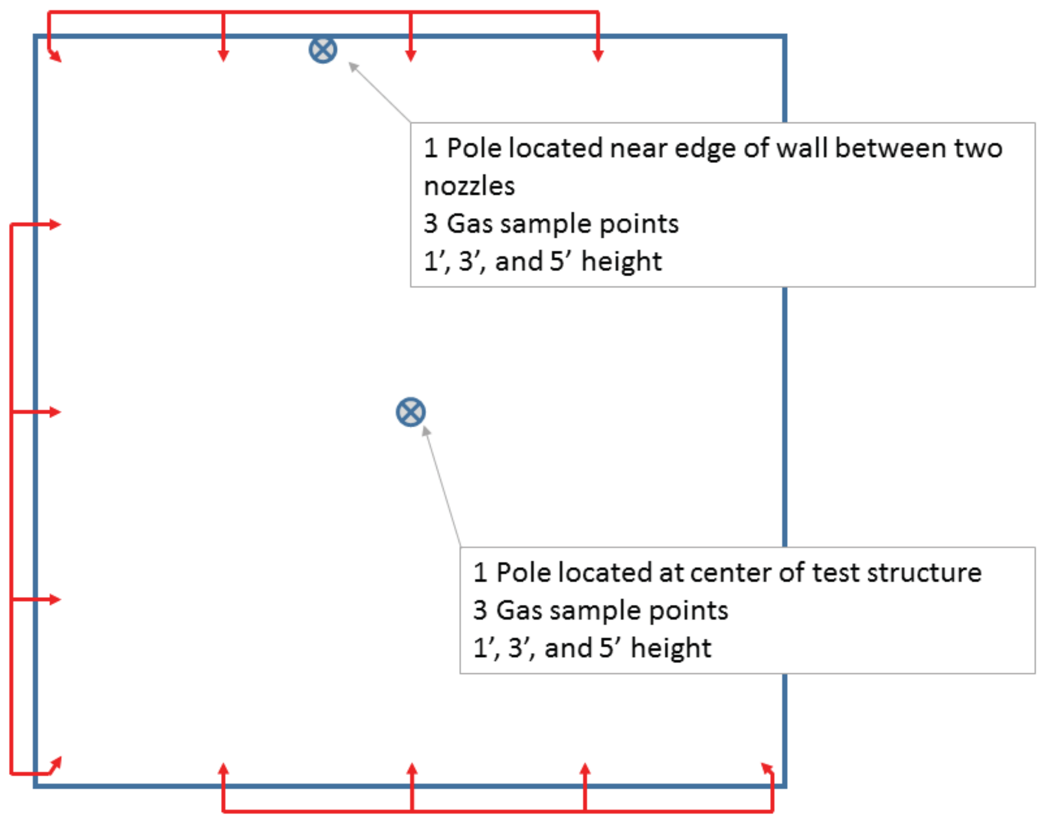

Figure 18. Locations of the Six Sampling Points for Gas Analysis

3.10. Measurement of Hydrogen Fluoride Concentration

Novec is a perfluorinated ketone with the molecular formula $C_6F_{12}O$. Complete combustion of the agent will produce carbon dioxide and hydrogen fluoride as shown in the following reaction:

$$C_6F_{12}O + 2.5\ O_2 + 6\ H_2O \rightarrow 6\ CO_2 + 12\ HF$$

Thus, combustion of Novec will produce 12 volumes of hydrogen fluoride on a per molecule basis. Combustion of Novec under dry conditions will result in incomplete combustion and produce carbonyl fluoride, CF_2O. Carbonyl fluoride is a highly reactive gas that will react with available water to form carbon dioxide and hydrogen fluoride according to the following reaction:

$$CF_2O + H_2O \rightarrow CO_2 + 2\ HF$$

Hydrogen fluoride is an extremely hazardous compound. Relevant Occupational Safety & Health Administration (OSHA) time-weighted average (TWA), short-term exposure limit (STEL), and the National Institute for Occupational Safety and Health (NIOSH) immediately dangerous to life and health (IDLH) values for hydrogen fluoride are presented in Table 3.

Table 3. Health and Safety Guidelines for Hydrogen Fluoride

Guideline	Value
OSHA 8-h TWA	3 ppm
OSHA 15-min STEL	6 ppm
NIOSH IDLH	30 ppm

Because of the threat to human health posed by hydrogen fluoride, a detection kit consisting of a Draeger pump and dual-range hydrogen fluoride detection tubes was obtained. The dual-range tubes were calibrated for hydrogen fluoride concentrations up to 15 or 90 ppm, depending on mode of operation. This kit was used by personnel in self-contained breathing apparatuses to measure hydrogen fluoride concentration within and without the test structure starting 10-min after discharge of the agent in all test scenarios involving a fire in which hydrogen fluoride could have been produced. Measurements were continued until it was determined to be safe for unprotected personnel to enter the facility. Although these measurements were primarily performed in the interest of safety, they do provide some information about hazardous gasses produced under these test conditions.

3.11. Test Scenarios

To confirm proper operation, initial discharge tests of the system were performed with water. Once the system was deemed fully operational, tests with Novec were performed. Three different Novec discharge scenarios were conducted.

3.11.1. Novec Discharge Tests

Scenario one involved discharging Novec into the test structure with no fire present for the purposes of optimizing the discharge parameters (quantity of Novec discharged, discharge time, discharge pressure, etc.). The Tripoint Instruments gas analyzers were used to measure the concentration of Novec at six points in the protected space. Discharge parameters were adjusted until the performance criteria (design concentration, discharge time, retention time) were met. Several tests were required to complete this optimization. Data collected during these discharge tests were used to refine the parameters used in subsequent CFD modeling.

3.11.2. Cup Fire Tests

Scenario two involved a discharge of Novec into the test structure that contained an array of 36 small steel cups of burning jet fuel at various locations. Each cup was filled with 150 mL of water and 120 mL of Jet-A fuel. The cups were evenly spaced at 5-ft intervals within the test structure, with a 2.5-ft gap between the structure wall and nearest cups. A diagram of the cup arrangement is illustrated in Figure 19. After ignition, the cups were allowed to burn for 30-s before activation of the Novec discharge system. This test demonstrated the ability of Novec to extinguish small fires, and the ability of the agent to disperse throughout the protected space.

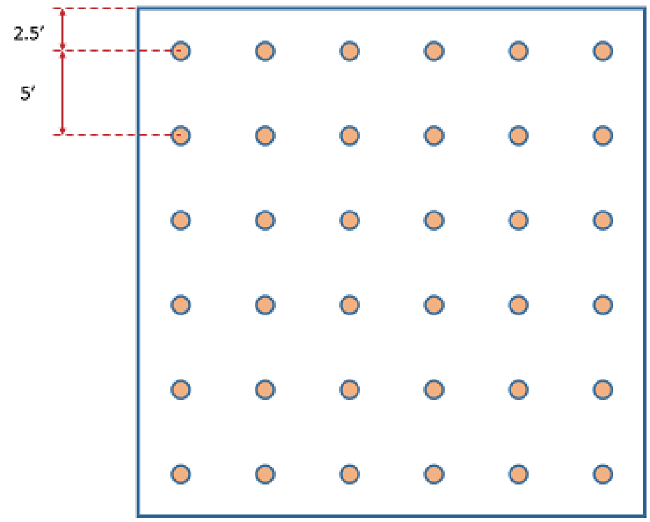

Figure 19. Location of the 36 Fuel Cups

3.11.3. Pool Fire Tests

Scenario three consisted of a discharge of Novec into the test structure onto a burning pool of jet fuel. Jet-A fuel (4.6 gal) was poured into the conical depression at the center of the test structure, resulting in a pool of fuel approximately 5-ft in diameter. After ignition, the fuel was allowed to burn for 30-s before activation of the Novec discharge system. This test demonstrated the ability of Novec to extinguish a relatively large fire that caused significant air turbulence and updraft in the test structure.

4. RESULTS AND DISCUSSION

4.1. Discharge Parameter Optimization

A total of eight Novec discharge tests with no fire were performed. During these tests, nozzle type, discharge time and initial tank pressure were adjusted to vary the agent flow rate, discharge velocity, and total quantity of agent discharged. A summary of the discharge test parameters is presented in Table 4.

Table 4. Summary of Novec Discharge Test Parameters

Test Number	Installed Nozzles (80 and 120 deg)	Test Structure Wall Height (ft)	Initial Tank Pressure (psi)	Discharge Duration (s)	Temperature (F)	Humidity (%)	Average Tank Pressure During Discharge (psi)	Average Flow Rate per Manifold (lb/s)	Expected Weight Discharged (lb)	Actual Weight Discharged (lb)	Peak 1-ft Center Concentration (%)	Peak 1-ft Wall Concentration (%)
20170320-1	NF50	4	90	8	62.9	57.1	82.7	5.00	230	174.5	3.0	3.5
20170322-1	NF80	4	45	10	80.9	76.1	40.1	5.46	230	229.8	4.5	4.7
20170331-1	NF80	8	45	10	75.4	83.1	40.5	5.57	230	228.0	4.5	4.7
20170405-1	NF20	8	60	35	76.2	100	55.0	1.60	230	233.0	6.7	6.9
20170411-1	NF20	8	40	45	68.1	86.8	36.3	1.33	230	236.8	6.3	6.5
20170412-1	NF20	8	80	30	78.1	71.0	73.6	1.90	230	237.0	6.1	6.7
20170413-1	NF20	8	100	26	68.3	84.9	92.0	2.13	230	230.8	5.7	6.2
20170413-2	NF20	8	82	42	81.1	43.1	72.8	1.90	325	326.3	8.1	8.2

For the first test (test 20170320-1), it was decided to discharge 230 lb of Novec over a period of 10 s. The agent quantity was chosen based upon predictions from CFD modeling, and the 10-s discharge time was based upon NFPA 2001 requirements. Bete NF50 nozzles were chosen. The vendor specification for these nozzles indicated an initial tank pressure of 90 psi would result in the desired discharge time and agent quantity. Unfortunately, an error occurred during discharge that resulted in a discharge time of only 8 s and delivery of less than the desired quantity of Novec. From a review of camera footage of the discharge it appeared that the velocity of the agent exiting the nozzle resulted in loss of agent over the 4-ft walls of the test structure.

For the second test (test 20170322-1), the system was altered by using a larger NF80 Bete nozzle and reducing the initial tank pressure to 45 psi. This was intended to reduce nozzle velocity and the quantity of agent that was being lost over the walls during discharge. Instrumentation recorded 229.8 lb (goal was 230 lb) of Novec discharged. Figure 20 is a photograph taken during test 20170322-1. The vapor visible in the photograph is primarily water vapor (mist), which condenses from the air due to rapid cooling caused by the Novec discharge. Nevertheless, the visible vapor cloud demonstrates that the energetic discharge and nozzle velocity of Novec causes turbulence within the test structure resulting in transport of air and Novec well above the walls of the test structure and leading to loss of agent.

Figure 20. Novec Being Discharged into the First Version of the Test Structure

Figure 21 is a plot of Novec concentrations measured during test 20170322-1. The Novec concentration measured by the sensor located 1 ft above the center of the test structure reached a peak concentration of 4.5 percent, while the concentration measured by the sensor located near the wall and 1-ft above the floor reached a peak concentration of 4.7 percent—both below the desired design concentration of 5.4 percent. The concentration measured by both 1-ft sensors dropped rapidly over time. At 4 min (240 s), concentrations remained above 3.5 percent, but by 10 min (600 s) after discharge, both concentrations were below 1.5 percent.

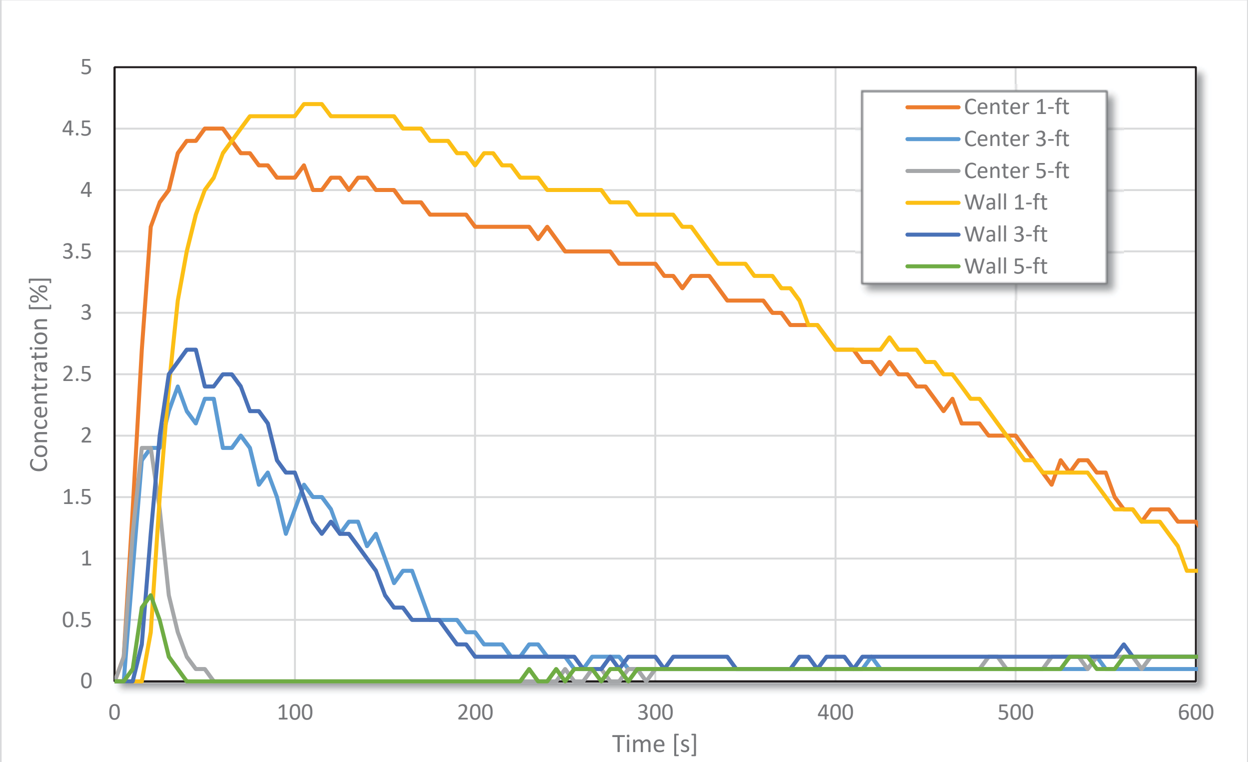

Figure 21. Novec Concentration Measured during Test 20170322-1

Because of the visible vapor cloud well above the 4-ft high test structure walls and the rapid drop off in measured Novec concentration, it was theorized that turbulence caused by the discharge process was causing a significant quantity of Novec to flow over the walls and out of the test structure. To limit this loss, the test structure was modified to extend the walls to 8-ft height (see section 3.5. and Figure 9). An additional discharge test (test 20170331-1) was performed in the modified test structure using discharge parameters identical to the previous test. A comparison of Novec concentrations measured during these two tests is presented in Figure 22. For simplicity, only the concentrations measured by the sensors positioned 1-ft from the floor of the test structure are included. Although the increase in wall height had minimal effect on peak Novec concentrations, it improved the retention of Novec in the test structure over time, in particular past the 5-min mark. Improved retention of Novec was expected to facilitate identification of a set of discharge parameters that would result in approaching the NFPA 10-min (85 percent of the design concentration) requirement. It was therefore decided to retain the modifications to the test structure walls for all subsequent tests.

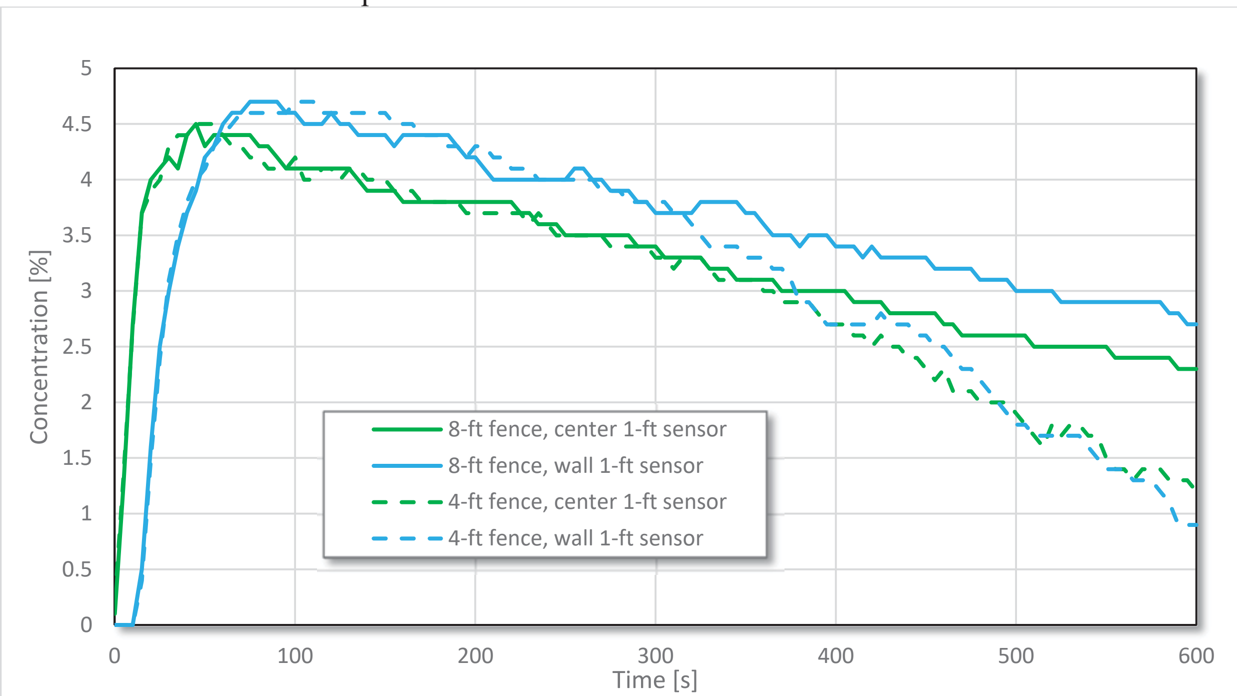

Figure 22. Comparison of Novec Concentrations Measured during Tests 20170322-1 and 20170331-1

To further reduce the quantity of Novec lost during the energetic discharge process, the system was modified by using NF20 nozzles having a smaller nozzle orifice size and by increasing the discharge time from 10 to 35 sec, which required an initial tank pressure of 60 psi. This was intended to reduce the droplet size, velocity, and momentum of the Novec mist as it was propelled out of the nozzles. Figure 23 shows the Novec gas concentration measured during test 20170405-1 under these conditions. For reference, the design concentration goal of 5.4 percent and the 85 percent retention concentration goal of 4.59 percent are indicated by dashed lines. Test 20170405-1 produced peak concentrations of 6.9 percent and 6.7 percent, well above the design concentration. The system provided coverage of the protected space in one minute and maintained fire suppression concentration for more than 4-min. It did not meet the NFPA 2001 minimum agent concentrations at 10-sec and 10-min.

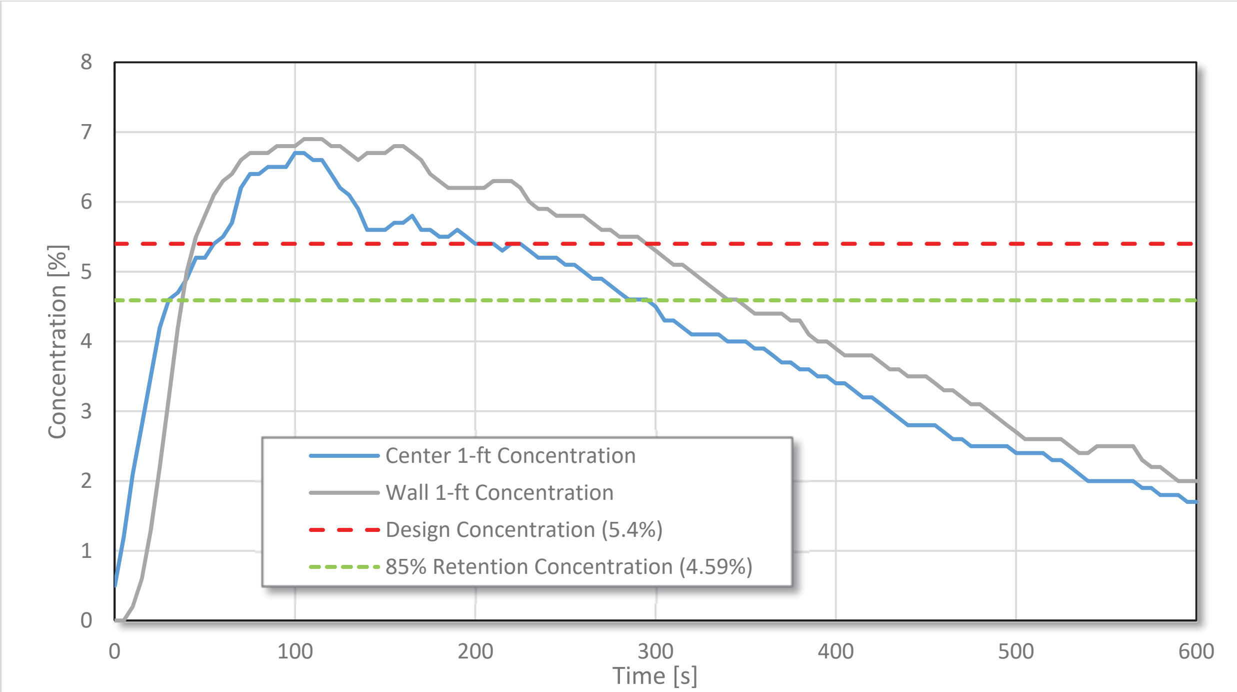

Figure 23. Novec Concentration Measured during Test 20170405-1

Tests 20170411-1, 20170412-1, and 20170413-1 continued the optimization process by changing the initial tank pressure to 40, 80, and 100 psi, respectively while continuing to use the Bete NF20 nozzles. his altered the discharge times to 44, 30, and 26 s, respectively. Figure 24 is a plot of Novec concentrations measured in all four tests. For simplicity, only the average of the

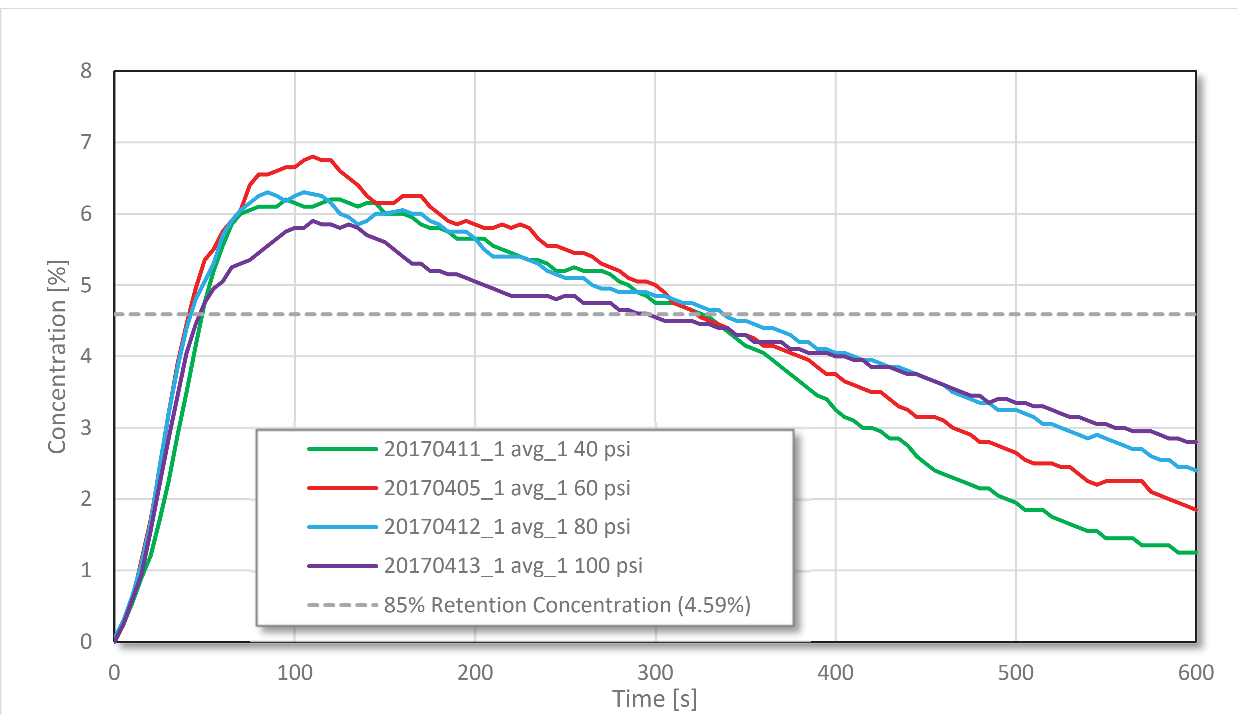

Figure 24. Novec Concentration Measured during Tests 20170411-1 through 20170413-1

two 1-ft sensors is plotted for each test. An initial tank pressure of 60 psi produced the highest peak Novec concentration, while initial pressure of 100 psi produced the highest retention of Novec. All discharges met the 85 percent retention goal of 4-min, but not the NFPA 2001 10-min requirement. After reviewing the data it was decided that the test performed at an initial tank pressure of 80 psi offered the best balance between peak agent concentration and agent retention in the test structure. The remaining tests in this series were done at initial tank pressures of 80 psi.

The final test without fire (test 20170413-2) was performed to observe the effect that increasing the quantity of Novec discharged would have upon the measured Novec concentration. The quantity of agent discharged was increased to 325 lb, while continuing the use of the Bete size NF20 nozzles and an initial tank pressure of 80 psi. This required a discharge time of 42s. Figure 25 presents a comparison of the Novec concentration measured during tests 20170412-1 (230 lb) and 20170413-2 (325 lb). Again, only the average of the two 1-ft sensors is plotted for each test for simplicity. Test 20170413-2 produced a higher average peak concentration of Novec (8.1 percent vs. 6.3 percent), and significantly extended the time that the Novec concentration remained above the design concentration (approximately 380 vs. 220-s).

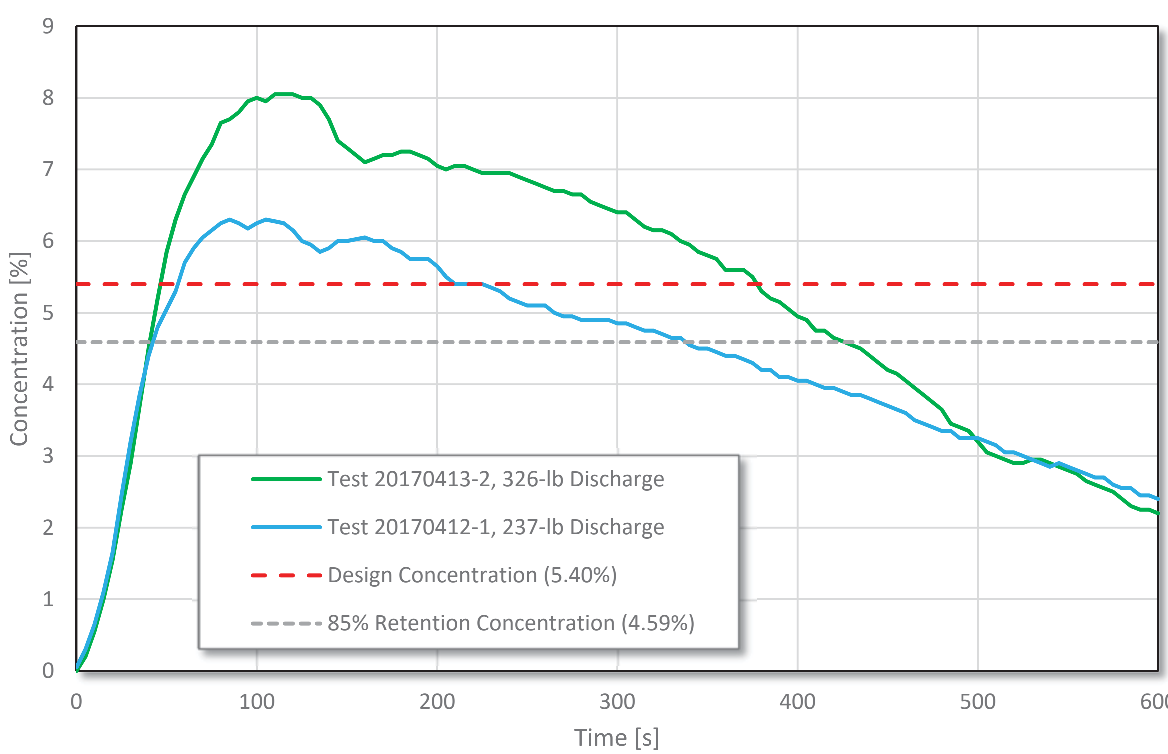

Figure 25. Comparison of Novec Concentrations Measured during Tests 20170412-1 and 20170413-2

At this point it was decided that additional system changes would provide minimal enhancements and to conduct all remaining tests using this final set of conditions, namely Bete NF20 nozzles, initial tank pressure of 80 psi, and 325 lb of Novec discharged over 42 s . This configuration met the design concentration and the performance requirement discharge time and retention duration goals, but failed to meet the NFPA 2001 10-s and 10-min concentrations.

4.2. Cup Fire Tests

The first fire scenario used to evaluate the Novec discharge system involved an array of 36 burning cups, as described in sections 3.6. and 3.11.2. Prior to performance of this test with Novec, a dry run was performed in which water was discharged into the test area in which the burning cups were arranged. This water-only test was performed to verify the proper function of all equipment, in particular that the cups would not move, tip, or overflow as a result of the agent stream.

4.2.4. Control Cup Fire Test with Water

When this test using water was performed, the exact discharge parameters for the future Novec discharge had not been finalized. To insure the fuel cups would function as intended in future Novec tests, discharge parameters for this test were so chosen as to maximize the flow rate of water onto the fuel cups. The largest size Bete nozzles in our inventory, size NF120, were selected for use. The agent reservoirs were pressurized to an initial pressure of 100 psi. A discharge time of 10 s was selected. These parameters resulted in a total discharge of 291 lb (34.9 gal) of water. The average flow rate was thus 29.1 lb/s, or 3.49 gal/s. In comparison, the parameters that were eventually chosen for the future Novec test produced a discharge of 325 lb (24.4 gal) over 42 s, with an average flow rate of 7.73 lb/s, or 0.580 gal/s. Thus, the water-only discharge test involved the discharge of 40 percent more agent by volume than the later Novec discharge test. In addition, the flow rate for the water-only discharge test was a factor of six greater than the later Novec discharge test.

A photograph taken during this test, just before the discharge of water was initiated, is presented in Figure 26. Note that this test occurred before additions to the test structure walls were installed, as described in section 3.5.

Figure 26. Fuel Cup Fire Water-Discharge Test

After the 10-s discharge of water, a total of 16 of the burning fuel cups had been extinguished. Of the 16 cups positioned in the interior of the array 15 were extinguished, while only one of the

20 cups on the exterior of the array was extinguished. It was noted that the position of the nozzles, spray pattern, and throw distance resulted in water being directed over the exterior cups where it then fell on the area surrounding the interior cups. Due to the large volume of water, and the high application rate, this result illustrates the near-maximum potential of a liquid agent to extinguish this fire scenario under these conditions. Any improved extinguishment observed during the application of Novec in this fire scenario is therefore likely due to the ability of the gaseous agent to disperse as a flooding agent throughout the test structure and extinguish fires that were not directly under the flow of agent. The results of the fuel cup water-discharge test are summarized in Figure 27.

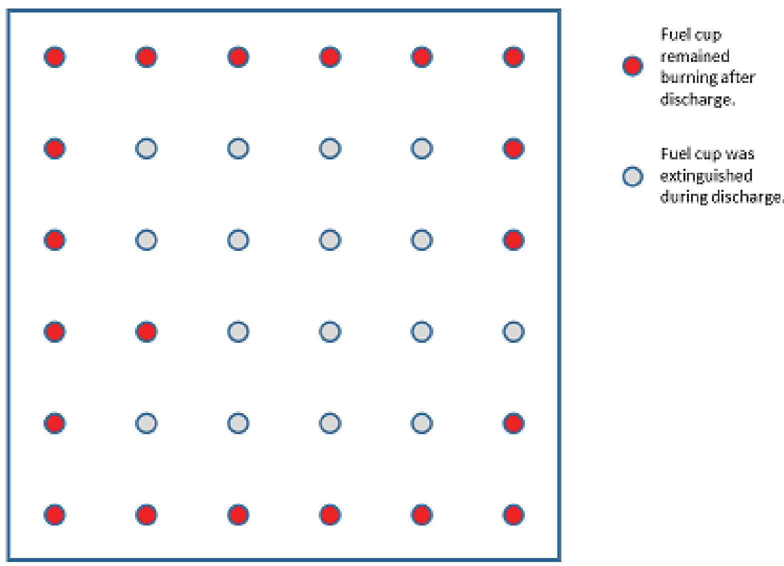

Figure 27. Results of the Fuel Cup Fire Water-Discharge Test

4.2.5. Cup Fire Test with Novec

The fuel cup fire suppression test using Novec was performed using the same set of nozzles, initial tank pressure, discharge time, and expected discharge weight as was used for the final non-fire test, test 20170413-2. A summary of test parameters is presented in Table 5. All 36 cups filled with burning Jet-A were extinguished within 20 s after discharge of agent began. As with the water discharge discussed previously, it was noted that the stream of agent flowed over the 20 cups along the perimeter to either evaporate or fall to the ground towards the center of the test structure. The extinguishment of the perimeter cups seems to have been a result of evaporation and diffusion of Novec back into the perimeter space.

Novec concentration was not measured during this test, as smoke and combustion products would have caused interference in the gas analyzer. However, 20 s into the discharge during test 20170413-2 (which was performed under the same discharge conditions) the average Novec concentration of the two sensors located 1 ft off the floor was only 1.6 percent. The rims of the fuel cups were approximately 2 in above the floor. Thus, the Novec concentration at that height must have been at or above 4.15 percent, the minimum extinguishing concentration for Jet-A as determined by cup burner test. A photograph taken during this test, just after the discharge of Novec was initiated, is presented in Figure 28.

Table 5. Summary of Cup Fire Novec-Discharge Test Parameters

Test Number	Installed Nozzles (80 and 120 deg)	Test Structure Wall Height (ft)	Initial Tank Pressure (psi)	Discharge Duration (s)	Temperature (F)	Humidity (%)	Average Tank Pressure During Discharge (psi)	Average Flow Rate per Manifold (lb/s)	Expected Weight Discharged (lb)	Actual Weight Discharged (lb)	Peak 1-ft Center Concentration (%)	Peak 1-ft Wall Concentration (%)
20170509-1	NF20	8	82	42	73	70	73.9	1.927	325	334.1	NA	NA

Figure 28. Fuel Cup Fire Novec-Discharge Test

4.3. Pool Fire Tests

The pool fire discharge test using Novec was performed using the same set of nozzles, initial tank pressure, discharge time, and expected discharge weight as was for the final non-fire test, test 20170413-2. A summary of test parameters is presented in Table 6.

Table 6. Summary of Pool Fire Novec-Discharge Test Parameters

Test Number	Installed Nozzles (80 and 120 deg)	Test Structure Wall Height (ft)	Initial Tank Pressure (psi)	Discharge Duration (s)	Temperature (F)	Humidity (%)	Average Tank Pressure During Discharge (psi)	Average Flow Rate per Manifold (lb/s)	Expected Weight Discharged (lb)	Actual Weight Discharged (lb)	Peak 1-ft Center Concentration (%)	Peak 1-ft Wall Concentration (%)
20170525-1	NF20	8	82	42	74.9	56.5	73.1	1.91	325	330	NA	NA

The pool fire was extinguished 30 s after discharge of Novec was initiated. The Novec concentration was not measured during this test as smoke and combustion products would have caused interference in the gas analyzer. For reference, 30 s into the discharge during test 20170413-2 (which was performed under the same discharge conditions but with no fuel fire) the average Novec concentration of the two sensors located 1 ft off the floor was 2.9 percent. The fact that the fuel fire was successfully extinguished in test 20170525-1 indicates that the Novec concentration at the floor level where the fuel was located was at or above the extinguishing concentration of 4.15%. A photograph taken during this test just after the discharge of Novec was initiated is presented in Figure 29.

Figure 29. Pool Fire Novec-Discharge Test

4.4. Combustion Products

A considerable quantity of hydrogen fluoride was generated in the two fire extinguishment tests using Novec. In the second fire test, where the pool of jet fuel was extinguished, the hydrogen fluoride concentration at the center of the test structure exceeded 90 ppm, the limit of our measurement system. As discussed in section 3.10. , this was expected as hydrogen fluoride is a combustion product of most fluorinated organic compounds. Hydrogen fluoride is a combustion product of many other firefighting agents as well, including halon 1211 and halon 1301. Halon 1211 (CF_2ClBr) and halon 1301 (CF_3Br) are gaseous firefighting agents used in a wide variety of hand-held, vehicular, and structural firefighting systems. Both compounds contain the element fluorine, and are therefore capable of producing hydrogen fluoride (HF) during combustion. In addition, both compounds will produce hydrogen bromide (HBr), and, in the case of halon 1211, hydrogen chloride (HCl).

Combustion of a hydrocarbon fuel in air proceeds by a series of complex chemical chain-reactions involving the generation of numerous radical species, including hydrogen (H·), hydroxyl (·OH) and hydroperoxide (HOO·) radicals. Halon agents suppress fires by chemically disrupting this combustion process. Heat generated by the fire causes the relatively weak carbon–chlorine and carbon–bromine bonds to break, producing chlorine and bromine radicals.

$$CF_3Br + heat \rightarrow CF_3\cdot + Br\cdot$$

$$CF_2ClBr + heat \rightarrow CF_2 + Cl\cdot + Br\cdot$$

Chlorine and bromine radicals suppress the combustion process by chemically reacting with species produced during the combustion chain reaction. The final products of this process include hydrogen chloride (HCl) and hydrogen bromide (HBr). The carbon–fluorine bond is much stronger than the carbon–chlorine or carbon–bromine bond. As a result, fluorine radicals are generated only at much higher temperatures, and play less of a role in fire suppression. Nevertheless, intense fires will result in the complete combustion of halon agents and generate hydrogen fluoride (HF) in addition to the hydrogen chloride and hydrogen bromide.

Unlike halon agents, Novec suppresses fires primarily by removing heat from the fire. Novec has a very large heat capacity (higher than other agents such as FE-36 or FM-200 that suppress fires by this mechanism). At the extinguishing concentration, the air–Novec mixture has sufficient heat capacity to suppress the fire. The amount of heat the fire loses to the surrounding Novec agent exceeds the heat generated by the combustion process, cooling the fire until combustion no longer occurs. As with the halon agents, intense fires will result in the complete combustion of the Novec agent and generation of hydrogen fluoride (HF).

Extinguishing concentrations for halon and Novec agents are on the order of 5% for most hydrocarbons. Thus, none of these agents extinguishes fires by displacing oxygen in these applications.

Hydrogen fluoride, hydrogen chloride, and hydrogen bromide are all highly toxic and corrosive compounds known as hydrogen halides. Table 7 lists Center for Disease Control and Prevention (CDC)- and NIOSH-recommended exposure limits (REL), IDLH values, and median lethal concentration (LC_{50}) for the hydrogen halides. All three compounds have similar NIOSH exposure limitations, while hydrogen fluoride exhibits higher toxicity than the other two compounds in exposure studies involving rats (a lower LC_{50} value indicates a higher degree of toxicity).

Table 7. Toxic Values and Regulatory Limits of Three Hydrogen Halides

Value	HF	HCl	HBr
NIOSH REL (8-h TWA, ppm)	3; 6 (15-min)	5	3
NIOSH IDLH (instantaneous, ppm)	30	50	30
LC_{50} (Rat,1-h, ppm)	1,276	3,125	2,854

Table 8 presents the odor thresholds and a general description of the odor for the three hydrogen halides (Source: National Institute of Health Haz-Map Information of Hazardous Chemicals and Occupational Diseases). All three compounds are described as having an unpleasant and irritating odor. Similarly, all three compounds have an odor threshold below their recommended exposure Table 7. Toxicological Data and Regulatory Limits for Three Hydrogen Halideslimits; hydrogen fluoride has the lowest odor threshold of the three compounds, potentially giving it the largest margin of safety. In addition, a fire intense enough to combust a significant quantity of Novec or halon will produce smoke and other combustion products that will further degrade the air quality and be a deterrent to unprotected individuals remaining in the area. Still the potential exists for unprotected individuals or first responders to enter a toxic plume and inhale or be exposed dermally to these hazards before they realize the extent of the danger.

Table 8. Odor Thresholds and Odor Descriptions for Three Hydrogen Halides

Value	HF	HCl	HBr
Odor Threshold (ppm)	0.04	0.25	2
Odor Description	"Strong, irritating"	"Pungent, irritating"	"Sharp, irritating"

Table 9 presents the theoretical quantity of hydrogen halide gasses that would be produced from complete combustion of one pound each of Novec 1230, halon 1211, or halon 1301. Novec 1230 has the potential to produce two to three times as much hydrogen fluoride as the other agents on a per-pound basis, while the two halon compounds have the potential to produce a slightly greater total mass of hydrogen halides overall, on a per pound basis.

Table 9. Products Produced from Complete Combustion of One Pound of Agent

	Novec 1230	Halon 1211	Halon 1301
Hydrogen Fluoride, HF (lb)	0.76	0.24	0.40
Hydrogen Chloride, HCl (lb)	-	0.22	-
Hydrogen Bromide, HBr (lb)	-	0.49	0.54
Total (lb)	0.76	0.95	0.95

Table 10 presents the theoretical concentration of combustion products that would result from complete combustion and complete, even dispersal of 150 lb (a quantity typically found in wheeled flightline extinguishers) of Novec 1230, halon 1211, or halon 1301 in an 80×80×40-ft enclosure (representative of a small hangar or similar structure). This represents an extreme, worst-case scenario in which a large or intense fire resulted in the complete combustion of all applied agent. In each case, the resulting hydrogen fluoride concentration exceeds the NIOSH IDLH value by several orders of magnitude. Similarly, combustion of the halons produces hydrogen bromide and from 1211 hydrogen chloride concentrations that greatly exceed the NIOSH IDLH values. These values should be used for comparison purposes in this worst-case model scenario only, not as expected values from using an extinguisher on a jet fuel fire. Actual concentrations measured in a real-world discharge could be much higher, especially in the localized area near the point of combustion.

Table 10. Theoretical Concentration of Products Resulting from Complete Combustion and Dispersal of 150 lbs of Agent in an 80×80×40-ft Space. Calculated using CDC/NIOSH Values for Vapor Density

	Novec 1230	Halon 1211	Halon 1301
Hydrogen Fluoride, HF (ppm)	8,687	2,764	4,606
Hydrogen Chloride, HCl (ppm)	-	1,388	-
Hydrogen Bromide, HBr (ppm)	-	1,387	1,540
Total (ppm)	8,687	5,539	6,146

As demonstrated above, combustion of Novec 1230, halon 1211, or halon 1301 has the potential to produce large quantities of one or more hydrogen halides. These hydrogen halide combustion products are all very hazardous, with similar toxicity characteristics and odor thresholds, and corrosive. Complete combustion of all three agents generates similar total quantities of hydrogen halides. However, Novec 1230 produces two to three times as much hydrogen fluoride (the most toxic of the three hydrogen halide gasses) as either halon. Novec 1230 may be a suitable replacement agent for any application or environment currently approved for halon 1211 or halon 1301. The decision to use Novec must be based upon careful consideration of the risks posed to personnel and potential corrosive effects to equipment that could be exposed to these combustion products.

5. CONCLUSIONS

CFD M&S was preliminarily used to determine if a limited flood fire suppression application using Novec could demonstrate feasibility to potentially decrease the amount of agent required for floor-level fire protection compared to the agent quantity needed for total flood application. A prototype fire suppression system proposed for use on fuel fires in aircraft hangars and utilizing the clean-agent Novec 1230 was designed and built. During experimental system performance characterization, M&S was iteratively used to optimize Novec discharge settings to fine tune agent delivery efficiency.

The system was tested against two distinct live-fire scenarios. The first scenario consisted of an array of 36, 4-in diameter cups of burning Jet-A fuel evenly spaced over a 30×30-ft floor area. This scenario was intended to test the ability of the system to extinguish a large-area, uniformly distributed fire. Against this arrangement the system extinguished fires in all 36 cups within 20 s of initiating flow. The second scenario consisted of a 5-ft diameter pool fire of Jet-A more characteristic of a fire from a localized leak from a single aircraft. This fire was extinguished after approximately 30 s and required just 3/4 of the total agent dispersed into the 30×30-ft test area. Despite the demonstrated ability of the system to control or extinguish both categories of fires, the prototype system did not meet some requirements for total flood extinguishing systems prescribed by NFPA 2001. However, it is likely that further adjustment of the system would have enabled it to meet all requirements.

Successful extinguishment of small and medium-sized fires demonstrated the potential for use of Novec 1230 in a hangar or similar structure for the suppression of non-spraying liquid fuel fires at floor level. Novec 1230 has many advantages when compared to foam and halon agents currently used in many such structures. Unlike firefighting foam, Novec 1230 does not leave a residue requiring cleanup after discharge, and Novec 1230 has significantly lower ODP and GWP values than halon clean agents.

Combustion of Novec 1230 produced significant quantities of the toxic and corrosive compound hydrogen fluoride. Combustion of the firefighting agents halon 1211 and halon 1301 also produce hydrogen fluoride, as well as hydrogen bromide and for halon 1211, hydrogen chloride. However, Novec 1230 produces two to three times more hydrogen fluoride, the most hazardous of the three hydrogen halide compounds, than the two halons produce. Novec 1230 may be an acceptable replacement for halon 1211 and halon 1301 in applications and environments that already employ the halon agents. However, the decision to use Novec 1230 must be based upon careful consideration of the risks posed to personnel and equipment that could be exposed to these combustion products.

For existing Novec 1230 total flood systems where the design threat is fire at floor level, retrofitting with a limited flood system similar to the concept presented here may help significantly reduce the amount of hydrogen fluoride released in an actual fire emergency event.

6. REFERENCES

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AFFF	aqueous film forming foam
AFCEC	Air Force Civil Engineer Center
°C	degrees Celsius
CDC	The Center for Disease Control and Prevention
CFD	computational fluid dynamics
deg	degree
ft	foot
gal	gallon
GWP	Global Warming Potential
in	inch
IDLH	immediately dangerous to life and health
lb	pound
LC_{50}	median lethal concentration (aka 50% lethal concentration)
M&S	modeling and simulation
min	minute
NFPA	National Fire Protection Association
NIOSH	The National Institute for Occupational Safety and Health
ODP	Ozone Depletion Potential
OSHA	Occupational Safety & Health Administration
ppm	parts per million
psi	pounds per square inch
REL	Recommended Exposure Limit
s	second
SI	International System of Units
STEL	short-term exposure limit
TWA	time-weighted average
USAF	United States Air Force