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New Jersey 08405

Full-Scale Evaluation of Novec™ 1230

August 2019

Final Report

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16. Abstract

In the early 2000s, 3M™ released Novec™ 1230 Fire Protection Fluid, which has no ozone-depleting potential and a minimal global-warming potential. Prior to the Federal Aviation Administration's (FAA's) consideration for approval as a complimentary agent in Aircraft Rescue and Firefighting (ARFF) operations, Novec 1230's fire-extinguishing capabilities had to be evaluated in full-scale fire tests similar to the ones described in DOT/FAA/AR-95/87. A research team at the William J. Hughes Technical Center evaluated the extinguishing capabilities of Novec 1230 discharged from a flight line extinguisher in simulated wheel brake fire involving hydraulic fluid tests, three-dimensional inclined-plane fire tests, and pan fire tests with 16- and 30-foot (ft) diameters. While these tests were based on those performed in DOT/FAA/AR-95/87, some parameters were changed due to test site restrictions and to enhance repeatability. Novec 1230's performance on the simulated engine nacelle was previously evaluated in AFCEC-CX-TY-TR-2014-0033, the results of which were accepted for this research effort.

Under this research effort, Halotron® I also was tested on three-dimensional inclined-plane fire tests, 16-ft pan fire tests, and 30-ft pan fire tests. Halotron I's performance on the simulated engine nacelle fire tests was previously evaluated in NAWCWD TM 8572, the results of which were used as data for this evaluation. Data from these tests were used to compare Novec 1230's performance with that of Halotron I. While Halon® 1211 is still an FAA-approved clean agent for use at airports, ARFF vehicle manufacturers have not installed Halon 1211 extinguishing systems on their products in over a decade.

Throughout all experimental configurations, Novec 1230 required more agent by both weight and volume than Halotron I. The difference between performance parameters by percentage were consistent between the three experimental configurations with the exception of the simulated engine nacelle conducted by the United States Air Force and Navy. The results of the simulated engine nacelle tests were comparable with the results of the other experimental configurations with the exception of extinguishment time.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARFF	Aircraft Rescue and Firefighting
atm	Atmosphere
BTU	British thermal unit
CFR	Code of Federal Regulations
COF_2	Carbonyl fluoride
DNE	Did not extinguish
EPA	Environmental Protection Agency
°F	Degrees Fahrenheit
FAA	Federal Aviation Administration
ft	Foot
g	Grams
gpm	Gallons per minute
HCFC	Hydrochlorofluorocarbon
HF	Hydrogen fluoride
in.	Inch
lb	Pound
m	Mass
mol	Mole
mph	Miles per hour
NFPA	National Fire Protection Association®
psi	Pounds per square inch
TAFB	Tyndall Air Force Base
TDP	Thermal decomposition product
UL	Underwriters Laboratories®
U.S.	United States
USAF	United States Air Force
WJHTC	William J. Hughes Technical Center

EXECUTIVE SUMMARY

In accordance with the Montreal Protocol Clean Air Act, Halon® 1211 had been set to be phased out due to its ozone-depleting qualities. Production was banned at the beginning of 1994, with remaining stockpiles only permitted for use in emergency situations and critical firefighter training. Since then, replacement clean gaseous firefighting agents have been developed and tested. Some testing was detailed in DOT/FAA/AR-95/87, which compared the firefighting capabilities of Halon 1211 with two potential replacements, Halotron® I and perflourohexane (C_6). The Federal Aviation Administration (FAA) approved Halotron I as the Halon 1211 replacement for use in Aircraft Rescue and Firefighting (ARFF) operations at certificated Title 14 Code of Federal Regulations Part 139 airports.

In the early 2000s, 3M™ released Novec™ 1230, which has no ozone-depleting potential and a minimal global-warming potential. Prior to the FAA's consideration for approval as a complimentary agent in ARFF operations, Novec 1230's fire-extinguishing capabilities had to be evaluated in full-scale fire tests similar to the ones described in DOT/FAA/AR-95/87. A research team at the William J. Hughes Technical Center evaluated the extinguishing capabilities of Novec 1230 discharged from a flight line extinguisher in simulated wheel brake fire involving hydraulic fluid tests, three-dimensional inclined-plane fire tests, and pan fire tests with 16- and 30-foot (ft) diameters. While these tests were based on those performed in DOT/FAA/AR-95/87, the research team changed some parameters due to test site restrictions and to enhance repeatability. The United States Air Force (USAF) conducted previous evaluations, detailed in AFCEC-CX-TY-TR-2014-0033, which provided data and results for Novec 1230 on the simulated engine nacelle running fuel fire tests. In addition, a research team at Tyndall Air Force Base evaluated Novec 1230 discharged from a truck-based system with a simulated engine nacelle running fuel fire test at to evaluate Novec 1230's performance as a drop-in agent and to ensure the agent's performance was not hindered when discharged from an unoptimized system. The team conducted additional evaluations of Halotron I to provide comparable data on the altered experimental configurations.

Novec 1230 extinguished the simulated wheel brake fire involving hydraulic fluid tests with an average extinguishment time of 14.3 seconds while requiring an average of 78.2 lb of agent. On the three-dimensional inclined-plane fire tests, Novec 1230 extinguished the fires in an average of 13.7 seconds and required 85.9 lb of agent. Novec 1230 extinguished the 16-ft pan fires in an average of 12.7 seconds with 78.2 lb of agent. On the 30-ft pan fire tests, Novec 1230 failed to achieve complete extinguishment; however, in two of the three tests, the overwhelming majority of fire was suppressed. On the simulated engine nacelle with running fuel fire tests, Novec 1230 extinguished the fires in an average of 20.1 seconds with 124.2 lb of agent. When discharged from the truck-based system, Novec 1230 was discharged at a flow rate 38.7% greater than when discharged from an extinguisher. At this increased flow rate, Novec 1230 extinguished the engine nacelle fires in 40.3% less time and with 10.8% less agent as compared to the nacelle extinguisher tests. This indicated that Novec 1230's extinguishing capabilities are not hindered when discharged from an unoptimized, truck-based system at a higher flow rate.

Under this research effort, the team also tested Halotron I in three-dimensional inclined-plane fire tests, 16-ft pan fire tests, and 30-ft pan fire tests. Halotron I's performance on the simulated engine nacelle fire tests was previously evaluated in NAWCWD TM 8572, the results of which

were used as data for this evaluation. Data from these tests were used to compare Novec 1230's performance with that of Halotron I. While Halon 1211 is still an FAA-approved clean agent for use at airports, ARFF vehicle manufacturers have not installed Halon 1211 extinguishing systems on their products in over a decade.

On the inclined-plane fire tests, Novec 1230 required 5.4% more time and 18.2% more agent by weight when compared to Halotron I. Due to differences in each agent's density, the research team also performed a volumetric analysis. When comparing the volume of agent required to extinguish the inclined-plane fires, Novec 1230 required 9.1% more agent than Halotron I. On the 16-ft pan fire tests, Novec 1230 required 5.8% more time, 21.1% more agent by weight, and 11.8% more agent by volume. Neither agent was able to extinguish any of the 30-ft pan fires, but an analysis of the amount of fire suppressed showed that both agents performed similarly. On the engine nacelle fires, Novec 1230 extinguished the fires 30.7% faster than Halotron I, but required 20.9% more agent by weight and 11.7% more agent by volume. The difference in performance parameters between each agent was consistent throughout all equivalent tests, with the exception of extinguishment time on the simulated engine nacelle fires conducted by the USAF and U.S. Navy.

1. INTRODUCTION

Since Halon® 1211 ceased production in 1994 and the availability diminishes, stakeholders have sought suitable replacement clean agents. 3M™ is currently seeking Federal Aviation Administration (FAA) approval for a clean agent, Novec™ 1230, for use as a complementary extinguishing agent at airports certificated by Title 14 Code of Federal Regulations (CFR) Part 139 [1]. Novec 1230 has no ozone-depleting potential, low global-warming potential, and an atmospheric lifetime that is measured in days rather than years. Prior to the FAA's consideration for approval, the Novec 1230 extinguishing capabilities must be validated as outlined in the technical report DOT/FAA/AR-95/87 [2], as required by 14 CFR Part 139.5.

1.1 BACKGROUND

A clean agent is defined as a gaseous extinguishing substance that leaves no residue and does not conduct electricity. Halon 1211 was previously the primary clean agent used by Aircraft Rescue and Firefighting (ARFF) departments. However, it was found to have ozone-depleting qualities, and the United States (U.S.) Environmental Protection Agency (EPA) developed a plan to phase out the use of Halon 1211 in accordance with the Montreal Protocol Clean Air Act [3]. Halon 1211 production has been banned since January 1 1994, with remaining stockpiles only permitted to be used for emergency situations and critical firefighter training [3]. Since then, several other EPA-compliant clean agents have been developed and tested.

In October 1995, the FAA released DOT/FAA/AR-95/87, which evaluated the fire-extinguishing capabilities of two potential replacements for Halon 1211, Halotron® I and perflourohexane (C_6) [2]. The extinguishing capabilities of Halon 1211 and both potential replacement agents were evaluated with a series of tests thought to represent real-world applications. These tests consisted of (1) dry-pooled fuel fire tests, (2) three-dimensional inclined-plane flowing fuel fire tests, (3) simulated engine nacelle running fuel fire tests, and (4) simulated wheel brake fire involving hydraulic fluid tests. In addition, the throw ranges for each agent were compared using hand line tests. It was recommended that any future testing of potential replacements for Halon 1211 follow those test setups as closely as possible [2]. Halotron I extinguished a sufficient number of test fires while using an average of 1.5 times as much agent by weight than Halon 1211 did in the same tests and subsequently received approval for ARFF use at FAA-certificated airports. Agreements were later made to phase out production of the hydrochlorofluorocarbon HCFC-123, the main component of Halotron I, by 2020 [4]. Halotron I production is not thought to be impacted by this phase-out due to significant remaining inventories and its ability to be recycled [4].

In the early 2000s, 3M released Novec 1230 for use as a clean extinguishing agent. Novec 1230 received approval as a suitable replacement streaming agent under the EPA's Significant New Alternatives Policy in January 2003 [5]. Based on the test setups described in DOT/FAA/AR-95/87, a series of evaluations was developed for this research effort that would provide a comparison of the extinguishment capabilities of Novec 1230 to those of the current clean agent most widely used in the industry, Halotron I. Although Halon 1211 has been considered the baseline agent in previous evaluations, it is no longer produced, and no domestic ARFF vehicle manufacturers currently offer it as a complimentary agent system option.

1.2 PURPOSE

The purpose of this report is to describe and analyze the results from evaluations of the extinguishing capabilities of Novec 1230 in (1) simulated wheel brake fire involving a hydraulic fluid tests; (2) three-dimensional, inclined-plane fire tests; (3) 16- and 30-foot (ft) pan fire tests (which were done in place of the dry-pool fire tests); and (4) simulated engine nacelle running fuel fire tests. These test results will be compared to results from identical tests conducted with Halotron I, based on those described in DOT/FAA/AR-95/87 [2]. Data from evaluations conducted by the U.S. Air Force (USAF) and Navy were used as official test results and data for the engine nacelle fires [6 and 7].

2. OBJECTIVES

The objectives of this series of experiments are as follows:

- Evaluate the extinguishing capabilities of Novec 1230 on a variety of full-scale fires.
- Quantify the amount of agent necessary to extinguish each type of fire.
- Compare applicable results to data from previous evaluations of clean extinguishing agents.
- Obtain data for the currently accepted clean extinguishing agent performance on new experimental configurations performed for this research effort.
- Quantify the performance of Novec 1230 in terms of the current clean extinguishing agent.

3. EQUIPMENT AND MATERIALS

This section describes the materials and equipment used during each evaluation to discharge the agent, prepare the experimental configurations, and collect all relevant data.

3.1 FIRE-EXTINGUISHING AGENT AND EQUIPMENT

To satisfy all the requirements outlined in DOT/FAA/AR-95/87, a research team evaluated Novec 1230 when being discharged from a wheeled flight line fire extinguisher. The team also conducted an additional series of experiments to validate the use of Novec 1230 as a drop-in replacement for current truck-based, clean agent systems being discharged through a hand line, without the need to optimize the existing system.

Due to the changes in the experimental configurations from DOT/FAA/AR-95/87, the team repeated some tests using Halotron I to have accurate and comparable data. These tests included both 16- and 30-ft pan fire tests and the three-dimensional inclined-plane tests. Previous tests conducted by the U.S. Navy provided data on the engine nacelle fire tests using Halotron I [7].

3.1.1 Novec 1230 Properties

Developed by 3M, Novec 1230 is a fluorinated ketone that has the chemical symbol $C_6F_{12}O$ and is designated in clean agent standards as FK-5-1-12. It is a liquid under ambient conditions, but can transition to a gaseous state upon discharge from an extinguisher. In both states, it is electrically nonconductive. Novec 1230 extinguishes fires by absorbing energy from the surrounding space, suppressing the conditions under which combustion is able to occur. Because of its relatively low-vaporization heat and high-vapor pressure, it can evaporate over 50 times faster than water. Physical properties for Novec 1230 compared with those of Halon 1211 and Halotron I are given in table 1. [8]

Table 1. Physical Properties of Novec 1230, Halon 1211, and Halotron I at 77°F [8 and 9]

Property	Novec 1230	Halon 1211	Halotron I
Molecular Weight (grams per mole (g/mol))	316.04	165.4	150.7
Boiling Point at 1 atmosphere (atm) (degrees Fahrenheit (°F))	120.6	25.0	80.6
Saturated Liquid Density (pound mass per cubic foot (lbm/ft^3))	99.9	116.0	92.3
Density of Gas at 1 atm (lbm/ft^3)	0.851	0.435	0.383
Vapor Pressure (pounds per square inch (psi))	20.5	38.7	95.0

Novec 1230 is reported to have a minimal environmental impact [8]. This is considered to be a desirable characteristic due to the previous phase out of Halon 1211 caused by its negative effects on the environment. Although the environmental impacts are outside the scope of this research effort, it may be an important consideration if Novec 1230 is considered for approval as a clean extinguishing agent. Relevant environmental properties for Novec 1230, Halon 1211, and Halotron I are given in table 2.

Table 2. Environmental Properties of Novec 1230, Halon 1211, and Halotron I [8 and 9]

Property	Novec 1230	Halon 1211	Halotron I
Ozone-depleting potential	0.0	4.0	0.019
Global-warming potential	1.0	1890.0	341.0
Atmospheric lifetime (years)	0.014	16.0	3.5-11.0

As with other clean firefighting agents, there are still hazards associated with thermal decomposition products (TDPs). Novec 1230, similar to many other clean firefighting agents, decays into its TDPs when it reacts with a fire due to high temperatures, inducing a breakdown of its component molecules. The TDPs of greatest concern for fluorine-based agents are hydrogen fluoride (HF) and carbonyl fluoride (COF_2). COF_2 reacts with water and forms HF and carbon dioxide. HF converts to hydrofluoric acid upon interaction with water, forming an acid gas. Hydrofluoric acid is corrosive, toxic, and poses an immediate health risk, even in small amounts. It has been determined that the highest concentration of HF that is tolerable for humans in a 1-minute exposure is approximately 120 parts per million (ppm). [10]

Different fluorine-based firefighting agents have been found to produce HF concentrations that are considerably higher than Halon firefighting agents, with Novec 1230 having the capability to produce approximately 10 times the amount of HF than that of Halon 1311. The factors that have been found to affect the concentration of HF and other TDPs produced the most are the ratio between the fire size and the room volume, the concentration of the firefighting agent, and the agent discharge time [11]. The resultant TDP concentrations can be vastly diminished in fixed fire suppression systems by correctly designing the system for the application; however, when used in a streaming application during an ARFF operation, the factors affecting the production of TDPs are not easily controlled.

3.1.2 Amerex Model 776 Fire Extinguisher

Novec 1230 was discharged from an Amerex® Model 776 fire extinguisher for the simulated wheel brake fire test, three-dimensional inclined-plane fire test, and the 16- and 30-ft pan fire tests. For each test described in DOT/FAA/AR-95/87, agent was contained in an Amerex Model 600 extinguisher. Table 3 shows specifications for the Model 776 and Model 600 extinguishers, and figure 1 is a photograph of the Model 776 extinguisher. It should be noted that tests with Novec 1230 conducted in AFCEC-CX-TY-TR-2014-0033 used an Amerex Model 775 extinguisher [6]. All specifications of the 775 and 776 are identical with the exception of the wheels on each unit.

Table 3. Specifications for Amerex Model 776 and Model 600 Fire Extinguishers [6]

Specifications	Amerex Model 776	Amerex Model 600
Agent	Novec 1230	Halon 1211
Underwriters Laboratories® (UL) Rating	3A:80B:C	30A:240B:C
Capacity (lb)	150	150
Shipping Weight (lb)	422 (filled) 272 (empty) ±15	315 (filled) 165 (empty) ±15
Discharge Time (seconds (s))	22	48
Cylinder—DOT 4BW240 Operating Pressure (psi) Test Pressure (psi) Burst Pressure (minimum psi)	 125 480 960	 200 480 960
Discharge Range (ft)	30	30–40
Operating Temperature Range (°F)	-40 to +120	-65 to +120
Safety Disc Burst Range (psi)	400–500	400–500
Hose Length (ft)	40	50
Hose Diameter (in.)	1.0	0.75
Wheels (in.)	36 vulcanized rubber	16 × 4 semi-pneumatic
Height (in.)	62	59
Width (in.)	29	29
Depth (in.)	40	36

Figure 1. Amerex Model 776 Fire Extinguisher

3.1.3 Halotron I and Amerex Model 674 Fire Extinguisher

Halotron I is currently the only produced, FAA-approved clean extinguishing agent for ARFF applications. Table 4 shows the physical properties of Halotron I. The research team used Halotron I in this research effort to provide comparable data on new or modified experimental configurations.

The research team used an Amerex Model 674 extinguisher to discharge Halotron I in all respective tests conducted during this research effort. It should be noted that during the initial series of tests conducted under DOT/FAA/AR-95/87 with Halotron I, the agent was discharged from a Halon 1211 extinguisher with no performance modifications or alterations. Table 4 shows the specifications of the Model 674 extinguisher compared to the Amerex Model 776 extinguisher used for Novec 1230 testing, and figure 2 is a photograph of the Amerex Model 674 extinguisher.

Table 4. Specifications for Amerex Model 776 and Amerex Model 674
Fire Extinguishers [6 and 7]

Specifications	Amerex Model 776	Amerex Model 674
Agent	Novec 1230	Halotron I
UL Rating	3A:80B:C	10A:120B:C
Capacity (lb)	150	150
Shipping Weight (lb)	422 (filled) 272 (empty) ±15	388 (filled) 238 (empty) ±15
Discharge Time (s)	22	38
Cylinder Operating Pressure (psi) Test Pressure (psi) Burst Pressure (minimum psi)	DOT 4BW240 125 480 960	DOT 4BW500 125 480 1200
Discharge Range (ft)	30	30–40

Table 4. Specifications for Amerex Model 776 and Amerex Model 674
Fire Extinguishers [6 and 7] (Continued)

Specifications	Amerex Model 776	Amerex Model 674
Operating Temperature Range (°F)	-40 to +120	-40 to +120
Safety Disc Burst Range (psi)	400–500	400–500
Hose Length (ft)	40	50
Hose Diameter (in.)	1.0	0.75
Height (in.)	62	64
Width (in.)	29	30
Depth (in.)	40	42

Figure 2. Amerex Model 674 Fire Extinguisher

3.1.4 Modified Clean Agent Skid

Instead of using a wheeled flight line fire extinguisher for the simulated engine nacelle running fuel fire tests, a truck-based system mounted to a skid was used for hand line application. This was done for two reasons: (1) the USAF has performed identical experiments previously with a reliable set of data, and (2) it allows for a comparison of extinguisher application to hand line application. The use of this system provides validation to ensure Novec 1230 can be used as a direct drop-in replacement agent without the need to modify existing systems. Figure 3 is a photograph of the modified Fire Combat clean agent, skid-mounted system used in the test. The research team modified the skid system to include instrumentation and data collection systems. The team installed these modifications so they did not alter the performance of the system. The agent storage tank was positioned on top of four load cells to monitor the weight of the tank for determining the amount of agent discharged and flowrate across all the tests. Additionally, two pressure transducers with snubbers were installed on this system, one on top of the agent tank and the other immediately preceding the nozzle. These sensors were then connected to a data acquisition system, which was connected to a laptop running a custom LabVIEW® program to record and monitor all data. The specifications of this system were designed to meet the standards of the National Fire Protection Association® (NFPA) 414 Standard for Aircraft Rescue and Firefighting Vehicles for halogenated hand lines [12]. This Standard specifies a discharge range of at least 25 ft, a minimum discharge rate of at least 5 lb/s, a hose with an inner diameter of at least 1 in., and a hose length of at least 100 ft [12].

Figure 3. Modified Fire Combat Clean Agent Skid

3.2 TEST LOCATIONS

A research team at William J. Hughes Technical Center (WJHTC) conducted the simulated wheel brake test, three-dimensional inclined-plane test, and the pan fire tests. The WJHTC team performed these tests within a designated full-scale fire test area on a specialized concrete pad. The pad is pitched towards a drain to contain and transfer the fuel, firefighting agent, and contaminated water into a holding tank, thereby preventing contamination to the surrounding environment. Additionally, a water hand line and a foam hand line were available for safety.

A research team at Tyndall Air Force Base (TAFB) conducted the simulated engine nacelle running fuel fire tests using an F100 engine nacelle mockup. The team situated the nacelle on a concrete catch basin with a sump pit, which was designed to collect and contain most of the fuel and agent discharged during each test. After each test, the team pumped the sump into a holding tank for disposal later. A high-pressure foam hand line was available for safety.

3.3 TEST FUELS

JP-4 fuel was used for the Halon replacement tests in DOT/FAA/AR-95/87. However, due to the limited availability of JP-4 and the abundance of Jet-A fuel, the teams used Jet-A in the three-dimensional inclined-plane fire tests, 16- and 30-ft pan fire tests, and the simulated engine nacelle running fuel fire tests. Jet-A is a kerosene-based fuel with a regression rate lower than JP-4 fuel. Table 5 shows the relevant properties of JP-4 and Jet-A fuels.

Table 5. Properties of JP-4 and Jet-A Fuel [13 through 17]

Properties	JP-4	Jet-A
Flash Point (°F)	0.0	100.4
Auto-Ignition Temperature (°F)	474.8	410.0
Freezing Point (°F)	-52.2	-42.8
Boiling Point Range (°F)	113-572	300-572
Vapor Pressure at 68°F (psi)	1.76	0.0077
Density at 71°F (lb/ft^3)	47.45	50.57
Lower Flammability Limit (%)	1.3	0.7
Upper Flammability Limit (%)	8.0	5.0
Specific Energy (British thermal unit per pound mass (BTU/lbm))	18451	18451
Regression Rate (in./min)	0.148	0.130
Specific Heat at 104°F (BTU/lbm°F)	0.514	0.490

The simulated wheel brake fire test was representative of hot brakes igniting hydraulic fluid and the resultant oil and tire fire. The hydraulic fluid used for the testing in DOT/FAA/AR-95/87 [2] was specified as Military Specification MIL-H-5606F [18]. The tests conducted with Novec 1230 used Mobil Aero™ HFA Aviation Hydraulic fluid, which met MIL-H-5606A [19] specifications.

3.4 DATA COLLECTION

For all WJHTC evaluations, the team photographed the test area before, during, and after each test and recorded all the tests with video cameras in at least two different positions to capture alternate viewpoints. The team placed the cameras at a minimum offset of 90° from each other around the test fixture, allowing for the most comprehensive coverage of each test and uninterrupted documentation in the event that one camera's view became obscured. The camera positions for each test varied based on which test fixture was used, wind direction, extinguisher discharge direction, and test area obstructions present.

The WJHTC team recorded data on wind speed, weight of the extinguisher before and after testing, preburn time, discharge time, and time to extinguishment. The team members noted the time and details of any peculiarities such as fire spreading outside the test area, re-ignition of fire after the initial extinguishment, or accidental discharge of the extinguisher.

For all TAFB evaluations, the team took photographs of the test area before, during, and after each test, which was also recorded by two video cameras from different positions. A laptop computer running the custom LabVIEW program connected to the modified FireCombat skid system recorded discharge time, agent discharged, and tank and nozzle pressures.

The teams measured wind speed and monitored it for at least 3 minutes prior to each test to ensure there were no gusts that exceeded the respective test's threshold. The teams used handheld weather meters to measure and monitor the weather conditions at both test locations. The WJHTC team used a Mastech® MS6300 (figure 4) and TAFB team used a Kestrel® 5000 Environmental Meter (figure 5). A research team member sampled multiple areas around the test fixture prior to each test. If any measurement exceeded the threshold, testing was suspended until weather conditions were more favorable. The average and peak wind speeds were both recorded prior to each test.

Figure 4. Mastech MS6300 Weather Meter

Figure 5. Kestrel 5000 Environmental Meter [20]

For each WJHTC evaluation that used Jet-A fuel, the fuel was pumped through a Fill-Rite® FR4211D with a Tuthill 800C flow meter, shown in figure 6. The team used this pump to measure and distribute the fuel in each test. The team also used this pump in conjunction with a stopwatch to determine the fuel flow rate when conducting experiments on the three-dimensional inclined-plane test fixture.

Figure 6. Fill-Rite FR4211D Fuel Pump With a Tuthill 800C Flow Meter

In each experiment where an extinguisher was used, the extinguisher was weighed before and after discharge. The team used a Brecknell® CS-2000 scale, shown in figure 7, to weigh the extinguisher before each test, after each test, and during each refill procedure. The scale was attached to each extinguisher and lifted by a forklift. Each measurement was taken a minimum of two times and recorded. For the experiments that used the Fire Combat skid, the team continuously monitored and recorded the weight using the LabVIEW program and integrated load cells.

Figure 7. Brecknell CS-2000 Hanging Scale

Two research team members monitored and recorded times using handheld stopwatches. The stopwatches were used to determine when the preburn phase of each experiment concluded and extinguishment efforts began. The discharge and extinguishment times were recorded by hand then later verified and/or corrected using videos from each test.

4. TEST SETUP AND PROCEDURES

Sections 4.1 through 4.4 describe the pretest procedures, test configurations and procedures, posttest procedures, and data analysis used during this research effort.

4.1 PRETEST PROCEDURES

Prior to conducting any tests, team members measured the wind speed with a handheld anemometer at several locations around the test area to ensure the wind was consistently below the maximum allowable speed for the respective test. During gusts, both the average and maximum wind speeds were recorded. For the simulated wheel brake fire and three-dimensional inclined-plane fire, if the wind speed surpassed the predetermined threshold by a minimal amount, team members placed wind screens upwind of the test fixture (shielding the test area) and rechecked the wind speeds in multiple areas around the test fixture. However, if wind speeds in the immediate area could not be reduced below the test's limit, testing was suspended until conditions became favorable. In addition, testing was suspended if it began to rain to ensure accurate results for the firefighting agent capabilities.

While weather conditions were being monitored, team members weighed the extinguisher a minimum of two times and recorded the starting weight. Figure 8 is a photograph of the forklift lifting the scale and extinguisher configuration. For the engine nacelle fires using the clean agent skid unit, the data acquisition system measured and recorded the starting weight. This process included connecting the laptop to the data acquisition system and confirming all sensors were connected and functioning. Prior to the first test, the team calibrated the load cells by placing calibration weights on the agent tank and confirming the accuracy of the measurements.

Figure 8. Fire Extinguisher Being Weighed

The three-dimensional inclined-plane fire test and the 16- and 30-ft pan fires required the pans to be filled with water. This was done to ensure a consistent and even fuel layer and to protect the concrete test pad from spalling. For the 16- and 30-ft pan fires, the pan was filled until a minimum ¾ in. of water completely covered the bottom of the pan. For the inclined ramp, the team filled the pan approximately halfway with water (approximately 4 in.) prior to beginning the fuel flow.

Additional preparations for each test included setting up the video cameras, wetting the test pad, and setting up safety lines. For all WJHTC tests, prior to dispensing fuel, the team saturated the concrete around the test fixture to prevent spalling from the heat of the fire. Also, during the pan fires, team members stretched and charged an AFFF hose line. For TAFB tests, the team stretched and readied an AFFF hose line to be used as a backup line.

After all other preparations were made and weather conditions were favorable, a team member dispensed fuel into each test fixture. For the simulated wheel brake fire, the team member dispensed hydraulic oil from graduated buckets to ensure proper fuel volume and then dispensed the oil onto the test fixture. For the inclined ramp, a team member confirmed the flow rate by measuring the time it took to dispense 4 gallons of fuel into a graduated bucket through an alternate outlet. After confirmation, the team member shut down the fuel pump and configured valves to allow fuel to flow over the ramp. For the 16- and 30-ft pan fires, a team member dispensed fuel through a hose and nozzle that were connected to the fuel pump. The team monitored the volume from the flow meter on the fuel pump, and shut it down once the desired value was reached. For the engine nacelle, the team used the inline flow meter to confirm fuel flow prior to the warming process. The team used a wheeled propane torch to ignite the fuel until a significant portion of the fixture was on fire, after which the torch was removed from the test area.

4.2 TEST CONFIGURATIONS AND PROCEDURES

Sections 4.2.1 through 4.2.4 describe the setup and execution of each test that was performed. The research teams designed the tests to follow the ones outlined in DOT/FAA/AR-95/87 as closely as possible, with aspects of those tests being altered if necessary. Additionally, the simulated engine nacelle fire tests followed the procedures described in AFCEC-CX-TY-TR-2014-0033 [6].

4.2.1 Simulated Wheel Brake Fire Involving Hydraulic Fluid Test

The purpose of this test was to represent an aircraft brake fire scenario involving hydraulic fluid. The test setup consisted of an aircraft rim and tire mounted on a stand inside a 4-by-4-ft pan, which is shown in figure 9.

Figure 9. Simulated Wheel Brake Fire Involving Hydraulic Fluid Test Setup

The aircraft tire used in the DOT/FAA/AR-95/87 test was a deflated McDonnell Douglas F-4C aircraft tire, whose nominal dimensions are given in table 6 [21]. The deflated dimensions were not provided in DOT/FAA/AR-95/87. The tire used in this research effort was a deflated Boeing B-737-200 main gear tire, whose nominal dimensions are given in table 6 [21]. When deflated, the tire had a 36-in. diameter and 14-in. width. The tire was mounted on a 16-in. rim with a 14-in. width. The allowable wind speed threshold for testing with this configuration was 3 miles per hour (mph).

Table 6. Dimensions of Tires Used in Wheel Brake Fires [21]

Research Effort	Halotron I Evaluations (DOT/FAA/AR-95/87)	Novec 1230 Evaluations (this report)
Tire Size (in.)	30X11.50-14.50	40X14-16
Rim Diameter/Width (in.)	14.50/9.75	16/14

To begin, the research team dispensed 2 gallons of hydraulic fluid in the bottom of the pan, followed by 1 gallon on top of the tire itself, distributing the fluid as evenly as possible. The fluid in the pan was ignited the first, followed by the fluid on the tire. After the fire became fully involved, a 90-second preburn phase began. The fire was considered fully involved when all areas of hydraulic fluid appeared to be ignited. An example of a fully involved fire is shown in figure 10. After 90 seconds, the firefighter approached the tire and commenced extinguishing efforts. When the research team confirmed the fire was fully extinguished, the team recorded the time to extinguishment and discharge time and measured the extinguisher weight to determine how much agent had been discharged.

Figure 10. Fully Involved Simulated Wheel Brake Involving Hydraulic Fluid Test Fire

Another difference between the simulated wheel brake fire testing conducted in this research effort and DOT/FAA/AR-95/87 was the firefighter's approach. In DOT/FAA/AR-95/87, the firefighter took a direct approach parallel to the tire tread. For the simulated wheel brake fires with Novec 1230 conducted during this research effort, the firefighter took an offset approach, approximately 45° to the tire tread. The firefighter took this approach to provide consistency with the currently taught ARFF-training tactics.

4.2.2 Three-Dimensional Inclined-Plane Fire Test

The purpose of this test setup was to simulate a fire propagated by fuel flowing over sloped terrain into a pooled area. The test setup consisted of a concrete ramp, the top of which had a pipe that dispensed fuel at a rate of 4 gallons per minute (gpm) through 27 evenly spaced, ¼-in. holes. This rate was increased from the DOT/FAA/AR-95/87 tests to ensure the ramp was adequately covered in fuel. The 3-gpm flow rate specified in DOT/FAA/AR-95/87 did not completely cover the ramp so the research team gradually increased the fuel flow rate until the ramp was adequately covered. The fuel flowed down the ramp into a metal catch basin, which was partially filled with water to protect the concrete of the test pad. The ramp was 20 ft long, 61 in. wide, and had a slope of 4.7°. The catch basin was 4 ft long and 8 ft wide, with the wider side oriented parallel to the edge of the ramp. This fixture is shown in figure 11.

Figure 11. Ramp With Catch Basin

Before each test began, the research team cleaned the ramp, drained and rinsed the catch basin to remove any contaminants, and added new water. Then, the team pumped Jet-A fuel out of the pipe at a rate of 4 gpm. Once the fuel had covered the ramp and began pouring into the catch basin, the accumulation period began. This accumulation period lasted until 5 gallons of fuel had been dispensed, ensuring adequate fuel accumulation on the ramp and in the catch basin. After 5 gallons of fuel had accumulated, the fuel was ignited. Ignition began at the top of the ramp, below the fuel dispensing pipe, and continued down the ramp as necessary. Due to the continuous flow of fuel, upper portions of the ramp had to be reignited during the ignition process in some cases. It should be noted that the fuel flowing from the dispensing pipe did not ignite until it splashed onto the ramp throughout the entirety of each test. When the fire became fully involved, a 60-second preburn phase began, as shown in figure 12. Fully involved was defined as when all of the catch basin and all of the fuel flowing down the ramp were on fire. The firefighter then commenced extinguishing efforts, beginning at the catch basin and moving up the ramp towards the fuel-dispensing pipe. When the fire was fully extinguished, the team shut down the fuel supply to the ramp, recorded the time to extinguishment and discharge time, and measured the weight of the extinguisher again to determine how much agent had been discharged. The wind speed threshold for testing with this fixture was 5 mph.

Figure 12. Three-Dimensional Inclined-Plane Fire Test During Preburn

4.2.3 Pan Fire Tests

In DOT/FAA/AR-95/87, the effectiveness of Halon 1211 and both potential replacement agents were evaluated using a dry-pool fire test. This test was intended to simulate fuel spills during flight line operations. The test was performed by pouring fuel onto a dry concrete surface over a given area that varied between 200 and 800 sq ft, igniting the fuel, and attempting to extinguish the fire in the shortest possible amount of time [2]. However, there were concerns that performing such a test on the test pad at the WJHTC would induce spalling in the concrete and that the low fuel quantity-to-area ratio would produce inconsistent fires, which could possibly self-extinguish during extinguishing procedures. In light of these concerns, the research team modified the testing parameters by increasing the fuel load for a given area and using water as the surface medium for the pooled fuel. These modifications to the test procedures provided a consistent fuel load and equivalent fire area for all same-sized pan tests regardless of application method. Due to these alternative configurations, a direct comparison of results between this research effort and that of DOT/FAA/AR-95/87 for representative spilled fuel fires does not allow for an accurate comparison of extinguishing performance. For this reason, the research team performed these tests with both Novec 1230 and Halotron I to allow for a comparison of the data under identical test conditions.

The alternative configurations consisted of a shallow steel pan with a 30-ft diameter, and a steel ring with a 16-ft diameter that could be placed in the pan and used to contain fuel in a smaller area. Both the ring and the pan were 6 in. deep. The ring and the pan allowed for the testing of fires with areas of approximately 200 and 700 sq ft, respectively. In both configurations, the pan was partially filled with water prior to dispensing the fuel. Using water as a test bed protects the concrete pad and test fixture from damage and produces a uniform fuel layer across the surface. The uniform fuel layer ensured that the entire area would burn. Figure 13 shows a research team member dispensing fuel into the 16-ft ring. Another research team member had previously filled the 30-ft pan with water.

Figure 13. The 30-ft Pan With 16-ft Ring

Prior to each test, the team cleaned the steel pan to ensure that there was no contaminates that could influence each test. Cleaning consisted of debris removal, rinsing the pan with water, and then removing any remaining puddles with squeegees. The pan was then filled with water until it reached a depth of at least ¾ in. at the shallowest section.

After the team filled the pan with an adequate amount of water, they added the prescribed amount of fuel to either the ring or the entire pan for each test. The volumes of Jet-A fuel specified were 19.8 gallons for the 16-ft ring and 70 gallons for the 30-ft ring. These values were determined based on a calculated fuel consumption of a steady-state, fully involved pooled fuel fire with no wind, to ensure a burn time of at least 1 minute regardless of which fuel was used. These amounts were determined to be sufficient to ensure the fuel had not been exhausted prior to being considered extinguished for each configuration. The fuel was ignited after the firefighter dispensed the proper amount of fuel into the ring or the pan. Ignition began at one point on the edge of the fuel layer and continued around the edge until a significant portion of fuel was ignited. The fire was then allowed to naturally spread across the pooled fuel. The fire was considered fully involved once the entire pool was on fire, as shown in figures 14 and 15 for the 16-ft ring and 30-ft pan tests, respectively. Once the fire became fully involved, the team conducted a 20-second preburn phase, after which extinguishing efforts began. When the firefighter extinguished the fire or depleted the extinguisher, the team recorded the time to extinguishment and total discharge time, and measured the extinguisher weight to determine how much agent was discharged. The wind speed threshold for testing with these fixtures was 7 mph.

Figure 14. Fully Involved Fire in 16-ft Ring

Figure 15. Fully Involved Fire in 30-ft Pan

4.2.4 Simulated Engine Nacelle Running Fuel Fire Test

This test utilized the USAF's F100 nacelle mockup, pictured in figure 16, which is designed to simulate an engine fire with fuel continuously leaking onto the ground. The TAFB research team conducted these tests at the Silver Flag test site. All tests conducted during this research effort for this experimental configuration utilized Novec 1230 discharged from a hand line supplied by the Fire Combat clean agent skid unit. This alteration of discharge method was done for two reasons: the USAF has previously conducted equivalent tests using an equivalent Novec 1230 extinguisher, and altering the discharge method would provide validation that hand line application does not hinder the extinguishing capabilities of the agent. The previous tests conducted by the USAF, as detailed in AFCEC-CX-TY-TR-2014-0033, produced a valid and relative data set to be used in this research effort. In light of this available data set, it was decided to use this experimental configuration as a verification of extinguishing capabilities when discharged from a hand line [6]. The hand line application is representative of a typical ARFF response under conditions matching this experimental configuration. The U.S. Navy also performed clean agent tests on the simulated engine nacelle running fuel fire test fixture using Halon 1211 and Halotron I. These tests were detailed in NAWCWD TM 8572, and the relevant Halotron I tests were accepted as data to be used during this research effort [7].

The test apparatus consisted of two concentric metal cylinders that had a length of 16 ft and internal volume of 189 ft^3, and was raised 47 in. off the ground over a catch basin. The cylinder was divided into four sections, with a 36-in.-long front section (fan section), the two 33-in.-long middle sections (compressor and low pressure turbine sections), and the 90-in.-long rearmost section. Between each section was a series of metal baffles that were 2 in. wide, 1/8 in. thick, and spaced 2 in. apart. While modifications to this test fixture have been made since used in DOT/FAA/AR-95/87, the dimensions have remained the same. Figure 16 is a photograph of the nacelle, and figure 17 shows a cross-sectional diagram of the nacelle with relevant parts and dimensions labeled. The nacelle can be moved around the catch basin to account for changes in wind direction while keeping the afterburner section above the catch basin. [7]

Figure 16. Simulated Engine Nacelle Running Fuel Fire Test Apparatus

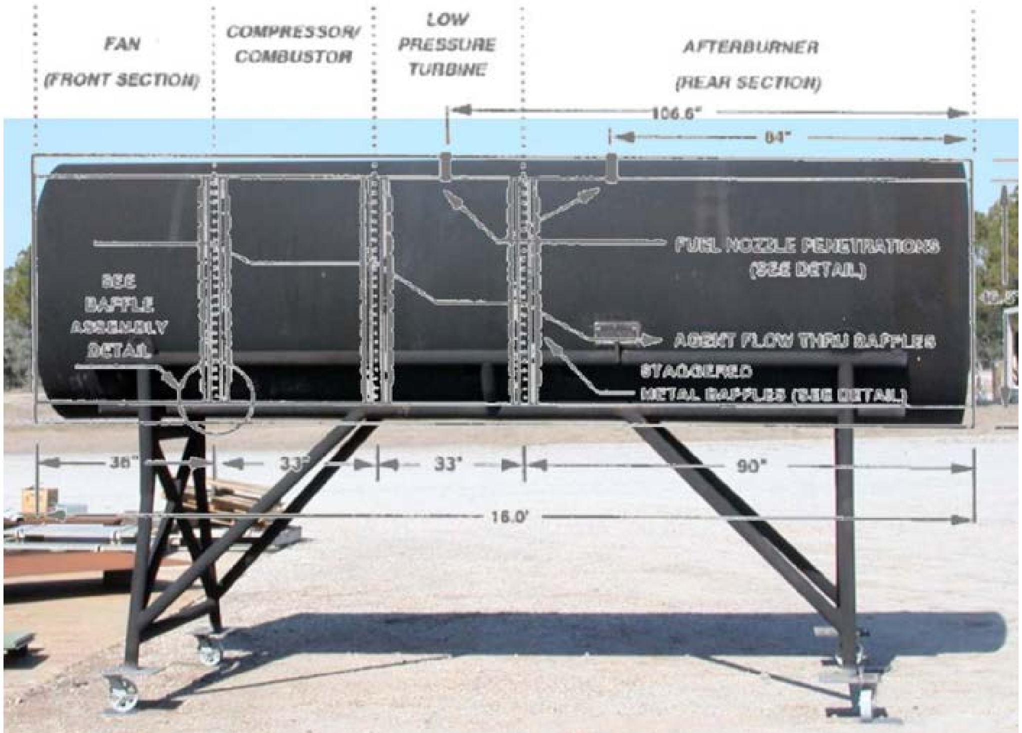

Figure 17. Simulated Engine Nacelle [7]

The procedure for this test followed that of the rear-engine fire tests detailed in AFCEC-CX-TY-TR-2014-0033, which was split into distinct pretest and test phases. To begin the pretest phase, the team confirmed that all instrumentation and the data acquisition system was functioning and accurate, the agent tank was pressurized, and the pressure and weight of the agent tank were recorded. Next, a team member started the flow of Jet-A fuel at a rate of 2 gpm through the afterburner nozzle. That fuel was then ignited, and the tail pipe was heated to a temperature of within 25° of 550°F. A team member verified the temperature using a handheld infrared thermometer. The fuel flow was then shut off, and the tail pipe was allowed to cool to a temperature of within 25° of 475°F, again verified by a handheld infrared thermometer. A team member then started fuel flows through the low-pressure turbine and afterburner nozzles at a rate of 2 gpm each, providing a total flow rate of 4 gpm. The fuel was allowed to flow until 25 gallons had been dispensed. If spontaneous ignition occurred during this process, the team member shut off the fuel flow, allowed the fixture to cool further, and restarted the fuel flow. [6]

Prior to beginning the test phase, team members charged the hand line and recorded instrumentation measurements. Then, the team began the test phase by igniting the two fuel flows from the low-pressure turbine and afterburner nozzles using torches inserted through the corresponding ignition ports. Next, the firefighter ignited the fuel in the catch basin and allowed it to burn for 15 seconds, after which extinguishing efforts commenced. Once the fire was extinguished, a team member recorded the time to extinguishment and amount of agent discharged as determined by load cell values on the clean agent skid. The wind speed threshold for testing with this setup was 5 mph.

4.3 POSTTEST PROCEDURES

After a test was completed at the WJHTC, the research team weighed the extinguisher with any remaining agent, hose, and nozzle. The extinguisher weight was used to determine the amount of agent discharged during that test. A team member shut the extinguisher valve, discharged any remaining agent in the hose, and then disconnected the hose from the extinguisher. The extinguisher tank was positioned horizontally, and the discharge valve was opened to depressurize the extinguisher. This was done to conserve as much agent as possible. The Novec 1230 extinguisher was completely depressurized, while the Halotron I extinguisher was bled until 5-10 psi remained. These differences are solely attributed to the refilling procedures for each extinguisher.

Once the discharge valve of the Novec 1230 extinguisher was removed, the extinguisher was hung from the scale. New agent was pumped into the extinguisher from a 55-gallon drum while monitoring the weight. Once it was filled to the desired weight, the extinguisher was slowly pressurized with dry nitrogen while being agitated to promote the dissolution of nitrogen into the agent and achieve the required pressure. To ensure consistency between tests, the extinguisher was refilled and repressurized to the same amounts each time, a total weight of 422 lb and an internal pressure of 125 psi. After refilling and repressurizing the extinguisher, the team member weighed it again and recorded that as the starting weight for the next test, if the test was expected to occur the same day. An on-site 3M representative verified this process.

To refill the Halotron I extinguisher after being mostly depressurized, a team member connected a set of valves and gauges to the extinguisher's discharge port. These valves and gauges were connected to a bulk tank, which was pressurized with a cylinder of argon. The extinguisher was then hung from the scale to monitor the weight during the refill process. The liquid side of the bulk tank was opened to allow Halotron I to flow into the extinguisher until a total weight of 468 lb had been reached. Then, the liquid side of the Halotron I tank was closed and the gas side was opened, allowing argon and gaseous agent to flow into the extinguisher and pressurize it. The extinguisher was slowly pressurized to 150 psi, as verified by the extinguishers pressure gauge. The valve and associated hoses were then removed from the extinguisher, and the extinguisher was weighed again. This weight was used as the starting weight if another test was expected to be conducted. An on-site representative from American Pacific verified this process.

Refilling procedures differed slightly for the engine nacelle tests, which used the clean agent skid unit. First, a team member isolated the agent tank from the rest of the system using the discharge valve and pressurization valves and then depressurized the tank. The clean agent skid unit is equipped with an agent fill port, which was then connected to the pump and used to refill the agent tank. The skid's load cells were used to monitor the weight during the refilling process. Agent was pumped into the tank until the desired weight was achieved. The fill hose was then disconnected, and the tank pressurization valve was opened very slowly to promote the dissolution of nitrogen into the agent. After reaching equilibrium, the pressurization valve was fully opened.

Following the completion of each test, the team serviced and prepared each test fixture for the following test. This involved removing any water, fuel, or agent that remained; rinsing off the fixtures; and removing any standing water. After the team serviced the extinguishers and test fixtures and recorded all data, the test was considered complete.

4.4 DATA ANALYSIS

To determine the discharge time and time to extinguishment for tests that used an extinguisher, the values logged on the data sheets were cross-referenced with video footage from the corresponding tests. Time to extinguishment was calculated as the time between the initial discharge and the earliest time when no fire could be seen in any of the footage. Discharge time was calculated as the total time the firefighter had the hose nozzle open and was dispensing agent. The amount of agent used was divided by the total discharge time to determine the discharge rate.

From each video, a team member measured the time when the firefighter was directing discharge at the test area, as well as the time that discharge took to extinguish only the fire within the confines of each test fixture. These measurements represented the required discharge and extinguishment times, respectively. The team member multiplied the required extinguishment time by the calculated discharge rate to provide an estimate for just the amount of agent that was necessary to extinguish the test fire. In some instances, the firefighter directed the discharge to fire that had spread outside the test fixture. When this occurred for a minimum of 1 second, the team member used the discharge rate to estimate the weight of agent not directed at the test fixture and accounted for this when calculating the required discharge and time to extinguishment values.

For each test configuration, the team made a table listing the test number, date, average wind speed, maximum wind speed during gusts, test fixture extinguishment time, total discharge time, total agent used, estimated agent used for test fixture extinguishment, and flow rate for each test in that setup. Any tests that were not considered to be official were not included in the tables and not used in any of the corresponding calculations.

The team performed further analysis to calculate the volume of agent discharged during each evaluation. This was done for both Novec 1230 and Halotron I by using the saturated liquid densities at 1 atm for each agent. The liquid density was assumed to remain constant, and the vapor weight for each agent was assumed to be negligible in this analysis. These assumptions are corroborated by the manufacturer recommended use of a calibrated liquid level gauge to determine the amount of agent present in the skid unit during refilling procedures. [22] This method provided another basis of comparison of the results in an attempt to account for the difference in agent densities. The value for estimated volume of agent used is derived from the weight of each agent divided by the saturated liquid density of the respective agent.

Next, the team compared the results of each evaluation with Novec 1230 to results from evaluations of Halotron I, using Halotron I as the baseline. This was done due to Halotron I being the only currently produced, FAA-approved clean agent at indexed airports. The research team felt this would be a more accurate representation of agent performance due to the availability of equivalent testing data and the real world ubiquitous use of Halotron I.

5. TEST RESULTS AND DISCUSSION

The WHJTC research team tested Novec 1230 in March and April of 2017 and tested Halotron I in August through October of 2017. The TAFB research team tested Novec 1230 at the end of May 2017. This section details the results of those tests, while comparing them to the results of similar tests with Halotron I, the only currently produced, FAA-approved, clean-extinguishing agent.

5.1 SIMULATED WHEEL BRAKE FIRE INVOLVING HYDRAULIC FLUID TEST RESULTS

The research team conducted four simulated wheel brake fire tests. The results of three tests were considered to be official and used in the analysis. The results of Test 3 were discarded due to reignition of the hydraulic fluid caused by a small pocket of fire not seen by the firefighter. Table 7 shows the results for the extinguishment time, discharge time, and agent used for each test.

Table 7. Results for Novec 1230 Simulated Wheel Brake Fire Involving Hydraulic Fluid Test

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Discharge Rate (lb/s)
1	3/7/2017	2.5	2.5	17	17	91	91.0	5.35
2	3/7/2017	0.0	2.5	15	16	85	79.7	5.31
4	3/7/2017	1.1	2.2	11	15	87	63.8	5.80
Average				14.3			78.2	

The Test 1 fire was extinguished in 17 seconds, with a total discharge time also of 17 seconds and 91 lb of agent used, all of which was necessary to extinguish the fire. The Test 2 fire was extinguished in 15 seconds, with a discharge time of 16 seconds and 85 lb of agent discharged, an estimated 79.7 lb of which was necessary to extinguish the fire. The Test 4 fire was extinguished in 11 seconds with 15 seconds of discharge time. A total of 87 lb of agent was used during Test 4, 63.8 lb of which was estimated to be necessary to extinguish the fire. On average, each of the three official wheel brake fire tests took 14.3 seconds to extinguish and required 78.2 lb of agent to extinguish the fixture.

The Novec 1230 tests with this setup differed from the evaluations described in DOT/FAA/AR-95/87 in the direction that the firefighter took to approach the tire. During tests with Halon 1211 and Halotron I, the firefighter took an approach path that was parallel to the tire tread, whereas for the Novec 1230 testing, the firefighter made a diagonal approach instead, as shown in figure 18. This diagonal approach path was taken to more closely align with currently taught ARFF techniques. Because of this, a larger section of the tire surface and pan was obstructed, which could have adversely affected the firefighter’s ability to extinguish the fire as compared to previous testing. This may have resulted in additional repositioning around the test fixture to completely extinguish the fire. This obstructed view was the reason Test 3 was removed from the official results. A small pocket of fire remained on the opposite side of the tire from where the firefighter was positioned after closing the bail, and subsequently the fire reignited the test fixture.

Figure 18. Approach Path for Simulated Wheel Brake Fire Involving Hydraulic Fluid Test

Each Novec 1230 simulated wheel brake fire test had shorter extinguishment times than the test that preceded it. The same firefighter was used for each test, which could be an indicator of the firefighter becoming familiar with the test fixture and the extinguishing process, resulting in more efficient agent application. For each test, the portion of the fire that was directly in front of the firefighter was extinguished quickly, taking between 4 to 6 seconds. The firefighter spent the remainder of the extinguishment time repositioning around the fixture while applying agent.

The results for the Novec 1230 simulated wheel brake fire tests will not be compared to the results of Halotron I from DOT/FAA/AR-95/87. While the test configurations were very similar, the research team concluded that the differences between the tests conducted in both research efforts skewed the results significantly. It should be noted that only one test for Halotron I was conducted during the evaluations described in DOT/FAA/AR-95/87. After thorough review of video footage from both series of tests, the research team found that the offset approach in conjunction with the larger tire caused a significantly greater portion of the test fixture to be obscured compared to previous testing. This affected the firefighter’s view of the fire and hindered the direct application of agent. As previously described, the majority of the discharge times during the Novec 1230 tests consisted of the firefighter repositioning around the test fixture to ensure all fire was extinguished. In light of the differences between test parameters and the associated effects, a comparison of the results from both tests would not be representative of either agent’s extinguishing capabilities.

5.2 THREE-DIMENSIONAL INCLINED-PLANE FIRE TEST RESULTS

A total of four Novec 1230 three-dimensional inclined-plane fire tests were conducted, three of which were considered to be official and used in this analysis. The Test 2 results were discarded due to an improperly filled extinguisher. The results for all official Novec 1230 tests are provided in table 8.

Table 8. Results for Novec 1230 Three-Dimensional Inclined-Plane Fire Test

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/s)
1	3/9/2017	0.9	2.2	10	11	74	67.3	6.73
3	3/21/2017	0.0	1.8	11	16	94	64.7	5.88
4	3/28/2017	2.9	4.0	20	21	132	125.8	6.29
Average				13.7			85.9	

The Test 1 fire was extinguished the in 10 seconds, with a discharge time of 11 seconds. A total of 74 lb of agent was discharged, 67.3 lb of which was necessary to extinguish the fire. The Test 3 fire had a discharge time of 16 seconds, 5 seconds of which was not directed at the test fixture but at fires around the fixture. A total of 94 lb of agent was discharged while requiring 64.7 lb to extinguish the fixture. The Test 4 fire was extinguished in 20 seconds with a discharge time of 21 seconds. A total of 132 lb of agent was discharged, requiring 125.8 lb to extinguish the text fixture. On average, a discharge of 13.7 seconds and 85.9 lb of Novec 1230 was required to extinguish the fires.

The research team conducted additional tests on this fixture using Halotron I due to the differences in experimental configurations from the tests conducted in DOT/FAA/AR-95/87. A total of four tests were conducted overall, with three tests being considered official. The results for the official tests are listed in table 9. Test 1 was not considered an official test due to a clogging issue with the fuel-dispensing pipe on the test fixture.

Table 9. Results for Halotron I Three-Dimensional Inclined-Plane Fire Test

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/s)
2	10/23/2017	0	1.6	11	13	72	60.9	5.54
3	10/23/2017	0	0.7	10	12	68	56.7	5.67
4	10/23/2017	2.5	3.8	18	19	106	100.4	5.58
Average				13			72.7	

The Test 2 fire was extinguished in 11 seconds with a discharge time of 13 seconds. A total of 72 lb of agent was discharged with 60.9 lb required to extinguish the fire. The Test 3 fire was extinguished in 10 seconds with a discharge time of 12 seconds. A total of 68 lb of agent was discharged, of which 56.7 lb were necessary to extinguish the fire. The Test 4 fire was extinguished in 18 seconds with a discharge time of 19 seconds. A total of 106 lb of agent was discharged, of which 100.6 lb was necessary to extinguish the fire. For the three official inclined-plane tests conducted at the WJHTC, Halotron I took 13 seconds and required 72.7 lb of agent on average to extinguish the fires.

As shown in tables 8 and 9, Test 4 required a relatively drastic increase in agent required by weight. Novec 1230 required 1.9 times the amount of agent as the average of Tests 1 and 3. Halotron I required 1.7 times the agent by weight as compared to the average from Tests 2 and 3.

The research team attributed this increase to the increased wind velocity present in both tests. Unlike the other official tests in both test series, the average wind speed for Test 4 of each agent was greater than the measured peak winds in previous tests, but it still was below the threshold for this experimental configuration. Additionally, the wind direction in both tests was partially directed towards the firefighter, as shown from the smoke in figures 19 and 20. Due to the wind direction and the inability to adjust the test fixture, the firefighter was required to approach the test fixture and execute extinguishing procedures from a partially downwind direction in both tests. This means that smoke, gaseous agent, and extinguishment byproducts were being continually blown at the firefighter, possibly causing visual obstructions. This may have resulted in inefficient agent application, agent being carried away by the wind instead of toward the fire, and likely increased oxygen supply to allow the fuel to burn more rapidly. This combination of effects is thought to be the cause of the increased agent required in both tests. Due to the presence of comparable test conditions, peak winds below the specified threshold, and a similar increase of agent required, the research team deemed Test 4 of each agent to be representative of agent performance and considered them both to be official tests.

Figure 19. Novec 1230 Three-Dimensional Inclined-Plane Fire Test 4

Figure 20. Halotron I Three-Dimensional Inclined-Plane Fire Test 4

Table 10 provides a summary of the results for both Novec 1230 and Halotron I on the three-dimensional inclined-plane flowing fuel fires. The values provided in the table are the average results of both agents, and all difference values listed reference the results of the Halotron I testing as the baseline. On average, Halotron I performed marginally better than Novec 1230 in this experimental configuration. Overall, Novec 1230 took 0.7 seconds longer (a 5.4% increase) and required 13.2 lb more agent by weight (an 18.2% increase) than Halotron I on average to extinguish the test fixture. When considering agent required by volume, Novec 1230 required 0.072 ft^3 more agent than Halotron I, a difference of 9.1%. As previously discussed, in tests with sustained winds over 1 mph, both agents required significantly more agent to extinguish the fire.

Table 10. Agent Performance Comparison for the Three-Dimensional Inclined-Plane Fire Tests

Agent	Extinguishment Time (s)	Agent Required (lb)	Estimated Volume (ft^3)	Time Difference (%)	Weight Difference (%)	Volume Difference (%)
Halotron I	13.0	72.7	0.788	0	0	0
Novec 1230	13.7	85.9	0.86	5.4	18.2	9.1

5.3 THE 16-FT PAN FIRE TEST RESULTS

A total of three 16-ft pan fire tests were conducted using Novec 1230; all tests were considered to be official. Table 11 provides these test results.

Table 11. Results of the Novec 1230 16-ft Pan Fire Tests

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/s)
1	3/21/2017	2.0	3.6	12	16	106.0	79.5	6.63
2	3/21/2017	2.0	2.9	10	14	91.0	65.0	6.50
3	3/28/2017	3.6	6.7	16	19	107.0	90.1	5.63
Average				12.7			78.2	

Test 1 had a total discharge time of 16 seconds, and the fire was extinguished in 12 seconds. A total of 106 lb was discharged, of which 79.5 lb was required to extinguish the fire. Test 2 had a total of 14 seconds of agent discharge, and the fire was extinguished within 10 seconds. A total of 91 lb of agent was discharged, of which 65 lb was required to extinguish the fire. Test 3 had a total discharge time of 19 seconds, and the fire was extinguished in 16 seconds. During Test 3, a total of 107 lb of agent was discharged, of which 90.1 lb was required to extinguish the fire. On average, Novec 1230 extinguished the 16-ft pan fires in 12.7 seconds and required 78.2 lb of agent.

Due to the differences between experimental configurations between the 16-ft pan fire test and the dry-pool fires of DOT/FAA/AR-95/87, the research team conducted additional tests using Halotron I. The most notable differences between testing configurations was the amount of fuel and substrate on which the fuel was distributed. A total of three 16-ft pan fire tests were conducted using Halotron I; all tests were considered official. Table 12 shows the results of these tests.

Table 12. Results of the Halotron I 16-ft Pan Fire Tests

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/sec)
1	8/14/2017	0.0	2.2	11	12	67	61.4	5.58
2	8/14/2017	3.4	6.7	13	14	75	69.6	5.36
3	8/16/2017	2.2	3.8	12	13	68	62.8	5.23
Average				12			64.6	

Test 1 had a total discharge time of 12 seconds, taking 11 seconds to extinguish the fire. A total of 67 lb of agent was discharged, requiring 61.4 lb to extinguish the fire. Test 2 had a total discharge time of 14 seconds and an extinguishment time of 13 seconds. A total of 75 lb of agent was discharged, of which 69.6 lb was required to extinguish the fire. Test 3 had a total discharge time of 13 seconds and an extinguishment time of 12 seconds. A total of 68 lb of agent was discharged, of which 62.8 lb was required to extinguish the fire. On average Halotron I extinguished the 16-ft pan fires in 12 seconds and required 64.6 lb of agent.

A summation and comparison of the 16-ft pan fire tests results of Novec 1230 and Halotron I are provided in table 13. The values provided in the table are the average results of both agents, and all difference (i.e., time, weight, and volume) values listed are based on the results of the Halotron I tests as the baseline. A comparison of results from the 16-ft pan fire tests show

Halotron I performed marginally better than Novec 1230. Novec took an average of 0.7 second longer to extinguisher, an increase of 5.8%. Novec required an additional 13.6 lb of agent on average to extinguish the fire, an increase of 21.1% as compared to Halotron I. When compared to the volume of agent discharged, Novec 1230 required approximately 0.083 ft^3 more than Halotron I, an increase of 11.8%.

Table 13. Agent Performance Comparison for the 16-ft Pan Fire Tests

Agent	Extinguishment Time (s)	Agent Required (lb)	Estimated Volume (ft^3)	Time Difference (%)	Weight Difference (%)	Volume Difference (%)
Halotron I	12.0	64.6	0.7	0	0	0
Novec 1230	12.7	78.2	0.783	5.8	21.1	11.8

5.4 THE 30-FT PAN FIRE TEST RESULTS

The research team conducted a total of three 30-ft pan fire tests using Novec 1230; all tests were considered official. Table 14 shows the total discharge times and amount of agent discharged for each 30-ft pan fire test. Since none of the 30-ft pan fires were successfully extinguished with Novec 1230, values for the amount of time and agent required to extinguish the fires could not be determined. Additionally, values for the times when the discharge began to sputter and reached the gas point are provided in the table. The time to sputter is defined as the time when the agent discharge stream begins to change from a continuous flow of liquid agent to bursts of liquid agent separated by gaseous discharge. These gaseous bursts start slow and become more rapid until the gas point is reached. The gas point is defined as the time when the discharge is only propellant gas and gaseous agent. These values are also listed in table 14 in addition to total discharge time. The flow rate values for all tests conducted in this experimental configuration are based on the gas point time instead of the total discharge time. Although the flow rate is likely reduced during the time the discharge is sputtering, the effects are assumed to be minimal, and therefore negligible. This assumption is corroborated by the discharge stream consisting of primarily liquid agent and no significant reduction in extinguishing capabilities was observed during this period of time. Liquid agent may still be able to be discharged after the gas point has been reached; however, it is not discharged in a continuous stream, and extinguishing capabilities are vastly diminished. The time to sputter has been provided as both a reference point in each test and a characterization of the discharge stream at the point the fire was most diminished.

Table 14. Results for Novec 1230 30-ft Pan Fire Test

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Discharge Time (s)	Time to Sputter (s)	Time to Gas Point (s)	Agent Used (lb)	Flow Rate (lb/s)
1	3/28/2017	2.9	5.8	33	17	23	150	6.52
2	4/05/2017	2.2	6.9	27	20	25	145	5.8
3	4/13/2017	2.7	2.7	23	18	22	140	6.36
Average						23.3	145	

During Test 1 of the Novec 1230 30-ft pan fire, the agent discharge began to sputter 17 seconds after discharge began, and the extinguisher reached its gas point after 23 seconds. In total, the discharge time was 33 seconds and 150 lb of agent was discharged. Figure 21(a) shows the point when the least amount of fire remained in the test fixture. It should be noted that this was the only 30-ft pan fire test that the firefighter did not step into the pan prior to the gas point. The firefighter did advance into the pan and closer to the remaining fire immediately following the gas point; however, no further progress was made, and the fire continued to grow during this time. Figure 21(b) shows the point immediately following the end of discharge.

Figure 21. Test 1: Novec 1230 30-ft Pan Fire

Test 2 of the Novec 1230 30-ft pan fire had similar results to Test 1, with the fire becoming greatly diminished but failing to be extinguished. Test 2 had a total discharge time of 27 seconds and a gas point of 25 seconds. Test 2 had the longest discharge time prior to beginning to sputter. During Test 2, the firefighter knocked down a greater portion of the fire and made entry into the pan significantly quicker than during Test 1. The firefighter stepped into the pan just as the discharge began to sputter. The firefighter experienced difficulty while attempting to extinguish the fire within inches of the back edge of the pan. The firefighter directed the agent stream in sweeping motions from one side of the remaining fire to the other, closely following the perimeter of the pan. As the firefighter directed the agent stream back and forth across the fire, the fuel reignited prior to completing a single sweep. An example of this is shown in figure 22(a), where the firefighter has just completed a left-to-right sweep but the fuel on the left side has already reignited. This is also the point when the least amount of fire remained in the pan during Test 2. This continued until the firefighter ceased discharging the extinguisher. The firefighter continued discharging the extinguisher for 2 seconds after reaching the gas point, during which the fire grew rapidly. Figure 22(b) shows the remaining fire immediately following the end of discharge. A total of 145 lb of agent was discharged during Test 2.

Figure 22. Test 2: Novec 1230 30-ft Pan Fire

Novec 1230 failed to extinguish the 30-ft pan fire in Test 3 as well. The discharge from the extinguisher began to sputter 18 seconds after discharge began, and reached the gas point 4 seconds later, a total of 22 seconds after discharge began. The firefighter ended the discharge 1 second after the extinguisher reached its gas point for a total discharge time of 23 seconds. In total, 140 lb of agent was discharged during this test. Although the team did not perform a quantitative analysis, a qualitative analysis of video footage reveals a significantly lower percentage of the pan was extinguished in Test 3. The point when the fire was diminished furthest is shown in figure 23(a). The firefighter had the greatest difficulty extinguishing the leading edge of the fire during Test 3, causing rapid fuel reignition from all directions and preventing advancement into the pan. The firefighter was able to extinguish a portion of the fire eventually, allowing for advancement into the pan 1 second after the discharge had begun to sputter and also allowing a greater portion of the fire to be knocked down. Unfortunately, by the time any significant progress was made, the extinguisher had begun sputtering and, shortly after, reached the gas point. The firefighter ended the discharge within 1 second of the extinguisher's gas point and exited the pan. Figure 23(b) shows the fire remaining in the pan immediately after the discharge ended.

Figure 23. Test 3: Novec 1230 30-ft Pan Fire

Although all attempts were made to keep all variables constant between tests (such as the use of the same firefighter using the same agent application technique from an upwind direction), the team later found minor discrepancies through in-depth review of the video footage from each evaluation. One such discrepancy the team found during the footage review from Test 3 was the distance from the 30-ft pan at which the firefighter began discharging. The firefighter began discharging agent closer to the pan than in the previous two tests, limiting the amount of agent discharged on approach to the pan and concentrating the agent that was discharged to a smaller area. The team considers this discharge distance to be the main varying factor in results from Tests 1 and 2. While this distance was also observed in other tests, it appeared to have less of an effect than what was observed upon review of Test 3. Thorough review of the recorded footage from both current and previous tests showed there was an optimal range from the firefighter where Novec 1230 exhibited the greatest extinguishing capability. When the agent stream was directed in close proximity to the firefighter, the discharge was too concentrated to effectively extinguish any meaningful area, causing rapid reignition after the discharge was directed somewhere else. At greater distances, the agent stream appeared to become too dispersed to effectively suppress the fire. During Test 1, the firefighter initially attempted to extinguish the fire without entering the pan. With the exception of the leading edge, the majority of the fire was quickly knocked down, but the agent stream became ineffective when attempting to extinguish the fire remaining on the opposite side of the pan. This deviation from discharging agent within the optimal range is not considered to be the only reason extinguishment was not achieved, but is considered a large factor. Furthermore, these fire tests were conducted after all the tests described in previous sections were completed, with the same firefighter used in all tests. This means that the firefighter had discharged the extinguisher and extinguished many fires preceding these tests. This shows that even with experience, maintaining the optimal range between the nozzle and base of the fire is challenging.

The research team also conducted additional 30-ft pan fire tests using Halotron I. As previously stated, this was due to the changes in experimental configurations between this research effort and the dry-pool fires described in DOT/FAA/AR-95/87. The team conducted a total of three 30-ft pan fire tests with Halotron I; all tests were considered official. Halotron I also failed to extinguish any of the 30-ft pan fires. The test results are provided in table 15, which presents the equivalent data from the Halotron I tests that was provided with the Novec 1230 tests, maintaining the same definitions and methods of calculations.

Table 15. Results for the Halotron I 30-ft Pan Fire Tests

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Discharge Time (s)	Time to Sputter (s)	Time to Gas Point (s)	Agent Used (lb)	Flow Rate (lb/s)
1	8/16/2017	3.1	4.9	36	22	31	153	4.94
2	10/3/2017	0	0.9	36	25	34	149	4.38
3	10/3/2017	0	3.4	33	23	30	152	5.07
Average						31.6	151.3	

During Test 1 of the 30-ft pan fires with Halotron I, the extinguisher began to sputter after 22 seconds, reached the gas point after 31 seconds, and was discharged for a total of 36 seconds. A total of 153 lb of agent was discharged. Test 1 also had the highest winds of the three tests, and was the only test with a sustained wind. The firefighter extinguished the bulk of the fire from outside of the pan, advancing into the pan approximately 4 seconds after the extinguisher began to sputter. The time when the firefighter began advancing into the pan was also the same time when the fire had been diminished the most, as shown in figure 24(a). As shown in the previous Novec 1230 tests, the fire persisted around the perimeter of the opposite edge of the pan. Ultimately, the fire was unable to be extinguished, with the firefighter ending discharge 5 seconds after the gas point. The fire continued to grow after the gas point had been reached; however, the firefighter continued to direct the miniscule pockets of liquid agent being discharged at the fire. The size of the fire immediately following the end of discharge is shown in figure 24(b).

Figure 24. Test 1: Halotron I 30-ft Pan Fire

Test 2 of the 30-ft pan fire tests with Halotron I failed to extinguish the fire, with fire persisting around the perimeter of the pan opposite the firefighter. The extinguisher began to sputter after 25 seconds, reached the gas point after 34 seconds, and the discharge was ended after 36 seconds. A total of 149 lb of agent was discharged during this test. Unlike the Test 1 with Halotron I, the firefighter was able to extinguish the fire around the perimeter of the pan furthest away by advancing into the pan slightly more rapidly, approximately 3 seconds before sputtering began. Even though fire remained on the top lip of the pan in this area, it did not reignite the fuel in the pan during the discharge period. As the firefighter was extinguishing the fire most distant from the initial discharge point, the fuel on the right side of the pan reignited. The firefighter then redirected the discharge towards the reignited fuel. At this point in the test, the fire had been diminished furthest, as shown in figure 25(a). As the firefighter attempted to extinguish the remaining fire, the extinguisher quickly reached its gas point. The firefighter then ended the discharge and exited the pan, as shown in figure 25(b).

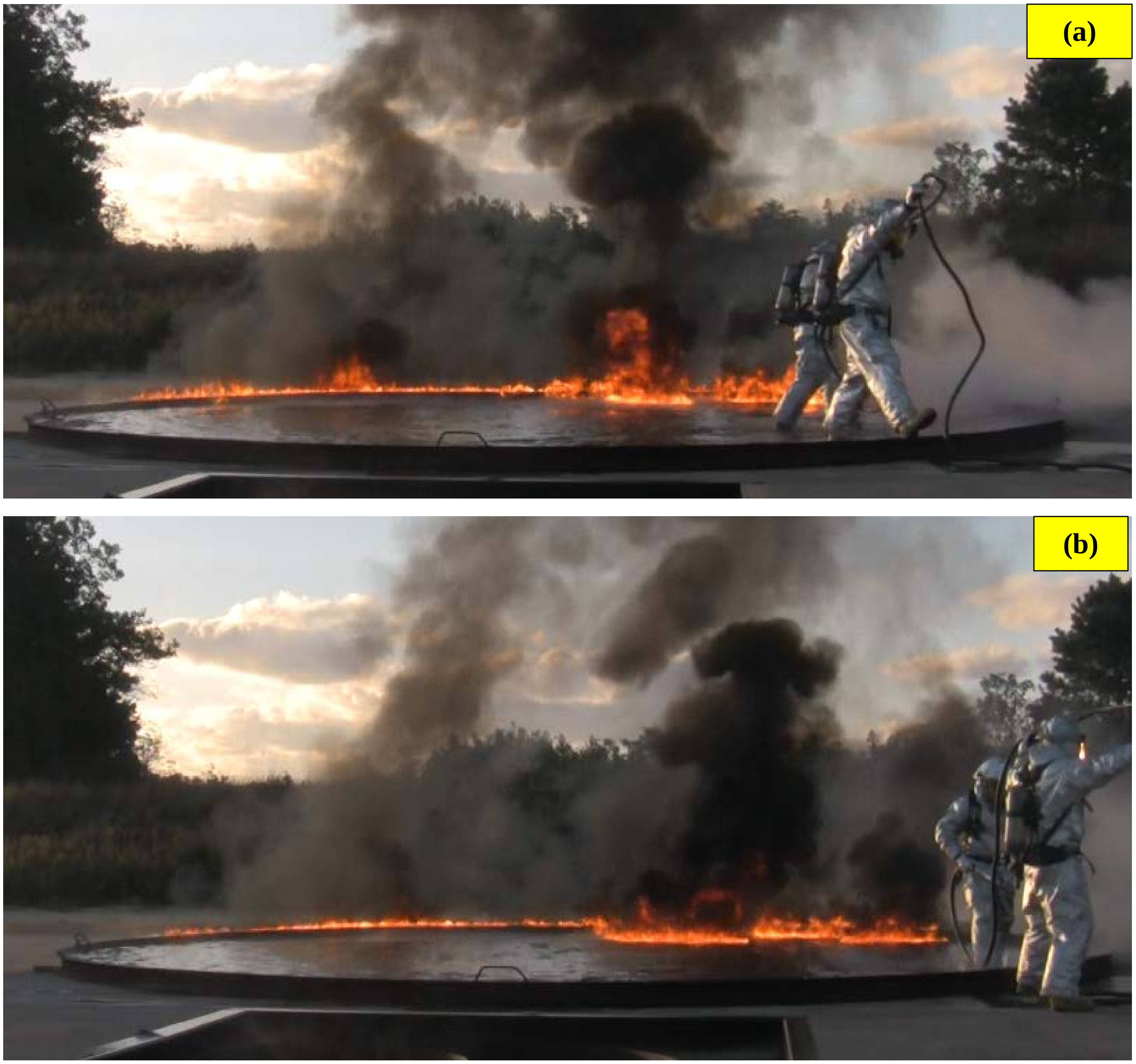

Figure 25. Test 2: Halotron I 30-ft Pan Fire

Test 3 of the 30-ft pan fire tests with Halotron I had similar results to the previous two tests. During Test 3, the extinguisher began to sputter 23 seconds after discharge began, reached its gas point after 30 seconds, and had a total discharge period of 33 seconds. A total of 152 lb of agent was discharged during this test. The firefighter was able to extinguish a significant portion of the pan, although it took slightly longer than the other two tests. This was due to fire remaining around the entire perimeter of the pan as the fire in the middle of the pan began to be extinguished. This required the firefighter to redirect the agent around the edge of the pan closest to his position prior to advancing into the pan. The extinguisher began sputtering 1 second after the firefighter advanced into the pan. The fire in the pan was diminished furthest as the extinguisher reached its gas point, as shown in figure 26(a). Although there appears to be a large amount of fire remaining, the bulk of it is located outside of the test fixture. The firefighter continued discharging the extinguisher for 3 seconds after reaching the gas point. The firefighter then ended the discharge and exited the pan, as shown in figure 26(b).

Figure 26. Test 3: Halotron I 30-ft Pan Fire

Overall, neither Novec 1230 nor Halotron I successfully extinguished the fires in the 30-ft pan fire tests, which means a quantitative analysis of performance could not be performed on these tests. The team made the following observations regarding test data:

- With the exception of Test 3 with Novec 1230, each fire was able to be diminished to a small area around the perimeter of the pan regardless of agent used.

- Neither agent provided any protection against reignition.

- Both agents exhibited an optimal range in which the discharge was most effective.

- Neither agent was able to extinguish fire on the opposite side of the pan without the firefighter advancing into the pan.

5.5 SIMULATED ENGINE NACELLE RUNNING FUEL FIRE TEST RESULTS

Detailed in AFCEC-CX-TY-TR-2014-0033, previous tests evaluated the extinguishing capabilities of Novec 1230 discharged from an Amerex Model 775 extinguisher on a simulated engine nacelle running fuel fire. The research team considered these evaluations to be satisfactory representations of this research effort's requirements and deemed it unnecessary to repeat them due to the availability of an accurate data set. The team accepted a portion of this data as official results for this research effort and used the data for the following analysis. Table 16 shows the test results that were accepted and considered official results. Of the 11 evaluations, the team accepted 7 as official tests. The team excluded Tests 1 and 8 due to the lack of a reported discharge time, excluded Test 3 due to a structural defect with the test fixture, and excluded Test 4 due to a failure to extinguish the fire. Only the results in table 16 will be used for all analyses. [6]

Table 16. Novec 1230 Tests Results From AFCEC-CX-TY-TR-2014-0033 [6]

Test	Wind Speed (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Discharge Rate (lb/s)
2	0.0	20	25	132	105.6	5.28
5	6.2	22	21	122	122*	5.81
6	6.7	22	22	139	139.0	6.32
7	2.6	20	20	138	138.0	6.90
9	5.0	21	22	139	132.7	6.32
10	2.9	18	19	121	114.6	6.37
11	1.1	18	20	124	111.6	6.20
Average		20.1			124.2	

*Value based only on total agent discharge

The fires accepted as official results required an average of 124.2 lb of agent and 20.1 seconds to be extinguished. The value listed for agent required in Test 5 was not calculated based on the extinguishment time and discharge rate; instead, the overall agent used is listed. This is due to Test 5 having a longer extinguishment time than discharge time.

Halotron I's extinguishing capabilities also have been evaluated previously on simulated engine nacelle running fuel fire tests using the F100 nacelle test fixture. These evaluations are detailed in NAWCWD TM 8572. [7] The report evaluated two types of Halotron I extinguishers of equivalent capacities, the Buckeye W-150 and the Amerex Model 674. To maintain consistency through any comparisons, the research team used only the Amerex Model 674 test results as official results and in the following analysis. These tests used JP-8 fuel for the fires, using the same engine nacelle mockup and procedures as previously described tests. A total of 11 Amerex extinguisher tests were conducted, of which 3 fires were successfully extinguished. Only the data from the successful tests were accepted as official results and used in any analysis or comparison. The accepted test results are given in table 17. The agent required values listed in table 17 were determined in NAWCWD TM 8572, unlike the previous agent required values. The values in table 17 are likely to be more accurate due to being based on a dynamic flow rate instead of averaged across the whole discharge period. It should be noted that the largest difference between values obtained between the two methods for this set of test results was approximately 3% with a 0.5% average difference. Additionally, the DOT/FAA/AR-95/87 results for the simulated engine nacelle running fuel fires with Halotron I were not used for any analysis or comparisons. This is due to the use of an updated F100 nacelle fixture and the agent being discharged from an optimized extinguisher. The results from NAWCWD TM 8572 were deemed to be more representative of the agent's performance using the same test fixture and procedures that Novec 1230 was evaluated with. [7]

Table 17. The NAWCWD TM 8572 Test Results for Halotron I With Amerex Extinguisher 674 [7]

Test	Wind Speed (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/s)
1	0-3	44	45	136	135	3.02
2	0-6	17	20	89	73	4.45
11	5-8	26	34	131	100	3.85
Average		29			102.7	

For the accepted NAWCWD TM 8572 tests, the average extinguishment time was 29 seconds and required an average of 102.7 lb of Halotron I to extinguish the fires [7]. Compared to Novec 1230, Halotron I required an additional 8.9 seconds (44.3%) to extinguish the fires, but did so using 21.5 lb (17.3%) less agent.

A summary of the average results for both Halotron I and Novec 1230 on the simulated engine nacelle flowing fuel fire tests is presented in table 18. The estimated volume of agent discharged was based on the saturated liquid densities of each agent. All values listed for the differences between the results are referenced to the Halotron I values. While not part of the following analysis, it is important to note that Halotron I extinguished 3 out of the 11 nacelle fires, and Novec 1230 extinguished 9 out of 11 fires.

Table 18. Summary of Results From Simulated Engine Nacelle Running Fuel Fire Tests

Agent	Extinguishment Time (s)	Agent Required (lb)	Estimated Volume (ft^3)	Time Difference (%)	Weight Difference (%)	Volume Difference (%)
Halotron I	29	102.7	1.113	0	0	0
Novec 1230	20.1	124.2	1.243	-30.7	20.9	11.7

As shown in table 18, Novec 1230 extinguished the fires 30.7% faster than Halotron I. However, Novec 1230 required more agent by weight and volume than Halotron I. By weight, Novec 1230 required 21.5 lb more agent than Halotron I, an increase of 20.9%. By volume, Novec 1230 required 0.13 ft^3 more agent on average than Halotron I, an increase of 11.7%.

5.6 DROP-IN VALIDATION FOR TRUCK-BASED SYSTEMS

During this research effort, the team conducted further performance evaluations of the Novec 1230 on the simulated engine nacelle running fuel fire tests. In each of the previously described evaluations, the Flight Line extinguisher had been optimized to maximize the agent performance. However, these evaluations were conducted to validate that the agent's performance was not affected when being discharged from a truck-based system, which had not been optimized for the agent. This means that no modifications were made to the system in preparation of discharging a new agent. The only change made to the system's configuration was the propellant gas. Novec 1230 requires nitrogen to be used as the propellant gas instead of argon, which is used for Halotron I. The regulator was not changed, and it was set to the system's factory specification.

In total, the research team performed three official simulated engine nacelle running fuel fire tests, discharging Novec 1230 from a hand line supplied by a truck-based system. The test results and average results of all tests are given in table 19.

Table 19. Results for Simulated Engine Nacelle Running Fuel Fire Test With Novec 1230

Test	Date	Average Wind (mph)	Maximum Wind (mph)	Extinguishment Time (s)	Discharge Time (s)	Agent Used (lb)	Agent Required (lb)	Flow Rate (lb/s)
1	5/26/2017	0.0	1.0	15	20	161.6	121.2	8.08
2	5/26/2017	1.5	1.5	13	16	140.6	114.3	8.79
3	5/26/2017	2.0	4.0	11	14	123.3	96.9	8.81
Average				13			110.8	

All three attempts resulted in successful extinguishment of the fire. Although this was an expected result due to the increased flow rate and agent tank capacity of the truck-based system, the team performed these tests to ensure system optimization was not required to maintain the agent's extinguishing capabilities. Test 1 had an extinguishment time of 15 seconds, with a discharge time of 20 seconds. A total of 161.6 lb of agent was used, of which 121.2 lb was required for extinguishment. For Test 2, the extinguishment time was 13 seconds, with a discharge time of 16 seconds. A total of 140.6 lb of agent was used, of which 114.3 lb was necessary to extinguish the fire. Test 3 was extinguished in 11 seconds with a total discharge time of 14 seconds. A total of 123.3 lb of agent was used, of which 96.9 lb was necessary to extinguish the fire. On average, the fires were extinguished in 13 seconds and required 110.8 lb of agent to extinguish the fire.

It should be noted that the same firefighter was used for all three tests, which were conducted in relatively rapid succession. As shown by the discharge and extinguishment times between tests, the firefighter's proficiency increased between each test. The firefighter who performed these tests has fought many fires using the engine nacelle test fixture and has previous experience discharging Novec 1230 from an extinguisher. Even with this prior experience, significant reduction in extinguishment times and the amount of agent discharged was observed between tests. While further testing was not performed, the extinguishment times and agent required values were not expected to be further reduced significantly.

A summary of the results from the simulated engine nacelle with running fuel fire tests with Novec 1230 is provided in table 20. These results are the overall averages from both series of tests that used Novec 1230. The values listed for differences between results references the tests that were conducted with an extinguisher.

Table 20. Summary of Results for Simulated Engine Running Fuel Fire Tests With Novec 1230

Discharge Type	Extinguishment Time (s)	Agent Required (lb)	Flow Rate (lb/s)	Time Difference (%)	Weight Difference (%)	Flow Rate Difference (%)
Extinguisher	20.1	124.2	6.17	0	0	0
Hand Line	13	110.8	8.56	-40.3%	-10.8%	38.7%

As shown in table 20, an increase in flow rate of 38.7% reduced extinguishment times by an average of 40.3%. The amount of agent required to extinguish the fires was also reduced by 10.8% when discharged through a hand line. Although there was an average reduction in agent required, the overall amounts are comparable. Overall, there is no indication that the Novec 1230 extinguishing capabilities are hindered when discharged from an unoptimized truck-based system. In fact, all comparable results indicate the performance of the agent may be enhanced when discharged at a higher rate.

The team performed additional analysis on the flow rate of the agent discharged through the hand line. The team calculated the flow rate from the weight data obtained from the load cells on the Fire Combat skid unit and recorded through a custom LabVIEW program. This was done to ensure that the agent met the NFPA 414-required minimum-specified flow rate of 5 lb/s [12]. The flow rates in each test exceeded the minimum acceptable flow rate and remained above that level for the entire duration of each discharge. Between the three tests, the average discharge rate was 8.56 lb/s. A graph of the flow rate over the entire discharge period for each test is shown in figure 27. A rolling average filter was applied to the data in an attempt to reduce the variance between measurements due to signal noise.

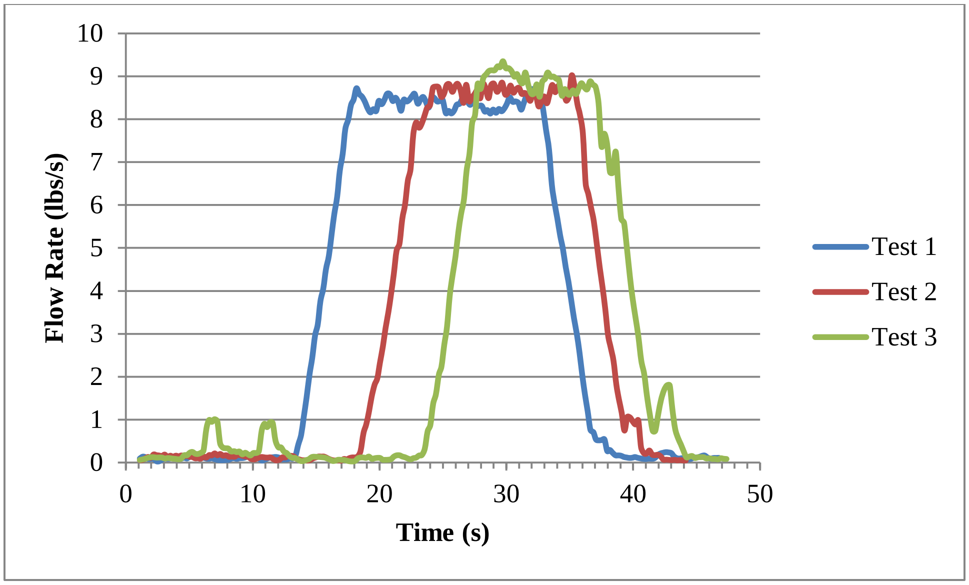

Figure 27. Average Flow Rate for Simulated Engine Nacelle Running Fuel Fire Tests

5.7 OVERALL AGENT COMPARISON

Table 21 provides a summary of Novec 1230's performance compared to that of Halotron I across all equivalent tests. Throughout all experimental configurations, Novec 1230 required more agent by both weight and volume than Halotron I. Novec 1230 required an average of 20.1% by weight and 10.9% by volume more agent than Halotron I in equivalent tests. The difference between performance parameters by percentage were consistent between the three experimental configurations, with the exception of the simulated engine nacelle running fuel fire tests conducted by the USAF and U.S. Navy. The agent required results of the simulated engine nacelle tests were consistent with the results of the other experimental configurations with Novec 1230 requiring more agent by weight and volume than Halotron I. However, Novec 1230 extinguished the simulated engine nacelle fire tests notably faster than Halotron I. Including the simulated engine nacelle fires, Novec 1230 extinguished the test fires 19.5% faster than Halotron I. When disregarding the results of the simulated engine nacelle tests, Novec 1230 took an average of 5.6% longer than Halotron I to extinguish the test fires.

Table 21. Summary of Novec 1230 Performance by Experimental Configuration

Test Type	Time Difference (%)	Weight Difference (%)	Volume Difference (%)
Inclined Plane	5.4	18.2	9.1
16-ft Pan	5.8	21.1	11.8
Engine Nacelle	-30.7	20.9	11.7

6. CONCLUSIONS

For the simulated wheel brake fire involving hydraulic fluid tests, Novec™ 1230 required an average of 14.3 seconds and 78.2 pounds (lb) of agent to extinguish the fires. Since the research team used a larger tire and offset approach path, a significant portion of the test fixture was obstructed, which required the firefighter to reposition around the test fixture. In each test, the fire around the test fixture that was not obstructed on the firefighter's initial approach was extinguished in 4 to 6 seconds. In each test, the firefighter spent the remainder of the time repositioning around the fixture and applying agent to the rest of the fire. Therefore, comparing the results from DOT/FAA/AR-95/87 for the simulated wheel brake fire with Halotron® I would not produce a valid conclusion of either agent's extinguishing capabilities. Overall, Novec 1230 extinguished all three official simulated wheel brake fire tests. The results show the extinguishment time and agent required were reduced in each successive test. The simulated wheel brake fire test in which Novec 1230 performed best extinguished the fire 23% faster with 18% less agent than the average of all three tests.

In the three-dimensional inclined-plane tests, Novec 1230 took an average of 13.7 seconds and required 85.9 lb of agent to extinguish the fires. Halotron I took 13 seconds and required 72.7 lb of agent to extinguish the fires. Comparing these results, Novec 1230 took 0.7 seconds longer and required 13.2 lb more agent to extinguish the fires, increases of 5.4% and 18%, respectively. When considering the volume of agent required, Novec 1230 required 0.072 cubic feet (ft^3) more than Halotron I, an increase of 9.1%. Of note for this test series were the effects of a sustained wind on the performance and application efficiency for both agents. In tests with comparable sustained winds, Novec 1230 required 90% more agent and Halotron I required 70% more agent to extinguish the fires than other equivalent tests for each respective agent.

For the 16-ft pan fire tests, Novec 1230 had an average extinguishment time of 12.7 seconds and required 78.2 lb of agent to extinguish the fires. Halotron I had an average extinguishment time of 12 seconds and required 64.6 lb of agent to extinguish the fires. Compared to Halotron I, Novec 1230 took 5.8% more time and required 21.1% more agent by weight to extinguish the fires. When considering the volume of agent required to extinguish the fires, Novec 1230 required 11.8% more agent to extinguish the fires. Both agents successfully extinguished all of the 16-ft pan fire tests.

Both Novec 1230 and Halotron I were unable to extinguish any 30-ft pan fires. Although the extinguishment time and agent quantity required values could not be determined, the team made a qualitative performance comparison based on the area of fire remaining. In two out of three Novec 1230 tests, and in all Halotron I tests, an overwhelming majority of the fire was suppressed with only small areas of fire remaining around portions of the pan perimeter. The cause for the test result in which Novec 1230 did not suppress the majority of fire in the pan was attributed to the distance at which the firefighter began discharging. Based on the area of fire that was suppressed in each test, both agents demonstrated nearly equivalent extinguishing capabilities. Additionally, these test observations showed that both agents' discharge streams have optimal ranges where extinguishment is most effective.

For the simulated engine nacelle running fuel fire tests, data from AFCEC-CX-TY-TR-2014-0033 were accepted as official tests for Novec 1230, and data from

NAWCWD TM 8572 were used as official tests for Halotron I. On average, Novec 1230 required 124.2 lb of agent and 20.1 seconds to achieve extinguishment and Halotron I, required an average of 102.7 lb of agent and 29 seconds. This means that although Novec 1230 extinguished the fires 30.7% faster than Halotron I, it required 20.9% more agent by weight to do so. By volume, Novec 1230 required 0.13 ft^3 more agent than Halotron I, an increase of 11.7%. Of note was the success rate of both agents, with Novec 1230 extinguishing 9 of 11 fires and Halotron I extinguishing 3 of 11 fires.

The research team also used simulated engine nacelle with running fuel fire tests to evaluate the performance of Novec 1230 when used as a drop-in replacement in a truck-based system. On average, the agent flow rate increased 38.7% when discharged through the hand line of the Fire Combat Skid system compared to the extinguisher application. Increasing the flow rate reduced extinguishment times by 40.3%, and also reduced the amount of agent required to extinguish the fires by 10.8%. These results indicate that Novec 1230's extinguishing capabilities are not hindered when being discharged from a truck-based system.

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