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Halon 1211 Alternative Systems Testing for Flight Decks: Report of Jet Engine Fire Testing

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FOREWORD

Personnel at the Naval Air Warfare Center Weapons Division (NAWCWD), China Lake, California, in conjunction with Hughes Associates, Inc. (HAI), have been conducting an evaluation for the replacement of Halon 1211 systems on U.S. Navy aircraft carrier flight decks and hangar bays. As such, an effort began in 1996 to provide an overall assessment.

To evaluate potential Halon 1211 replacement systems for flight deck use, a program was established to identify the threats from engine fires and determine suitable alternatives. A systems engineering approach was adopted in which understanding the fire threats and extinguishing requirements before recommending a replacement for Halon 1211 in naval aviation applications was critical. This approach required the use of a realistic test scenario that adequately simulated the small two- and three-dimensional engine and fires encountered in the field. This program focused on internal engine and nacelle fires.

This report provides a summary of the work completed for the internal engine and the nacelle fire series, a description of this testing, and a discussion of the results. Also included are the authors' conclusions and recommendations, as well as the future direction for the program.

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(U) Personnel at the Naval Air Warfare Center Weapons Division (NAWCWD), China Lake, California, in conjunction with Hughes Associates, Inc. (HAI), have been conducting an evaluation for the replacement of Halon 1211 systems on U.S. Navy aircraft carrier flight decks and hangar bays. As such, an effort began in 1996 to provide an overall assessment. This endeavor entailed four phases: (1) an alternative development status, (2) a requirements review, (3) a mission critical reserve evaluation, and (4) a replacement program plan. The effort described herein pertains to the fourth stage.

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14. SUBJECT TERMS

Halon 1211, Internal Engine Fires, Nacelle Fires, Extinguishing Agents, Carbon Dioxide (CO_2), Potassium Bicarbonate Powder (PKP), FE-36, FM-200, Water Mist, Halotron I, Windmilling, Engine Load, Engine Unload, Pool Fire, Pan Fire

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INTRODUCTION

Personnel at the Naval Air Warfare Center Weapons Division (NAWCWD), China Lake, California, in conjunction with Hughes Associates, Inc. (HAI), have been conducting an evaluation for the replacement of Halon 1211 systems on U.S. Navy aircraft carrier flight decks and hangar bays. As such, an effort began in 1996 to provide an overall assessment. This endeavor entailed four phases: (1) an alternative development status, (2) a requirements review, (3) a mission critical reserve evaluation, and (4) a replacement program plan. The effort described herein pertains to the fourth stage.

Based on Reference 1, engine fires represent the predominant small-fire threat on flight decks and flight lines. In these types of events, a concern exists that collateral damage from the extinguishing agent may occur to materials not in close proximity to the fire. So, the first step in identifying potential Halon 1211 replacement systems for flight deck use was to identify the challenges created by engine fires and then assess the potential of other agents to successfully meet them. Rather than exploring a drop-in replacement, personnel at the Naval Research Laboratory adopted a systems engineering approach (Reference 2). An integral part of this methodology is understanding the fire threats and extinguishing requirements before a viable recommendation for a replacement for Halon 1211 systems in naval aviation applications could be made.

This systems approach required the use of a realistic test scenario that adequately simulated the small two- and three-dimensional engines and fires encountered in the field. To accurately measure performance, the scenario replicated actual conditions, such as height and distance from personnel, clutter, obstacles, and flight deck wind. Other key fire parameters, such as size and severity (e.g., quantity and flow rate of fuel), were also recreated as closely as possible.

This program focused on internal engine and nacelle fires. The former may occur during start-up or shutdown and may result from improper procedures, severe ambient conditions, or mechanical failure. In the first two instances, the engine does not ignite properly during start-up and excess fuel is dumped into the combustor. That fuel can be blown into the turbine and tailpipe and subsequently ignite. In the case of a mechanical failure, a fuel line may rupture, the pressure and drain valve may malfunction, or the engine bearings may fail. Fuel may accumulate in the combustor, turbine, or tailpipe and subsequently ignite. These internal fires are colloquially referred to as tailpipe fires.

The *Internal Engine Fire Testing* section of this document summarizes the work completed for that series, a description of the tests, and a discussion of the results. The *Nacelle Fire Testing* section describes that series (conducted over 2 days at the conclusion of the engine fire testing). Finally, the authors provide their conclusions and recommendations resulting from both efforts, as well as the future direction for this program.

INTERNAL ENGINE FIRE TESTING

The internal engine fire testing involved four phases: (1) test scenario development, (2) scoping tests, (3) baseline testing, and (4) systems evaluation tests (Reference 3).

The first stage entailed collecting relevant information about engine fires that occur on flight decks for use in developing a test scenario representative of a typical worst-case threat. These data included engine specifications, such as the height above the ground, clutter, and fuel flow rate. The purpose of the second phase was to gain a practical understanding of how and where internal engine fires occur and how to replicate them. This scoping series was also helpful in verifying the parameters initially deemed important. The results were then used to develop a more refined matrix for the third stage, the baseline testing. The objective of that effort was to develop a repeatable exercise that was representative of fires encountered in the field. Then, the baseline scenario devised was used to conduct the systems evaluation series.

TEST SCENARIO DEVELOPMENT

Before devising the test scenario, the investigators needed to collect pertinent information regarding engines found on flight decks. Table 1 provides the results of the survey conducted. In some cases, data for various aircraft were not available and are denoted as such. In addition, in some instances, information, particularly the nacelle free volume, could not be obtained. The following categories were included in this survey.

1. Maximum fuel flow rate at idle.
2. Peak airflow rate through engine at idle.
3. Nacelle free volume.
4. Method of nacelle protection.
5. Height of bottom of inlet above ground level.
6. Height of bottom of exhaust above ground level.
7. Inlet dimensions.
8. Exhaust dimensions.

These data provided an improved understanding of the aircraft engine and nacelle design parameters in order to identify those that apply to a worst-case fire. The heights of the inlet and exhaust of the engines were of interest because an inherent assumption was that the largest dimensions presented the most severe challenge for personnel fighting a fire.

TABLE 1. Results of Engine Design Parameter Survey.

Aircraft and Engine Type	F-14A TF30-P-414A	F-14 F110-GE-400	F/A-18C/D F404-GE-400	F/A-18E/F F414-GE-400	CH-53 T64-GE-416	MH-47E T55-AE-714	SH-60B T700-GE-401C
Maximum fuel flow rate at idle	900-1200 lb/hr 2.21-2.95 gpm	950-1400 lb/hr 2.34-3.44 gpm	650 lb/hr 1.60 gpm 10,500 rpm	789 lb/hr 1.9 gpm 10,500 rpm	300-350 lb/hr 0.7-0.86 gpm 25% rpm	510 lb/hr 1.25 gpm 16,000 rpm	150–200 lb/hr 0.37–0.49 gpm
Maximum airflow through the engine at idle	100 lb/s 80000 ft^3/min	N/A	N/A	40 lb/s 32,000 ft^3/min	12-15 lb/s 9600-12,000 ft^3/min	14 lb/s 11,200 ft^3/min	12 lb/s 9600 ft^3/min
Nacelle free volume	N/A	N/A	47 ft^3	N/A	N/A	N/A	10 ft^3
Method of nacelle protection	Halon 1301	Halon 1301	Halon 1301	Halon 1301 (HFC 125 in future)	Halon 1301	N/A	N/A
Height of bottom of inlet to ground level	51 inches	51 inches	49 inches	N/A	Outboard engine, 112 inches; aft engine, 134 inches	N/A	N/A
Height of bottom of exhaust to ground level	42 inches	42 inches	69 inches	N/A	Outboard engine, 112 inches; aft engine, 139 inches	N/A	N/A
Approximate inlet dimensions	29.5 × 37 inches	29.5 × 37 inches	19 × 28 inches	N/A	1.5-inch-diameter cyclone separator tubes with EAPS; 6-inch channel height without EAPS	N/A	N/A
Approximate exhaust dimensions	40 inches in diameter	40 inches in diameter	18.5 inches in diameter	260-500 in^2	Outboard engine, 20 inches in diameter; aft engine, 24 inches in diameter	460 in^2	12-15 inches in diameter

gpm = gallons per minute, rpm = revolutions per minute, N/A = not available, EAPS = engine air particulate separator.

The procedures followed vary when fire extinguishers are required. The Naval Air Training and Operating Procedures Standardization (NATOPS) states that personnel should attack the fire through the tailpipe from the windward side and then direct the agent into it. If the fire is not extinguished, the agent should then be aimed into the aircraft engine intake (Reference 4). Rout and Hayes agree with this approach in the event that the fire can be seen in the tailpipe (References 5 and 6). On the other hand, Holly states that the first step should be to direct the agent into the inlet while the engine is windmilling (Reference 7). Several people interviewed said that the required guidelines are not appropriate in all cases. For example, aircraft are often parked on the carrier deck with their tails extending over the water (References 8 and 9). In this situation, attack through the tailpipe is not possible unless the aircraft is moved.

In addition, several individuals pointed out that the aforementioned scenario is not generally a concern when only a small amount of fuel is burning and the fire is contained within the engine (References 5, 8, and 10). However, if the fuel leaks into the nacelle or engine bay, the fire can potentially spread into these areas (References 8 through 11). None of the personnel contacted had witnessed a situation in which a handheld extinguisher had been used for this type of event. According to U.S. Naval Safety Center data, Halon 1211 has been utilized in a few cases to extinguish a nacelle fire (Reference 12). In one particular instance, a fire had started because a mechanic accidentally left a rag in the nacelle following maintenance.

This information may lead to the conclusion that aircraft engine fires are not a significant threat on the flight deck. However, U.S. Naval Safety Center data show that these types of events are not trivial. In the years between 1993 and 1995, engine fires accounted for 61% (125 of 204) of the reported incidents on the flight line in which Halon 1211 was used. Although this information is not explicitly for flight deck applications, a reasonable assumption is that the same problems occur on both flight lines and flight decks.

Experimental Setup

After reviewing the data collected in the background survey, the investigators decided that, for this effort, an actual, rather than simulated, aircraft engine should be used to achieve the realistic conditions required. As such, the unit was developed by using a Pratt & Whitney TF30-P-1 aircraft engine, which is similar to that company's F-14 TF30-P-414A. In fact, of all those surveyed, the fuel flow rates for this engine were the highest. Jet Propulsion-8 (JP-8) acted as the fuel instead of JP-5, which is currently used in Navy carrier-based aircraft. However, the JP-8 afforded a more conservative evaluation because its flashpoint (38°C or 100°F) is lower than that of JP-5 (60°C or 140°F) (Reference 13). A tube attached in front of the compressor section of the engine simulated the air inlet on an F-14. Figures 1 and 2 show the test site and a side view of the engine, respectively.

FIGURE 1. View of Test Site.

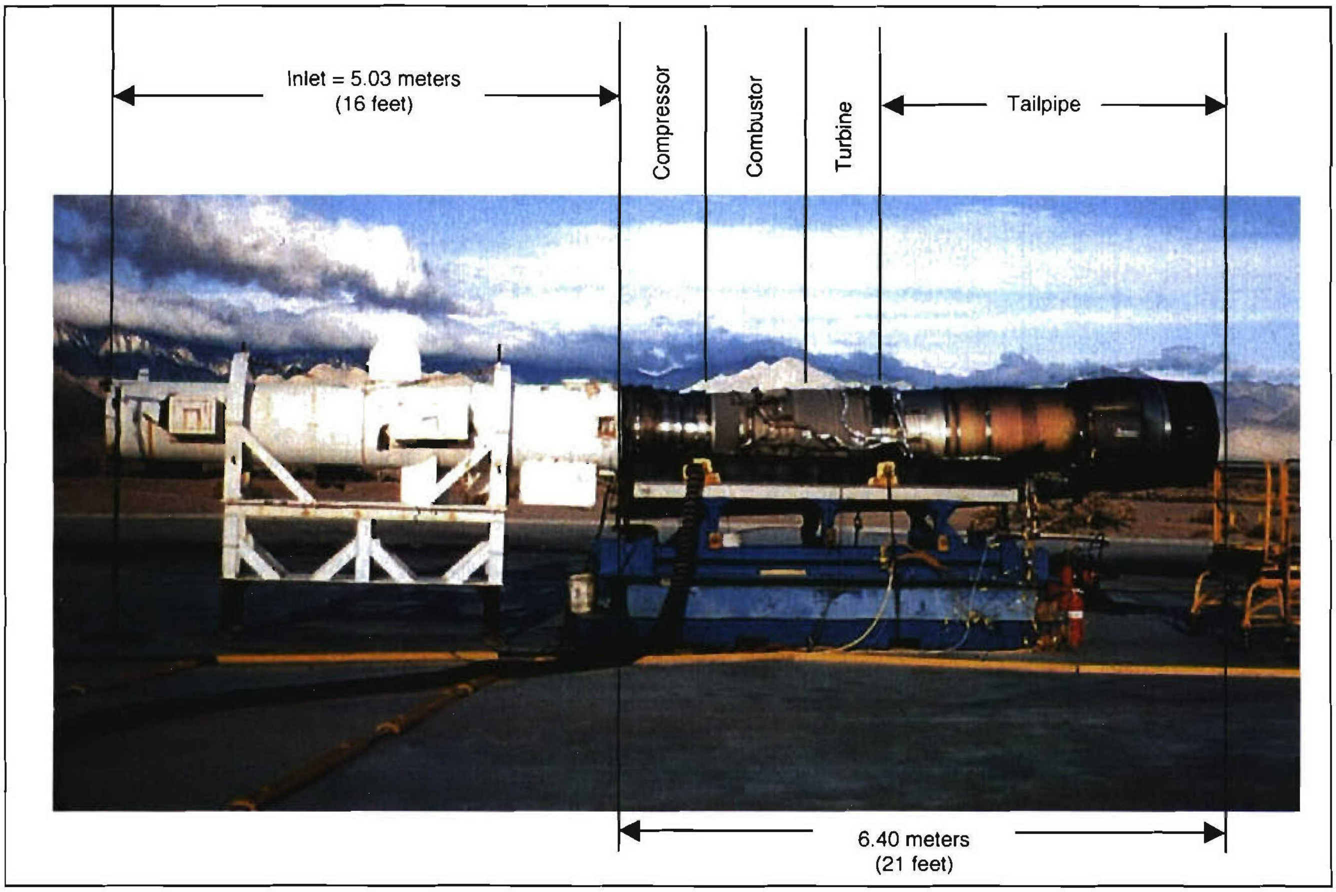


FIGURE 2. Test Article (Engine and Inlet) From Port Side.

For the scoping tests, personnel mounted the engine on a stand with the exhaust at approximately 2.1 meters (81 inches) above the ground. During the baseline series, a determination was made that the tailpipe was mounted too high. As a result, the stand was lowered so that the inlet was 1.24 meters (49 inches) and the exhaust was 1.70 meters (67 inches) above the ground. The data collected indicated that these dimensions were the same distances as those for the F-18C/D engine, the highest of fighter aircraft that land on carriers.

During both the scoping and baseline series, the fire was started by pooling fuel on the bottom of the tailpipe aft of the afterburner spray bar. For the initial tests, the fueling system was utilized to propel the stream through the engine at a rate of 3.4 liters per minute (0.9 gallon per minute), which approximates that required to start an engine of this type. However, the fuel flow rate increases after the engine starts and then idles. The maximum expected rate at idle conditions (see Table 1) is 13.3 liters per minute (3.5 gallons per minute). However, NAWCWD China Lake personnel believed that the pool sizes resulting from the higher fuel flow rates were not representative of those causing typical internal engine fires.

To devise a more repeatable fire scenario, in subsequent tests, a 30.5- by 30.5- by 4.4-cm (12- by 12- by 1.75-inch) steel pan was placed approximately 10 cm (4 inches) forward of the afterburner spray bar in the engine. The pan was filled with 1.4 liters (48 ounces) of JP-8 before each test. A piece of 90-degree, 4.4-cm (1.75-inch) angle iron was positioned above the pan to continuously replenish the fuel during the exercise and to create a small running fuel fire. The angle iron incorporated 11 slots cut through the V through which fuel dripped into the pan at a rate of 0.24 liter per minute (8 ounces per minute).

Airflow through the engine was provided by a "huffer" cart, which windmilled the engine. This device (Model A/M 32U-16, NAVAIRENGCEN Part Number 1203AS100-1), the version specifically designed for the TF30 engine in F-14 aircraft, was attached to the starter. The term *load* denotes the huffer cart beginning to windmill the engine.

External winds up to 30 knots were generated by three airboat engines, each of which incorporated a 1.8-meter (6-foot) propeller driven by a 5.7-liter (350-in^3) Chevrolet automobile engine. In addition, the revolutions per minute could be adjusted to vary the wind speed and to compensate for ambient conditions. A handheld anemometer (Pacer Industries Wind Speed Indicator Model WSI-66) positioned approximately 15 cm (6 inches) in front of the center of the inlet captured the resultant speeds.

Another handheld anemometer placed at the center of the tailpipe exit measured the velocity of the wind coming from the engine while idling and windmilling under three conditions (with no wind and with 15- and 30-knot headwinds). The peak speed in this area, 16 knots, occurred with a 30-knot headwind while the engine was windmilling. However, even higher velocities resulting from the flow of bypass air were recorded along the outer rim of the tailpipe exit. Table 2 provides the data captured in the center and along the outer rim of the tailpipe exit.

TABLE 2. Wind Speed at Tailpipe Exit.

Wind Conditions	Engine Windmilling	Wind Speed at Center of Tailpipe Exit, knots	Bypass Air at Outer Rim of Tailpipe Exit, knots
No wind	Yes	14	14
No wind	No	0	0
15-knot headwind	Yes	14	17
15-knot headwind	No	1	2
30-knot headwind	Yes	16	18
30-knot headwind	No	4	8

The engine and tailpipe were placed on a concrete test pad as depicted in Figure 3, which also shows the staging area used for the firefighters during this effort. During the scoping series, the fires were extinguished by using portable units containing 6.8 kilograms (15 pounds) of carbon dioxide (CO_2) (MIL-E-24269B [SH]) (Reference 14) and, in some limited cases, 9.1 kilograms (20 pounds) of Halon 1211 (MIL-E-24715) (Reference 15). The former are currently fielded, while the latter will be with the new P-25. Also, several tests were conducted with portable extinguishers (MIL-E-24091C [SH] size 1) (Reference 16) containing 8.2 kilograms (18 pounds) of potassium bicarbonate powder (PKP).

The safety officer, who stood behind the tailpipe during the tests, made the determination of when the fire was completely extinguished based on visual observations.

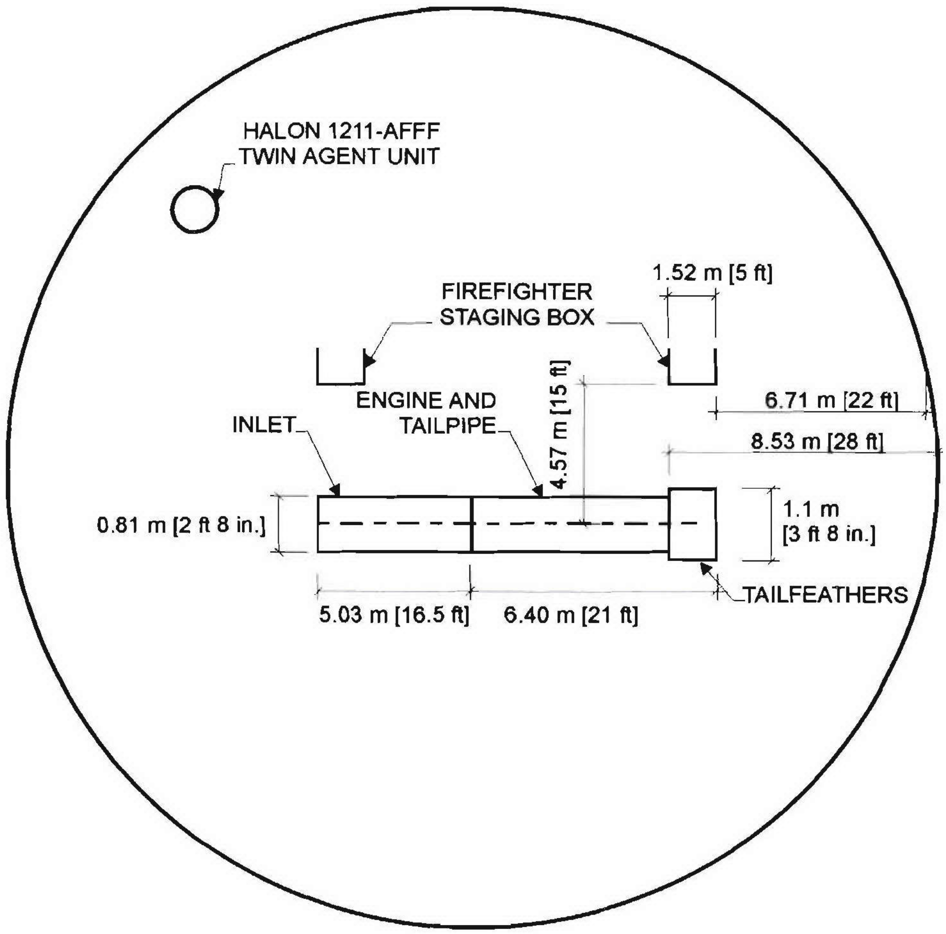


FIGURE 3. Plan View of Test Site. (Note: This drawing is not to scale.)

Agent and Extinguisher Specifications

Table 3 provides a comparison of the physical and chemical properties of the agents used in this evaluation. Table 4 summarizes the specifications for the portable units.

For this effort, a full extinguisher was weighed before discharging the agent for 5 seconds and then reweighed, and the data were recorded. Then, the agent was discharged for another 5 seconds, the extinguisher was reweighed, and the data were recorded. The average rates for the first 5 and 10 seconds of flow were computed by dividing the difference in the weights (before and after discharge) by the total discharge time. The total discharge duration and the average flow (based on the former) were derived from manufacturer's specifications. Table 5 presents the resultant information.

TABLE 3. Characteristics of Agents Used in Test Scenario Development.

	CO_2	Halon 1211	FE-36	FM-200	Halotron I, HCFC-123
Chemical Formula	CO_2	$CBrF_2Cl$	$CF_3CH_2CF_3$	C_3F_7H	$C_2HCl_2F_3$ + 7% inert gas mixture
Minimum total flooding extinguishing concentration, %	29	3 to 5	5.6 to 6.5	5.8 to 6.6	6 to 7
Boiling point at 1 atmosphere, °F	-110	26	29.3	2.6	80.6
Vapor pressure at 77°F, psia	900	38.7	39.5	66.4	95
ODP	0	4	0	0	0.014
GWP	1	Not calculated	9400	3800	90
Atmospheric lifetime, years	N/A	15	226	36.5	7 [a]
LC_{50}, ppm	70,000 [b]	31,000 to 100,000	>189,000	>800,000	>32,000
NOAEL, %	N/A	0.5	10	9	1.0
LOAEL, %	N/A	1.0	15	10.5	2.0

[a] Weighted average of the constituents.

[b] Threshold level for onset of harmful effects per *National Fire Protection Association (NFPA) Fire Protection Handbook*, 18th Edition (Reference 17).

ODP = ozone depletion potential, GWP = global warming potential, LC = lethal concentration (LC_{50} is concentration producing 50% lethality), ppm = parts per million, NOAEL = no observed adverse effect level, LOAEL = lowest observed adverse effect level.

TABLE 4. Specifications for Extinguishers Used in Test Scenario Development.

Manufacturer	Agent	Model or Part Number	Gross Weight, lb	Agent Quantity	Operating Pressure, psi	UL rating
Various	CO_2	Various	42-56	15 lb	900	10B:C
Amerex	Halon 1211	Model 372	37	20 lb	195	4A:80B:C
Ansul	FE-36	Clean Guard 14, Model CA-1481 P/N 422612	26	14 lb	75	2A:10B:C
		Prototype	32	20 lb	125	N/A
Metalcraft	FM-200	Prototype	15.5 35	10.75 lb 20 lb	360	N/A
Amerex	Water mist	Model 272	28	2.5 gal	100	2A:C
HAI	Water mist	Experimental	33	1.5 gal	1000	N/A
Amerex	Halotron I	Model 388	28	15.5 lb	125	2A:10B:C
Badger	Halotron I	Model 15.5 HB, P/N 23097	25.5	15.5 lb	125	2A:10B:C
Buckeye	Halotron I	Model 15, P/N 71550 Model 20, P/N 72001	25.5 33	15.5 lb 33 lb	25 150	2A:10B:C 2A:10B:C

TABLE 5. Measured Average Discharge Rates of Extinguishers Used in Test Scenario Development.

Agent	Manufacturer/ Model Number, etc.	Agent Quantity, lb	Total Discharge Duration, seconds [a]	Average Flow Rate for First 5 Seconds, lb/s	Average Flow Rate for First 10 Seconds, lb/s	Average Flow Rate for Total Duration, lb/s [a]
CO_2	Various/MIL SPEC	15	30	0.54	0.5	0.5
	Various/commercial	15	15	1.2	1.0	1.0
Halon 1211	Amerex	20	23	1.3	1.2	0.87
FE-36	Ansul CleanGuard 14, Model CA-1481 P/N 422612	14	14.5	1.2	1.0	0.96
	Ansul, prototype	20	Not specified	1.6	1.1	Not specified
FM-200	Metalcraft/prototype	10.75	Not specified	1.0	0.74	Not specified
		20	Not specified	1.3	1.2	Not specified
Halotron I	Amerex/Model 388	15.5	14	1.4	1.2	1.11
	Badger/Model 15.5 HB P/N 23097	15.5	14	1.5	1.2	1.11
	Buckeye/Model 15, P/N 71550	15.5	13	1.5	1.3	1.19
	Buckeye/Model 20, P/N 72001	20	15	1.9	1.6	1.33

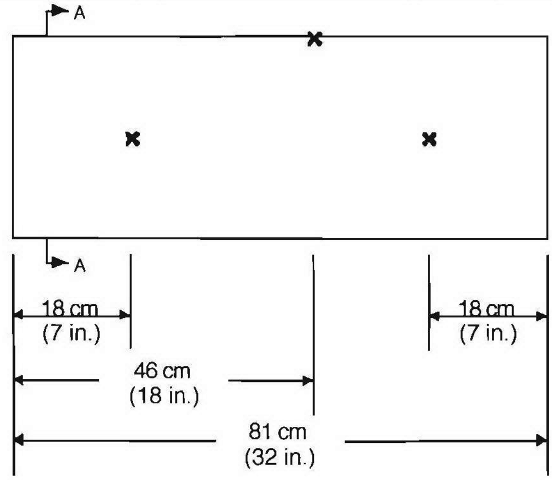
[a] Per manufacturer's specification sheets.

Instrumentation

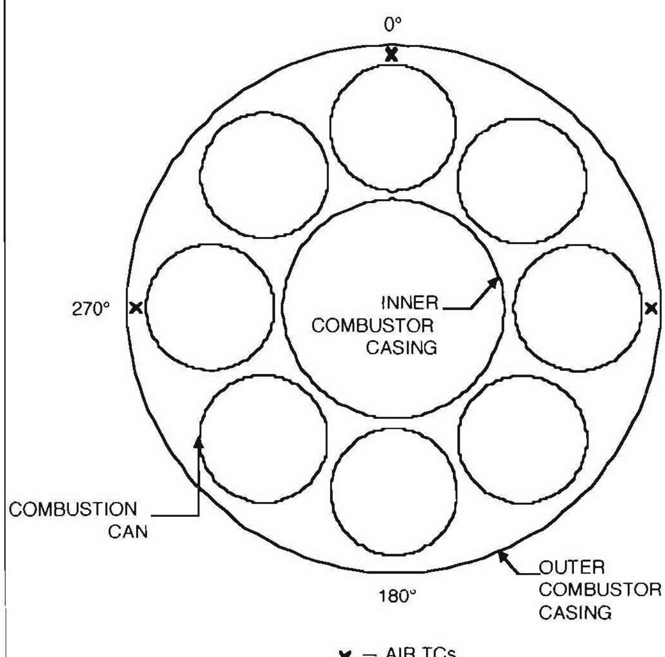
The engine incorporated devices to measure the air velocity, fuel flow rates, and fire temperatures. All of the instrumentation included in this section was interfaced with a data acquisition system that recorded data once a second (1 Hz).

The fuel flow rate was captured during the initial scoping and baseline tests via a Potter Aero. Corp. Model Number 3/16-0161D inline flow meter capable of recording information at between 0 and 3.78 liters per minute (0 to 1 gallon per minute). Type K thermocouples measured the air temperatures in the combustor, tailpipe, and turbine exit, as well as the surface temperature of the tailpipe and flame/air temperature aft of the tailpipe.

Figure 4 shows the locations of the eight thermocouples installed within the combustor to measure the air temperatures. The vantage points are from the sides of the engine and through the combustor at the cross section. One was mounted at 90 and another at 270 degrees at approximately one-half the distance between the outer surface of the combustion can and the outer casing. In addition, two were placed at 46 cm (18 inches) on either side of the forward end and two were positioned at 46 cm (18 inches) on either side of the aft end of the combustor section. Another, which was mounted at 0 degree at approximately one-half the distance between the outer surface of the combustion can and the outer casing, was positioned at one-half the horizontal length of the combustor section. These thermocouples provided information to determine the presence of a fire in the combustor and to assess the existing conditions.



(a) Elevation view of combustor viewed from port side.



(b) Elevation view of combustor viewed from aft side.
(Drawing enlarged to show detail.)

FIGURE 4. Location of Thermocouples in Combustor Section.

In addition, thermocouples were also mounted in the tailpipe section to capture air, surface, and flame temperatures. Figure 5 depicts their planned locations as viewed from the top to the bottom of that component. Four were installed at approximately 15 cm (6 inches) upstream of the exit to measure the exhaust temperatures. These thermocouples were located at 0, 90, 180, and 270 degrees, 20 cm (8 inches) from the outer surface of the tailpipe. Five sets of surface thermocouples were positioned every 30 cm (12 inches) beginning approximately 12 cm (5 inches) aft of the outermost ring of the afterburner spray bar. Each set consisted of a thermocouple mounted to the surface at 150 and 210 degrees with a screw.

Air thermocouples were located at 0 degree, 17 cm (7 inches), 71 cm (28 inches), and 127 cm (50 inches) aft of the afterburner spray bar approximately 3 cm (1 inch) below the top surface of the tailpipe in line with the first, third, and fifth surface thermocouples on the bottom of the tailpipe. In addition, nine air thermocouples were positioned 3 cm (1 inch) above the bottom of the tailpipe to measure flame temperature. The forward five of the nine air thermocouples were installed before test p1_52. These thermocouples began 8 cm (3 inches) inside the afterburner spray bar and continued for 85 cm (34 in.) with spacing ranging from 10 cm (4 inches) to 15 cm (6 inches).

Three thermocouples were added before Pan1 to monitor the pertinent conditions. One was attached to the port side of the pan to monitor the surface temperature, and the other two were positioned above the pan to measure flame temperature.

The investigators interfaced six already existing thermocouples (part of the original engine design) at the turbine exit with the data acquisition system.

Engine Speed

An onboard tachometer recorded the engine's speed. Because this instrument generated a sinusoidal output, the signal captured was converted to voltage by using a frequency-to-voltage converter and then interfaced with the data acquisition system.

Airflow Rate Measurements

A hot-wire anemometer (TSI Model 8455-09 with an adjustable range of 0 to 10,000 ft^2/min) positioned in the engine inlet just forward of the entrance to the compressor measured the air velocity through the engine.

Video Coverage

Two video cameras recorded each test. One provided a view of the aft to the forward end of the engine and the other was placed to capture the side of the engine. However, the latter was moved during the systems testing to afford a prospect of the inlet of the engine looking aft.

Weather Information

Two weather stations, one at the engine inlet and one at the tailpipe exit, measured the wind velocity and direction. The former, a Handar, Inc., Model 453A sensor capable of measuring wind speeds up to 60 meters per second (134 miles per hour), was connected to the data acquisition system. The other, a Davis Weather Monitor II, captured the wind speed and direction, as well as temperature, humidity, and barometric pressure. While this device did not interface with the data acquisition system, software included with the system, Weatherlink 4.04, collected the resultant data.

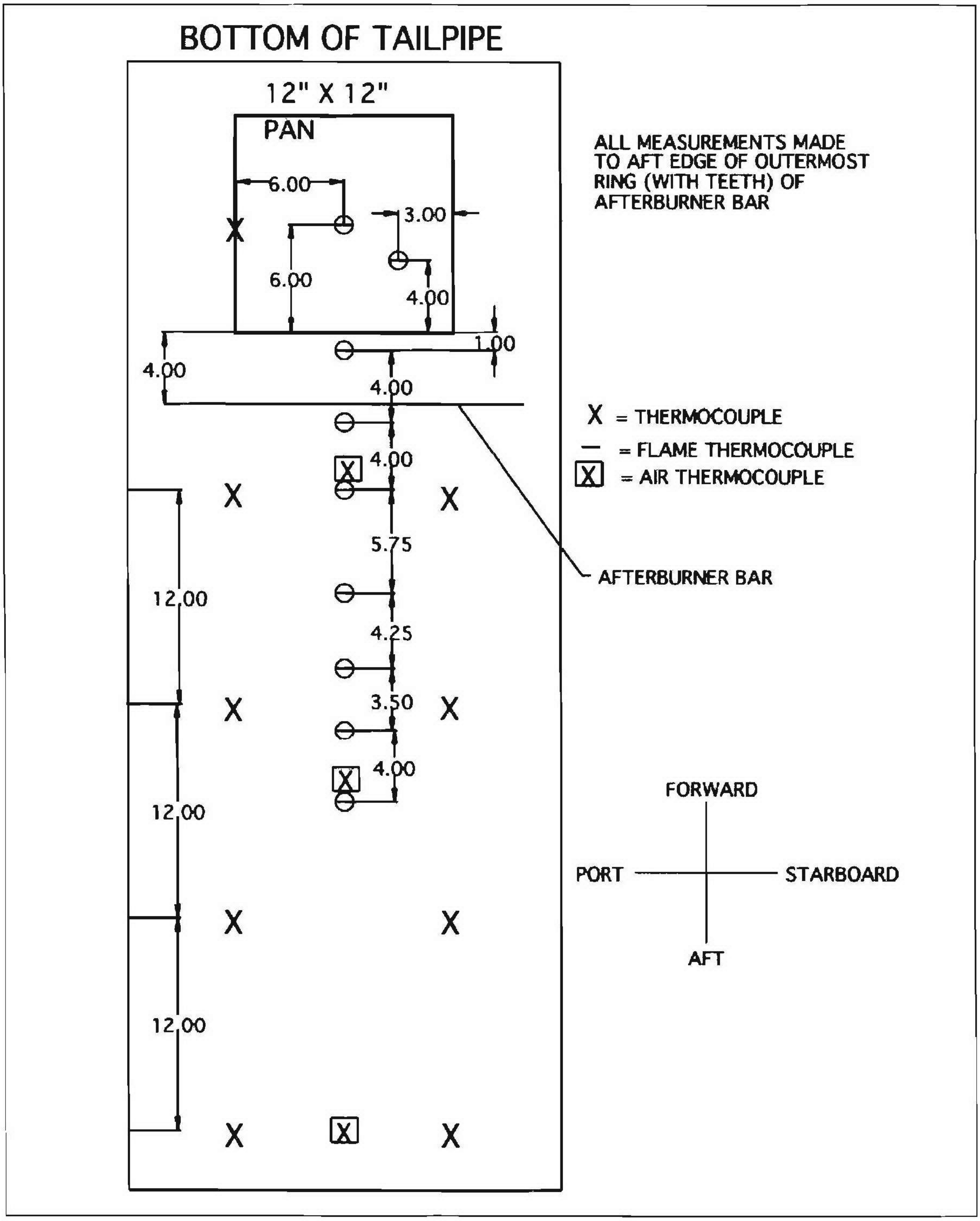


FIGURE 5. Location of Thermocouples in Tailpipe Section.

SCOPING TESTS

The scoping tests were conducted to identify the conditions necessary for an engine fire to start, as well as typical locations at which they occur. Another object was to determine if a scenario that simulates an event of this nature could be devised. In fact, the most difficult task during this effort was to replicate a standard, representative fire. For example, a literature search revealed no records of previous testing of this type. An engine fire is unusual on the flight deck; and, when one does occur, it can usually be blown out by windmilling the engine. Moreover, as previously mentioned, the personnel interviewed differed regarding the location of these fires (References 5, 7, 8, 9, 10, and 11). As a result, investigating all of the various possibilities was important.

One test constraint was that the engine was mounted on a stand that could not support it while running. As a result, the series had to be conducted in a manner that would ensure that the engine did not start. This limitation made it difficult to simulate the conditions in which engine fires actually occur in the field.

Appendix A provides a summary of the scoping series. During the initial tests (pre1 through pre7), attempts were made to start the fire with two existing igniters in the combustor. At first, this effort involved releasing the fuel, loading the engine, and energizing the igniters several seconds after the fuel flow began. The first step entailed opening the solenoid installed in the pressurized line so that the fuel could move through the nozzles into the combustor. In addition, different time intervals for releasing the fuel and loading the engine were examined. Also, a range of fuel flow rates was used to ensure that the initial conditions were neither too rich nor too lean. Some tests were conducted in which the combustor drain was plugged. This tack was taken to establish that the fuel draining from the combustor had not been the reason that a fire failed to start. Unfortunately, after all of these steps, a sustained ignition was not achieved. In one of these tests (pre4), the fuel was cycled on and off while the igniters were energized to determine if a brief flare-up of the aerosol fuel would ignite the pooled fuel in the combustor. Again, a sustained fire did not occur. The resultant conclusion was that the igniters could not be used to cause a fire with the pooled fuel.

The next step was to investigate two other ways to generate an engine fire. The first was to collect a pool of fuel in the tailpipe and manually light it. During these tests, the fuel flow was cycled on and off while the engine was loaded. However, while the fuel was on during this process, the investigators observed a mist issuing from the tailpipe. Unfortunately, measuring the amount that spewed out or that collected on the bottom of the tailpipe at the low point was not feasible. After the engine was unloaded and the fuel flow secured, the resultant pool was ignited by the safety officer. This objective was accomplished either by putting an accelerant (i.e., gasoline) on the pool or using a flaming rag to heat it. In all cases, the fire failed to be extinguished when the engine was windmilled.

The pool fires usually occurred slightly aft of the afterburner spray bar in the tailpipe. During some of the tests, the flame extended forward of that area. However, visually determining the exact location was difficult. One speculation was that the fires were too far aft and that a more representative region would be in the aft portion of the turbine section (Reference 8). This area was approximately 0.6 meter (2 feet) forward of the afterburner spray bar inside the inner tube through which core air passes through the engine. The inner tube was approximately 5 cm (2 inches) higher than the bottom surface of the tailpipe. Several tests were conducted to determine if a repeatable fire could be achieved in this location. Two procedures were adopted to deposit fuel on this shelf: flowing fuel while the engine was winding down and pouring fuel directly onto the shelf.

Unfortunately, regardless of the procedure followed, the investigators encountered two obstacles. First, amassing adequate pooling in this area was hindered by the fuel's tendency to run off the shelf into the tailpipe. Second, reaching the area with a torch to light the fuel was difficult; instead, often the fuel that had dripped into the tailpipe ignited. For these reasons, the scenario was not repeatable. In fact, even when ignition occurred, the resultant fires were considerably less expansive than those observed near the afterburner spray bar. In addition, the pool for the aft turbine fires was much smaller than those for the tailpipe. These fires were easily extinguished when the engine was windmilling.

The second initiation method was to use the engine's ignition system to create a spray fire that would eventually produce a sustained pool conflagration. The intent was to interrupt the fuel flow when the fire became self-sustaining. Moreover, because the engine igniting was undesirable, the fuel must not flow continuously. Unfortunately, often, when the fire appeared to be self-sustaining, it would go out as soon as the fuel flow ceased. Moreover, even when the desired outcome was achieved, the fire would usually go out when the engine was windmilled. As a consequence, the investigators determined that the scenario was difficult to repeat because no well-defined list of procedures would ensure that the desired fire could be generated. In general, these fires were visually similar to those in the aft turbine area and normally occurred at the aft portion of the turbine.

BASELINE SERIES

During a conference call on 4 August 1998, the test team participants deemed the first procedure (collecting a pool of fuel in the tailpipe and manually lighting it) as the most appropriate and repeatable exercise (Reference 18). The members agreed that, in comparison with the scenario for the aft turbine fire developed in the scoping tests, that for the tailpipe represented the worst-case conditions. This determination was based on the apparent size of the fire, as well as it not going out when the engine was windmilled. The results of the scoping series for this procedure were used to devise a matrix for the baseline tests, the purpose of which was to develop a reproducible exercise to replicate an internal engine fire. Table 6 summarizes the results.

One obstacle encountered during this series was that oil leaked from the tailpipe bearing, which had become cracked, into the same area as the JP-8 pool. This situation may have skewed some of the results. Determining the amount of oil present in the fuel was not feasible. However, in some cases, the smoke emanating from the tailpipe appeared lighter in color, an indication of oil.

TABLE 6. Baseline Tailpipe Fires Conducted To Develop Representative Scenario.

Test	Parameter	Description
Preburned for 60 Seconds, Windmilled for 60 Seconds, Attacked Fire From Tailpipe 15 Seconds After Windmilling		
p1_01	Fuel-flow duration	Flowed fuel for 30 seconds
p1_02	Fuel-flow duration	Flowed fuel for three 30-second cycles (60 seconds between each cycle)
p1_03	Fuel-flow duration	Flowed fuel for 30 seconds, tailpipe not drained/wiped out before test
p1_04	Fuel-flow duration	Flowed fuel for three 30-second cycles (60 seconds between each cycle)
p1_05	Fuel-flow duration	Flowed fuel for 30 seconds
p1_06	Fuel-flow duration	Flowed fuel for three 30-second cycles (60 seconds between each cycle)
p1_07	Fuel-flow duration	Flowed fuel for 30 seconds
p1_08	Fuel-flow duration	Flowed fuel for 30 seconds, fire was not sustained

TABLE 6 (Continued). Baseline Tailpipe Fires Conducted To Develop Representative Scenario.

Test	Parameter	Description
Flowed Fuel for 30 Seconds, Windmilled for 60 Seconds, Attacked Fire From Tailpipe 15 Seconds After Windmilling		
p1_09	N/A	Flowed fuel for 30 seconds and fire left to burn out
p1_10	Preburn time	Preburned for 30 seconds
p1_11	Preburn time	Preburned for 60 seconds
p1_12	Preburn time	Preburned for 120 seconds
p1_13	Preburn time	Preburned for 120 seconds
p1_14	Preburn time	Preburned for 60 seconds
p1_15	Preburn time	Preburned for 30 seconds
p1_16	Preburn time	Preburned for 30 seconds
p1_17	Preburn time	Preburned for 60 seconds
p1_18	Preburn time	Preburned for 120 seconds
Flowed Fuel for 30 Seconds, Preburned for 120 Seconds, Attacked Fire From Tailpipe 15 Seconds After Windmilling		
p1_19	Windmill duration	Windmilled for 30 seconds
p1_20	Windmill duration	Windmilled for 60 seconds
p1_21	Windmill duration	Windmilled for 60 seconds
p1_22	Windmill duration	Windmilled for 30 seconds
p1_23	Windmill duration	Windmilled for 60 seconds
p1_24	Windmill duration	Windmilled for 30 seconds
p1_25	Windmill duration	Windmilled for 60 seconds
Flowed Fuel for 30 Seconds, Preburned for 120 Seconds, Windmilled for 60 Seconds		
p1_26	Firefighting tactics	Attacked fire from tailpipe 40 seconds after windmilling
p1_27	Firefighting tactics	Attacked fire from tailpipe 40 seconds after windmilling
p1_28	Firefighting tactics	Attacked fire from tailpipe 15 seconds after windmilling
p1_29	Firefighting tactics	Attacked fire from tailpipe 40 seconds after windmilling
p1_30	Firefighting tactics	Attacked fire from tailpipe 15 seconds after windmilling
p1_31	Firefighting tactics	Attacked fire from tailpipe 40 seconds after windmilling
p1_32	Firefighting tactics	Attacked fire from inlet with two extinguishers while windmilling
p1_33	Firefighting tactics	Attacked fire from inlet with two extinguishers while windmilling
p1_34	Firefighting tactics	Attacked fire from inlet with two extinguishers while windmilling
p1_35	Firefighting tactics	Attacked fire from inlet with two extinguishers as windmilling stopped
p1_36	Firefighting tactics	Attacked fire from inlet with two extinguishers as windmilling stopped
p1_37	Firefighting tactics	Attacked fire from inlet with two extinguishers as windmilling stopped
p1_38	Firefighting tactics	Attacked fire from inlet with two extinguishers 40 seconds after windmilling stopped
p1_39	Firefighting tactics	Attacked fire from inlet with two extinguishers 40 seconds after windmilling stopped
p1_40	Firefighting tactics	Attacked fire from inlet with two extinguishers 40 seconds after windmilling stopped

TABLE 6 (Continued). Baseline Tailpipe Fires Conducted To Develop Representative Scenario.

Test	Parameter	Description
Flowed Fuel for 30 Seconds, Preburned for 120 Seconds, Windmilled for 60 Seconds (Continued)		
p1_41	Firefighting tactics	Attacked fire from inlet with one Halon 1211 extinguisher 40 seconds after windmilling stopped
p1_42	Firefighting tactics	Attacked fire from inlet with one Halon 1211 extinguisher 40 seconds after windmilling stopped
p1_43	Firefighting tactics	Attacked fire from inlet with one Halon 1211 extinguisher 40 seconds after windmilling stopped
p1_44	Ambient wind	~20-knot crosswind, attacked fire from inlet with one Halon 1211 extinguisher 40 seconds after windmilling stopped
p1_45	Ambient wind	~20-knot crosswind, attacked fire from inlet with one Halon 1211 extinguisher 40 seconds after windmilling stopped
p1_46	Ambient wind	~20-knot crosswind, attacked fire from inlet 40 seconds after windmilling stopped
p1_47	Ambient wind	~10-knot crosswind, attacked fire from inlet 40 seconds after windmilling stopped
p1_48	Firefighting tactics	Attacked fire from inlet with one extinguisher 40 seconds after windmilling
p1_49	Firefighting tactics	Attacked fire from inlet with one extinguisher 40 seconds after windmilling
p1_50	N/A	Attacked fire from inlet with one PKP bottle 40 seconds after windmilling stopped
p1_51	N/A	Attacked fire from tailpipe with one PKP bottle 40 seconds after windmilling stopped

Development of Representative Scenario

The basic scenario was to flow the fuel at a rate of 3.4 liters per minute (0.9 gallon per minute) for the specified time period (i.e., fuel-flow duration) while the engine was windmilling. Upon the flow being interrupted, the safety officer lit the pool in the tailpipe with a torch. The fire preburned for a predetermined period before the engine was loaded for a specified time to try to blow the fire out. After the huffer had been secured and the appropriate time period had elapsed, the firefighters started to attack the conflagration from either the tailpipe or inlet (as specified before the test).

For each particular evaluation, the investigators varied only the specified parameter and all of the others were held constant. Upon completion of the testing for each individual variable, the CO_2 quantities used to extinguish the fires were determined and the temperature data were analyzed. The alternative that resulted in the most reasonable worst-case conditions became part of the baseline fire scenario. Generally, this option corresponded to the exercise in which the largest quantity of CO_2 was required. Active duty personnel with flight deck experience were consulted to ensure that these choices fell into the range of standard operating conditions (References 8, 19, and 20).

The first parameter investigated during the scoping tests was fuel-flow duration. In p1_01 through p1_08, the fuel was allowed to issue for 30 seconds or for three 30-second cycles. This period was chosen because it is the standard amount of time that fuel flows in a naval aircraft when the engine does not light (References 8 and 9). After 30 seconds, the issue automatically stops. After waiting a period of time (typically 60 seconds), the pilot may try to start the engine again. Normally, the pilot attempts this action only two to three times before concluding that the aircraft is experiencing a problem.

During p1_01 through p1_08, the tailpipe was plugged, and the personnel involved followed no set procedures to drain and clean that area before each exercise. As a result, the same fuel-flow rate resulted in different amounts pooling in the region. As a consequence, some of the fires were noticeably more intense than others. Based on the test results and on visual observations, China Lake personnel with flight deck experience judged that three 30-second dumps resulted in excessive fuel amassing in the area. Therefore, one 30-second flow duration was chosen as the baseline (References 8 and 9).

The next step was to determine the effect of preburn times of 30, 60, and 120 seconds (p1_09 through p1_18). The temperature data and visual observations indicated that, the longer the fire burned before trying to extinguish it, the more intense it became. The longest period deemed appropriate before an attempt was made to extinguish a fire on the flight deck was 120 seconds.

The subsequent effort was to ascertain the impact on the fire of the windmilling lasting for 30 and 60 seconds (p1_19 through p1_25). While this condition may exceed 60 seconds in the Fleet, the need to protect the starter prevented extended-duration testing. As soon as the engine was loaded, the fire intensified and grew stronger the longer the windmilling continued. As a result, the team selected a windmill duration of 60 seconds for the baseline.

The firefighting tactics were assessed by varying the location at which CO_2 was introduced and the time at which the engagement effort began. Before this set of exercises, the individuals involved had been signaled to start the attack from the tailpipe 15 seconds after windmilling had stopped. For consistency, the firefighters responded from the same point (4.6 meters [15 feet]) away from the tailpipe for each test (see Figure 3). During p1_26 through p1_31, the assault efforts began before the engine had wound down completely, which took approximately 60 to 65 seconds. However, the engine had slowed sufficiently after 40 seconds so that the resultant airflow caused only a negligible effect on the agent being applied into the inlet. Next, exercises were conducted with a 40-second delay to determine how that factor impacted the amount of agent required for extinguishment.

The team also evaluated the effect of introducing agent, either CO_2 or Halon 1211, into the inlet (p1_32 through p1_43, p1_48, and p1_49). For the CO_2 tests, the agent was introduced at three different points (1) while the engine was windmilling, (2) 15 seconds after windmilling had stopped, and (3) 40 seconds after windmilling had ceased. The objective was to ascertain if the agent would reach the fire without air being drawn through the engine and to determine if the dilution effects would inhibit extinguishment.

All of the fires for which no artificial external wind was generated were extinguished when attacked through the tailpipe, regardless of the time engaged. In addition, with only one exception, the fires with no wind were successfully put out when the agent was introduced into the inlet. That exception was the instance in which only one CO_2 bottle at a time was discharged. Three valid tests were conducted with an external crosswind of 20 knots (p1_44, p1_45, and p1_46) in which Halon 1211 was used in two and CO_2 in the other. The time of assault was 40 seconds after windmilling had ceased. In two of these three exercises (one with Halon 1211 and one with CO_2), the fire was not extinguished until the personnel involved moved to engage the fire from the tailpipe. In addition, two tests were conducted in which a PKP bottle was utilized, one in which the agent was directed into the inlet (p1_50) and one in which it was introduced into the tailpipe (p1_51). In both cases, the fire was successfully put out.

Assessment of Reproducibility

Also of great importance was identifying a representative scenario that was reproducible. This effort involved tabulating and averaging the quantities of agent used in the tests. These values were then utilized to determine if the variability in the amounts required was acceptable, but not to ascertain the amount necessary to extinguish the fire. This judgment was based, in part, on data obtained from portable extinguisher testing (Reference 21). Thermocouple information was also used to assess test reproducibility by determining the intensity of the burning pool. For example, because measuring the heat release rate was not feasible, this method was deemed the best alternative.

The extinguishers used to fight the fires were weighed before and after use so that the amount of agent required could be determined. Appendix B provides a list of the extinguishers and the quantities of agent expended for each test. Tables 7 and 8 present the average agent mass required to put out the fire, as well as the standard deviations, for each specified parameter for the fires attacked through the tailpipe and inlet, respectively. Table 7 also indicates the conditions chosen as part of the baseline scenario. For all of the variables, except fuel-flow duration, this selection corresponded to the conditions that required the maximum amount of agent to quench the fire. In the case of fuel-flow duration, one 30-second cycle was chosen over three 30-second ones because personnel with flight-deck experience deemed that the resultant fire was too intense (References 8 and 9). Because of the small number of tests, an inherent assumption for the standard deviation calculation was that the data represented a sample rather than an entire population (Reference 22).

TABLE 7. Summary of CO_2 Quantities Used Based on Parameter for Baseline Testing (Tailpipe Attack).

Parameter	Description	Average CO_2 Expended, lb	Standard Deviation of CO_2 Expended	Standard Deviation, %	Tests Used in Analysis
Fuel-flow duration	One 30-second cycle [a]	7.6	4.9	64	p1_01, p1_05, p1_07
	Three 30-second cycles	14.3	7.3	51	p1_02, p1_06
Preburn duration	30 seconds	3.7	0.5	12	p1_10, p1_15, p1_16
	60 seconds	4.9	2.0	42	p1_11, p1_14, p1_17
	120 seconds [a]	6.4	1.8	28	p1_12, p1_13, p1_18
Windmill duration	30 seconds	4.2	1.2	29	p1_19, p1_22, p1_24
	60 seconds [a]	9.2	2.2	24	p1_21, p1_23, p1_25
Time of attack	15 seconds after windmilling stopped	6.8	2.7	40	p1_12, p1_13, p1_18, p1_21, p1_23, p1_25, p1_28, p1_30
	40 seconds after windmilling stopped	3.4	1.9	55	p1_26, p1_27, p1_29, p1_31

[a] Identifies parameter values chosen as part of the baseline scenario.

TABLE 8. Summary of Agent Quantities Used for Baseline Testing (Inlet Attack). [a]

Description	Average CO_2 Expended, lb	Standard Deviation of CO_2 Expended	Standard Deviation, %	Tests Used in Analysis
Two CO_2 bottles, fire attacked while engine windmilling	23.2	11.0	47	p1_33, p1_34
Two CO_2 bottles, fire attacked as windmilling stopped	18.6	4.0	21	p1_35, p1_36, p1_37
Two CO_2 bottles, fire attacked 40 seconds after windmilling stopped	11.4	3.6	32	p1_38, p1_40
Halon 1211, fire attacked 40 seconds after windmilling stopped	6.0	1.2	19	p1_41, p1_42, p1_43

[a] Either two CO_2 bottles discharged at the same time or one Halon 1211 bottle.

The average amount of CO_2 needed to extinguish the fires engaged through the tailpipe (see Table 7) ranged from 3.4 to 14.3 pounds. The values shown in Table 7 for the two instances included for the time of attack parameter indicate that less agent was required to put out the fire when the engine speed had slowed (i.e., more time was allowed for the engine to wind down). However, these results may be somewhat misleading. The set of 15-second tests conducted on the same day as the 40-second ones involved much lower CO_2 usage. The reason might be that different firefighters participated in the exercises. For example, some may have used a better technique. Even the fact that some personnel may have been taller than others can influence the results because of the improved view of the fire.

More CO_2 was required when the fires were attacked through the inlet than through the tailpipe. As Table 8 indicates, the minimum amount of agent needed for an inlet assault was when the fire was engaged after the engine had slowed down (i.e., 40 seconds after windmilling stopped). The maximum amount of agent was used when applied while the engine was windmilling. The probable cause is that the agent concentration was diluted by air being drawn into the engine.

As Tables 7 and 8 show, the standard deviations ranged from 12 to 64% of the average values. One feasible explanation for this inconsistency is that the same personnel did not always participate in the tests. Also, determining when the fire was out was difficult. The safety officer was responsible for signaling to the personnel involved when the fire was extinguished. However, communication was sometimes hindered by the noise level coming from the generators and the huffer cart. Also, the safety officer's limited view of the fire hindered making an accurate determination of the point at which the fire was actually extinguished.

In that the standard deviations measured for the CO_2 usage appear large, the reader may find it helpful to consider other results from extinguisher testing. In 1978, Beene and Richards performed a series to evaluate the ability of existing extinguishers when used in Class B machinery space fires on U.S. Coast Guard cutters (Reference 21). The standard deviations that resulted from the Beene and Richards effort, which ranged from a low of 0% to a high of 70%, are comparable to those for this work (Tables 7 and 8).

Based on this comparison, the variability of the agent quantities measured during the baseline series was reasonable. Because the purpose of the systems evaluation testing is to determine if an extinguishing system can put out the baseline fires, assessing test repeatability via this type of analysis at this juncture is appropriate.

The investigators used thermocouple data to determine the thermal conditions in the tailpipe and to determine the limits of the pool surface area. The intent was to establish the reproducibility of the scenario. The information from the thermocouples proved to be more helpful in a qualitative rather than quantitative sense. The location of the burning pool varied to the extent that certain thermocouples captured flame temperatures in some exercises but not in others. In addition, the peak temperatures at different areas varied from test to test. However, capturing the absolute temperatures was not as important as determining how they changed during the series. For the five thermocouples (e.g., flame thermocouples) located slightly above the bottom of the tailpipe, this aspect was particularly important because these data can be used to determine the limits of the fire area.

Figure 6 shows typical flame temperatures versus time as measured by the thermocouples during test pl_21. Flames 5 and 1 correspond to the devices in the most forward and most aft locations, respectively. Specific markings along the X-axis designate when the fire was ignited, when windmilling began and ended (i.e., engine load and unload), when CO_2 was first applied (i.e., agent), and when the safety officer signaled that the fire was out. During the 2-minute preburn period, at least two of the thermocouples were outside the flaming region. When windmilling began, the temperatures from all of the thermocouples, which appear to have been in the flaming region, increased (this behavior agrees with visual observations). The fuel apparently blew farther aft into the tailpipe than intended; as such, the pool surface area had expanded. Because these measurements were limited to five locations, an accurate determination of the volumes for the burning pool and fire was not possible.

The distances that the burning region extended forward before and after windmilling, as well aft after windmilling, were uncertain. To determine the actual fire volume, additional thermocouples, both forward and aft of those already in place, were added. Given the limited amount of data that can be collected in this type of exercise, these measurements are considered a critical means of ensuring that the tests are repeatable.

The temperatures judged to be within the burning region typically ranged between 500 and 800°C. Normally, these values are higher, from 800 to 1000°C. The lower numbers likely resulted from the thermocouples lying too closely to the pool surface and not being in the hottest portion of the flame.

The investigators analyzed the flame temperatures to determine if those data could be used to identify when the fire was put out. In this effort, the shape of the extinguishment curves and the actual temperature values were examined. In Figure 6, the time at which the safety officer determined that the fire was out corresponds to a "knee" in the graph (the point at which a dramatic change in the slope occurs). Temperature data from other tests indicated that the trend for this effort was reasonably consistent with that for other tests involving CO_2.

However, as Figure 7 suggests, the results for the Halon 1211 and PKP extinguishers were somewhat different than those for CO_2. The temperature time history graph for p1_42 shows data for a flame that is representative of those for the Halon 1211 and PKP exercises. In these instances, extinguishment occurred immediately after the temperatures started to drop sharply. The resultant thermocouple behavior (i.e., shape of the curve) was significantly different than that for CO_2 tests. As such, using the shape of the curve may be useful in identifying when extinguishment occurred. However, the agent involved must be considered.

Figure 8 provides the flame temperatures at the time the fire was extinguished for some of the baseline tests. As the line for p1_21 indicates, the temperatures were between approximately 280 and 380°C at that point. In comparison, Figure 7 shows that, for p1_42, those values ranged between approximately 600 and 700°C. Because of this discrepancy, the investigators analyzed the applicable data more carefully to determine if this trend was present in the other tests. The temperatures at extinguishment ranged from approximately 200 to 700°C. This outcome suggests that using temperature as a criterion to determine when the fire was extinguished may not be a reliable means. The variability that occurred may have been a function of the thermocouple location or may reflect differences in the size of the burning pool.

Supplemental baseline testing was conducted to demonstrate the capability of reproducing the pool fire in the tailpipe and to evaluate the effects of varying the wind conditions. Table 9 provides a summary of the results.

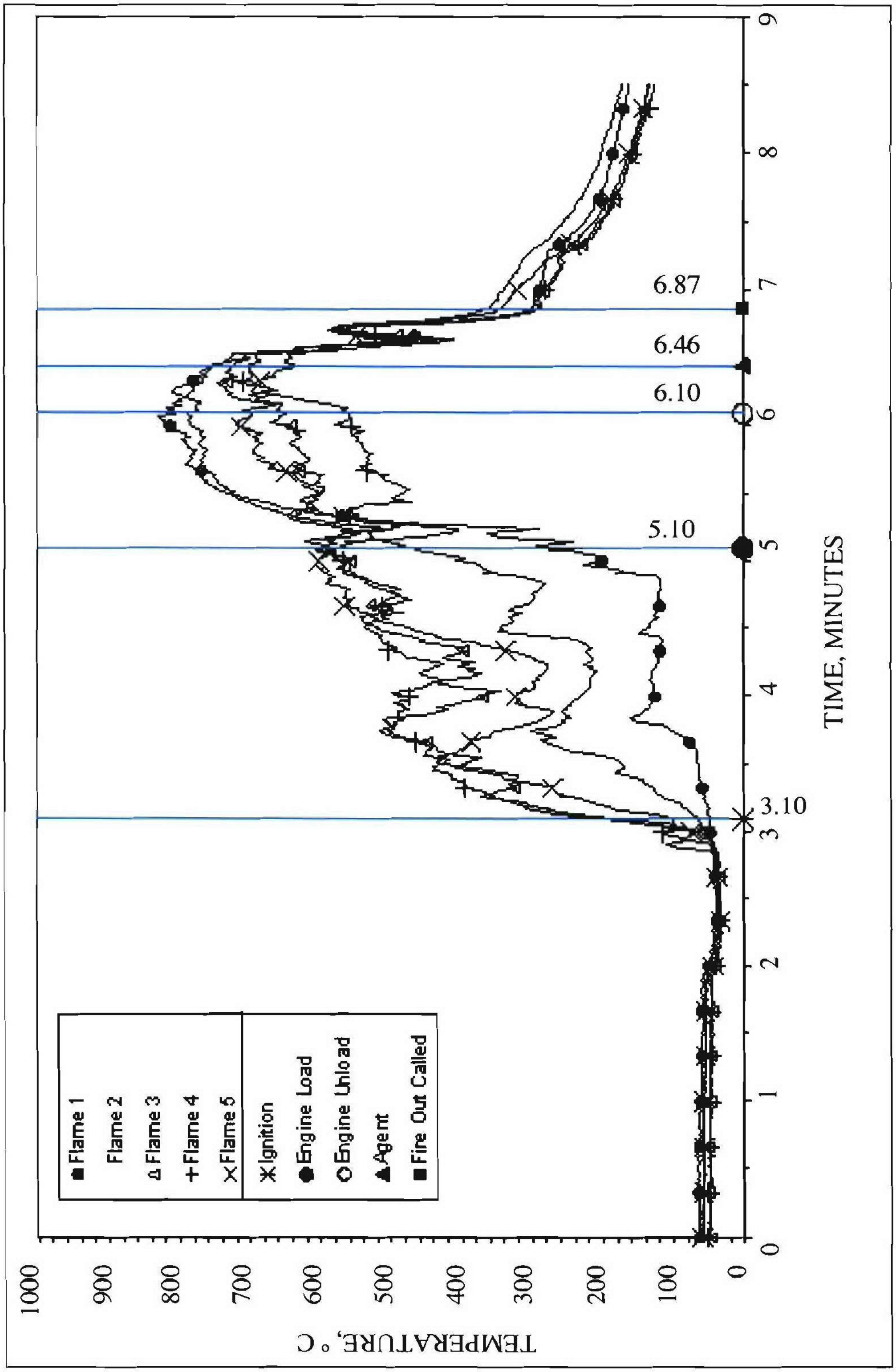


FIGURE 6. Typical Flame Temperatures vs. Time (Test p1_21).
(Note: Flame 2 does not have an identifier symbol.)

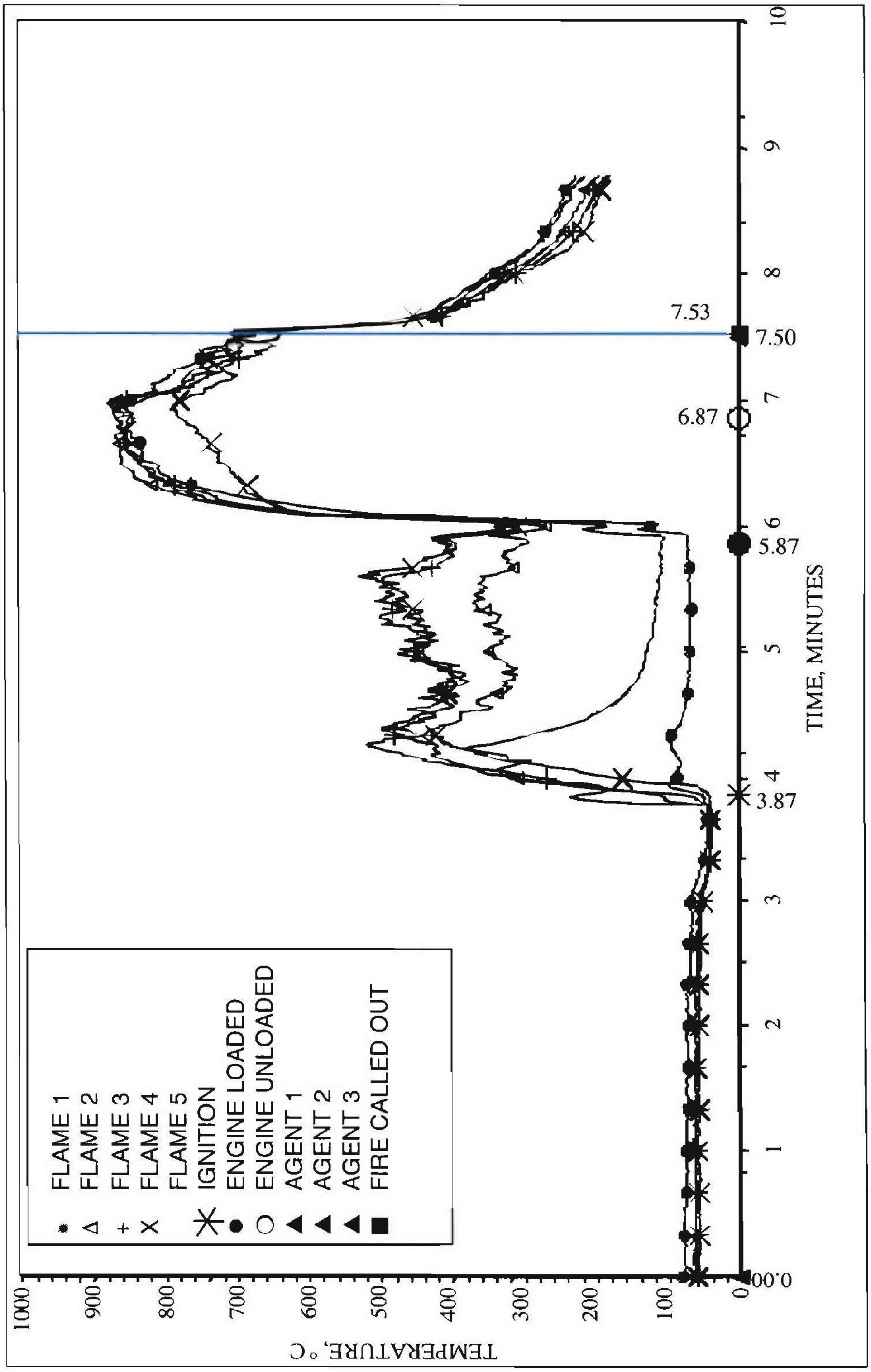


FIGURE 7. Flame Thermocouple Time History for Test p1_42
(Halon 1211 Used for Extinguishment Through Inlet).
(Note: Flame 5 does not have an identifier symbol.)

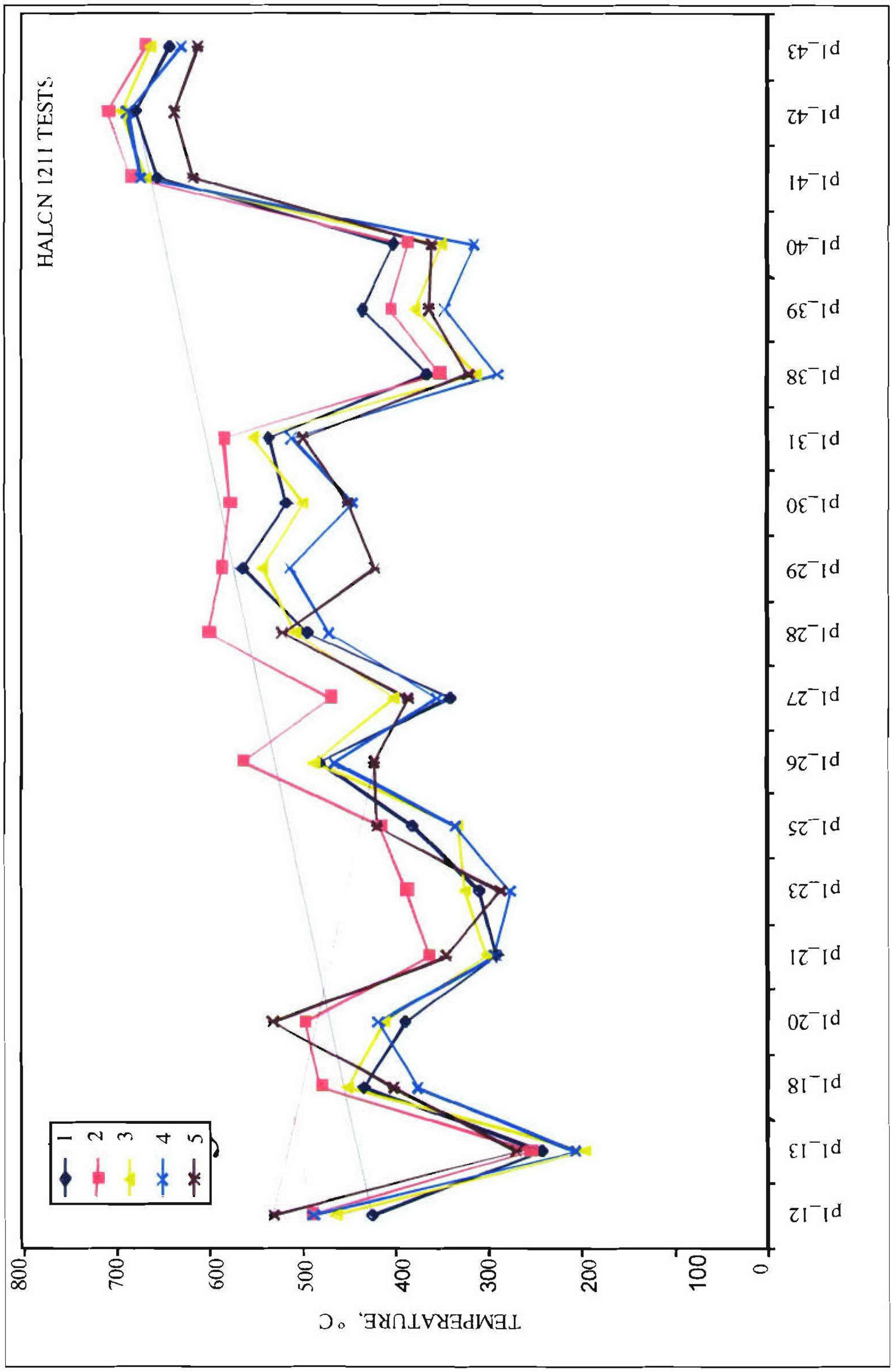


FIGURE 8. Flame Temperatures at Time Safety Officer Signaled That Extinguishment Had Occurred for Tests for Baseline Scenario Conditions (i.e., 30-second Fuel Dump, 120-second Windmill).

TABLE 9. Summary of Supplemental Baseline Tests.

Test	Point of Attack	Wind Conditions	Extinguisher Agent	Fire Extinguished From Initial Point of Attack?
p1_52	Tailpipe	No wind	CO_2	Yes
p1_53	Tailpipe	No wind	CO_2	Yes
p1_54	Tailpipe	No wind	CO_2	Yes
p1_55	Tailpipe	No wind	CO_2	Yes
p1_56	Tailpipe	No wind	CO_2	Yes
p1_57	Tailpipe	No wind	CO_2	Yes
p1_58	Tailpipe	30-knot crosswind	CO_2	Yes
p1_59	Tailpipe	30-knot crosswind	CO_2	Yes
p1_60	Tailpipe	30-knot crosswind	CO_2	Yes
p1_61	Tailpipe	30-knot crosswind	CO_2	Yes
p1_62	Tailpipe	30-knot crosswind	CO_2	Yes
p1_63	Tailpipe	30-knot crosswind	CO_2	Yes
p1_64	Tailpipe	30-knot headwind	CO_2	Yes
p1_65	Tailpipe	30-knot headwind	CO_2	Yes
p1_66	Tailpipe	30-knot headwind	CO_2	Yes
p1_67	Tailpipe	30-knot headwind	CO_2	Yes
p1_68	Tailpipe	30-knot headwind	CO_2	Yes
p1_69	Tailpipe	30-knot headwind	CO_2	Yes
p1_70	N/A	30-knot headwind	N/A	N/A
p1_71	Inlet	30-knot headwind	CO_2 (two at a time)	No
p1_72	Inlet	30-knot headwind	CO_2 (two at a time)	No
p1_73	Inlet	30-knot headwind	Halon 1211	Yes
p1_74	Inlet	30-knot headwind	FE-36 (14 lb)	No
p1_75	Inlet	No wind	CO_2 (two at a time)	Yes
p1_76	Inlet (during windmill)	No wind	CO_2 (two at a time)	No
p1_77	Inlet	No wind	FE-36 (14 lb)	Yes
p1_78	Inlet (during windmill)	No wind	FE-36 (14 lb)	No
p1_79	Inlet	30-knot headwind	FE-36 (14 lb)	No
p1_80	Inlet	30-knot headwind	CO_2 (two at a time)	Yes
p1_81	Inlet	30-knot headwind	Halon 1211	No
p1_82	N/A	No wind	N/A	N/A
p1_83	Tailpipe (no windmill)	No wind	CO_2	Yes
p1_84	Inlet (no windmill)	No wind	CO_2 (two at a time)	Yes
p1_85	Tailpipe (no windmill)	No wind	CO_2	Yes
p1_86	Inlet (no windmill)	No wind	CO_2	Yes
p1_87	Inlet	No wind	CO_2	No
Pan1	Tailpipe	No wind	CO_2	Yes
Pan2	Tailpipe	No wind	CO_2	Yes
Pan3	Tailpipe	No wind	CO_2	Yes
Pan4	Tailpipe	No wind	CO_2	Yes

TABLE 9 (Continued). Summary of Supplemental Baseline Tests.

Test	Point of Attack	Wind Conditions	Extinguisher Agent	Fire Extinguished From Initial Point of Attack?
Pan5	Tailpipe	No wind	CO_2	Yes
Pan6	Inlet	No wind	CO_2	Yes
Pan7	Inlet	No wind	CO_2	Yes
Pan8	Inlet	30-knot headwind	CO_2	No
Pan9	Inlet	30-knot headwind	CO_2	No
Pan10	Inlet	30-knot headwind	CO_2 (two at a time)	No
Pan11	Inlet	30-knot headwind	CO_2 (two at a time)	No
Pan12	Tailpipe	30-knot headwind	CO_2	No
Pan13	Tailpipe	30-knot headwind	CO_2	Yes
Pan14	Tailpipe	30-knot headwind	CO_2	Yes
Pan15	Inlet	30-knot headwind	CO_2 (two at a time)	No
Pan16	Tailpipe	30-knot headwind	CO_2	Yes
Pan17	Tailpipe	30-knot headwind	CO_2	Yes
pl_88	Inlet	30-knot crosswind	CO_2 (two at a time)	No
pl_89	Inlet	30-knot crosswind	CO_2 (two at a time)	No
pl_90	Inlet	30-knot crosswind	CO_2 (two at a time)	Yes

Development of a More Reproducible Fire Scenario

The results of the baseline series suggest that the pool fire on the bottom of the tailpipe is not easily reproduced. Typically, the fires occurred aft of the afterburner spray bar; but, on occasion (i.e., pl_66 and pl_75), the location was forward of that area. Moreover, the fires often looked different. Also, additional agent was required to put out small residual fires occurring in the approximate region of the aft turbine blades. Table 10 provides the average mass of agent expended for extinguishment during the tailpipe attacks, as well as the standard deviations. During this series, the fire was quenched only twice when engaged through the inlet, once with no wind by using 10.0 pounds of CO_2 (pl_75) and once with a 30-knot headwind by utilizing 7.5 pounds of CO_2 (pl_80).

TABLE 10. Summary of CO_2 Quantities Used Based on Wind Conditions for Baseline Series (Tailpipe Attack).

Wind Conditions	Average CO_2 Expended, lb	Standard Deviation of CO_2 Expended	Standard Deviation, %	Tests Used in Analysis
No wind	9.10	1.76	19.3	pl_53, pl_54, pl_55, pl_56, pl_57
30-knot crosswind	13.45	8.71	64.8	pl_58, pl_60, pl_61, pl_62, pl_63
30-knot headwind	35.92	2.21	6.2	pl_64, pl_65, pl_66

Because reproducing the baseline fire scenario was doubtful, the investigators explored a means of ensuring that the fire size and location remained constant. To this end, a 30.5- by 30.5- by 4.4-cm (12- by 12- by 1.75-inch) steel pan was placed approximately 10 cm (4 inches) forward of the afterburner spray bar. Before each test, the pan was filled with 1.4 liters (48 ounces) of JP-8. Then, after the data acquisition began, the safety officer ignited the fuel with a torch. The fire was allowed to preburn for 120 seconds for Pan1 through Pan5, compared to 60 seconds for Pan6 and Pan7. The longer time frame did not significantly affect the size of the fire or the ability to extinguish it. As such, the investigators used a 60-second preburn for all of the remaining tests. In addition, all unburned fuel was drained from the pan after each exercise.

Beginning with Pan4, 1.1 liters (36 ounces) of JP-8 were allowed to drip at a rate of 0.24 liter per minute (8 ounces per minute) into the pan through 11 slots cut in the V of a piece of 90-degree, 4.4-cm (1.75-inch) angle iron. The trickle began approximately 10 seconds after the fire was ignited during the preburn stage of the tests. This procedure added a third dimension to this scenario and also served to replenish the fuel during the exercises.

Visual observations indicated that windmilling the engine intensified the fire. This aspect was confirmed by the amount of agent required for extinguishment when compared to that used in previous baseline tests involving the pool fire on the bottom of the tailpipe. Therefore, the engine was windmilled during all subsequent tests.

Pan1 through Pan7 were performed under ambient wind conditions. Pan8 through Pan17 were conducted with a 30-knot headwind, an environment in which extinguishing the fire is more difficult because the air velocity through the engine increases. In addition, in this situation, the agent becomes diluted and the time that it remains at the flame/fuel interface decreases. A 30-knot crosswind at the inlet was evaluated in p1_88, p1_89, and p1_90. During these exercises, the resultant effects actually caused the agent (CO_2) to be pulled from the inlet. Moreover, the fire was extinguished during only one of the three tests involving the crosswind. During the other two, when the personnel involved failed to put out the fire while attacking it through the inlet, they moved to engage it through the tailpipe. However, even this technique proved more difficult because the effects of the crosswind at the inlet caused the fire to repeatedly reflash. A crosswind occurring concurrently at both the inlet and the tailpipe could not be replicated because of the length of the engine assembly and the configuration of the airboat engines. Consequently, the crosswind conditions did not simulate those on an actual flight deck. So, the investigators adopted the headwind scenario for all subsequent tests.

The reader can get an idea of the relative difficulty of extinguishing the pool fire on the bottom of the tailpipe in comparison to the pan fire by examining the CO_2 usage for both tailpipe and inlet attacks with no wind. Table 11 shows the amount of CO_2 required for successful extinguishment for each fire scenario. These data indicate that only slightly more agent was needed to quench the pan fire than to put out the pool fire when no wind was present.

For most of the baseline tests conducted with a 30-knot headwind, both fire scenarios (pan or pool) required multiple discharges of agent, meaning that the fire did not go out during the discharge of the first extinguisher (or pair of extinguishers). During the time required to put down the initial empty extinguisher and deploy the next extinguisher (approximately 10 seconds), the CO_2 from the initial discharge was swept out of the engine by the wind-induced airflow. Each extinguishing attempt was considered an independent event because of the lack of a continuous stream of agent and the airflow rate through the engine.

TABLE 11. Comparison of CO_2 Quantities Used During Baseline Tests.

Appendix B Reference	Location of Attack	Wind	Time of Attack After Windmilling, seconds	Number of Extinguishers Used at a Time	Pool Fire on Bottom of Tailpipe		Pan Fire	
					Successful Attempts	Standard Deviation	Successful Attempts	Standard Deviation
pl_52 through pl_57	Tailpipe	No wind	15	1	6[a]	1.76	2[b]	2.12
pl_75	Inlet	No wind	40	2	1[c, d]	N/A	2[e]	0.35
pl_64 through pl_69, Pan12, 13, 14, 16, 17	Tailpipe	30-knot headwind	15	1	6 of 6	N/A	4 of 5	N/A
pl_71, pl_72, and pl_80	Inlet	30-knot headwind	40	2	2 of 3	N/A	0 of 5	N/A

[a] 9.1 pounds of CO_2.
[b] 10.5 pounds of CO_2.
[c] 10.0 pounds of CO_2.
[d] Two extinguishers used simultaneously.
[e] 10.25 pounds of CO_2.

In the exercises in which a pool fire was attacked through the tailpipe with 30-knot headwinds, the personnel involved were successful in 6 of 16 attempts (38%). In comparison, for the same engagement and wind conditions, the pan fire was extinguished in only 4 of 13 attempts (31%). The investigators feel that the firefighter's technique is more critical in a fire scenario involving wind than in one without. For example, in some cases, the individuals involved inserted the horn farther into the tailpipe than others. Another factor that impacts putting out the fire is the angle at which the horn is directed. As a result, assessing the threat based on the amount of agent used was not feasible because different personnel participated in these tests.

Extinguishing fires when attacked through the inlet was also more difficult when wind was present. For example, in the tests in which a pool fire was engaged through the inlet with 30-knot headwinds, the personnel involved were successful in only one of five attempts (20%). Moreover, for the same engagement and wind conditions, the personnel failed to put out the pan fire in all five attempts.

Based on the results of the baseline series, the investigators made the following conclusions, which are applicable to the subsequent system evaluation tests.

1. Engaging the fire through the inlet is more difficult than doing so through the tailpipe.
2. The data collected for the CO_2 used when no external wind was being generated indicate that the threats presented by the pan and pool fires are similar.
3. Wind, the firefighter's technique, and the size and location of the fire are important variables.
4. The pan fire (with the trickle fuel flow) affords repeatability in terms of fire size and location.

5. A 60-second preburn followed by 60 seconds of windmilling represents a realistic scenario.
6. After windmilling stopped, an appropriate delay is 40 seconds before engaging the fire through the inlet and 15 seconds before attacking the fire through the tailpipe.

Accordingly, the investigators adopted the following sequence, which involves using the pan fire with the trickle fuel flow, for the systems evaluation series.

1. Pour the fuel.
2. Ignite the fire and start the trickle.
3. Preburn for 60 seconds.
4. Load the engine and windmill for 60 seconds; initiate the wind.
5. Unload the engine.
6. Attack the fire at 40 or 15 seconds after unloading the engine through the inlet or the tailpipe, respectively.
7. If an inlet attack is unsuccessful after discharging a predetermined quantity of agent, move to the tailpipe and engage the fire in that area.

SYSTEMS EVALUATION SERIES

The investigators conducted a series of systems evaluation tests to (1) assess the capability of commercial off-the-shelf (COTS) handheld portable units to extinguish the baseline pan fire, (2) identify potential modifications to COTS hardware to enhance performance, and (3) compare the relative ability of candidate Halon 1211 alternative agents to put out the baseline pan fire. Table 12 provides pertinent information, and Appendix C presents a summary of the amount of agent expended.

The measure of effectiveness for this effort was the ability to put out the baseline pan fire as a function of agent flow rate. Extinguishment was determined visually and confirmed via thermocouple readings. Most of the tests involved the worst-case scenario (a tailpipe fire occurring under 30-knot headwind conditions was attacked through the engine inlet). Exercises were also conducted with either no wind or a 15-knot headwind; and, in a few cases, the fire was engaged through the tailpipe.

The wind speed at the engine's inlet was measured several times a day with a handheld anemometer as the ambient conditions changed. Then, the airboat engine settings were adjusted when necessary to maintain the 30-knot headwind at the engine's inlet. Even with these precautionary measures, the air velocity through the engine varied. A hot-wire anemometer located in the inlet at the entrance to the compressor captured the air velocity (in ft^2/s) through the engine. The measurements after windmilling under 30-knot headwind conditions were typically less than 5 ft^2/s (i.e., as seen in Pan11 and Pan14). However, on several occasions, values of 10 ft^2/s or higher (i.e., p1_98 and p1_99) were recorded.

The presence of wind significantly influenced the test outcome as shown by the following examples. Tests p1_97 (conducted 22 March 1999) and p1_98 and p1_99 (both performed on 24 March 1999) involved consecutively discharging two 14.5-pound FE-36 portable extinguishers into the inlet under 30-knot headwind conditions. The fire was extinguished during p1_97, but not during the other two. The air velocity through the engine may have contributed to differences in these outcomes. For example, during p1_97, the air velocity was about 3 ft^2/s. However, during the other two exercises, a change in ambient wind conditions resulted in an air velocity of approximately 10 ft^2/s. Increased airflow through the engine can cause the agent to become diluted and shorten the time that it remains at the flame/fuel interface. To compensate, additional agent must be delivered into the inlet. The investigators also conducted several tests in which 15-knot headwinds were generated to compare the results with those for exercises performed without wind and under 30-knot headwind conditions.

TABLE 12. Summary of Systems Evaluation Series.

Test	Point of Attack	Wind Conditions	Extinguisher	Fire Extinguished From Initial Point of Attack?	Time From Attack to Extinguishment, seconds [a]
p1_91	Tailpipe	30-knot headwind	Amerex Water Mist (two, one at a time)	No	Not applicable
p1_92	Tailpipe	No wind	HAI Water Mist	No	Not applicable
p1_93	Tailpipe	No wind	Amerex Water Mist (two, one at a time)	No	Not applicable
p1_94	Tailpipe	No wind	HAI Water Mist	No	Not applicable
p1_95	Tailpipe	No wind	FE-36 (14-lb)	Yes	3
p1_96	Inlet	No wind	FE-36 (14-lb)	Yes	12
p1_97	Inlet	30-knot headwind	FE-36 (two 14-lb, one at a time)	Yes	47
p1_98	Inlet	30-knot headwind	FE-36 (two 14-lb, one at a time)	No	Not applicable
p1_99	Inlet	30-knot headwind	FE-36 (two 14-lb, one at a time)	No	Not applicable
p1_100	Inlet	~25-knot headwind	FE-36 (two 14-lb, one at a time)	No	Not applicable
p1_101	Inlet	30-knot headwind	Halon 1211 (two 20-lb, one at a time)	Yes	42
p1_102	Inlet	30-knot headwind	Halon 1211 (two 20-lb, one at a time)	Yes	39
p1_103	Inlet	30-knot headwind	FM-200 (two 10.75-lb, one at a time)	No	Not applicable
p1_104	Inlet	30-knot headwind	FE-36 (14-lb, two sets of two)	No	Not applicable
p1_105	Inlet	30-knot headwind	CO_2 (commercial, two sets of two)	No	Not applicable
p1_106	Inlet	30-knot headwind	FE-36 (14-lb, one set of two)	Yes	9
p1_107	Inlet	No wind	FM-200 (two 10.75-lb, one at a time)	No	Not applicable
p1_108	Inlet	No wind	FE-36 (two 14-lb, one at a time)	No	Not applicable
p1_109	Inlet	No wind	Amerex Halotron I (two 15.5-lb, one at a time)	No	Not applicable
p1_110	Inlet	30-knot headwind	Buckeye Halotron I (three 15.5-lb, one at a time)	No	Not applicable
p1_111	Inlet	30-knot headwind	Badger Halotron I (four 15.5-lb, one at a time)	No	Not applicable
p1_112	Inlet	30-knot headwind	Amerex Halotron I (15.5-lb, two sets of two)	No	Not applicable
p1_113	Inlet	30-knot headwind	CO_2 (commercial, two sets of two)	No	Not applicable
p1_114	Inlet	30-knot headwind	Buckeye Halotron I (20-lb, one set of two)	Yes	4
p1_115	Inlet	30-knot headwind	Halon 1211 (20-lb)	Yes	7
p1_116	Inlet	No wind	CO_2 (MIL SPEC, two, one at a time)	Yes	25
p1_117	Inlet	30-knot headwind	CO_2 (MIL SPEC, two sets of two)	No	Not applicable
p1_118	Inlet	30-knot headwind	FE-36 (14-lb, one set of four)	Yes	5
p1_120	Inlet	30-knot headwind	FE-36 (14-lb, two sets of two)	No	Not applicable
p1_121	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	Yes	7
p1_122	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	Yes	6
p1_123	Inlet	30-knot headwind	FE-36 (14-lb, one set of two)	No	Not applicable
p1_124	Inlet	30-knot headwind	Badger Halotron I (15.5-lb, one set of two)	No	Not applicable
p1_125	Inlet	30-knot headwind	Buckeye Halotron I (15.5-lb, one set of three)	Yes	4
p1_126	Inlet	15-knot headwind	CO_2 (MIL SPEC, two sets of two)	No	9
p1_127	Inlet	15-knot headwind	FE-36 (14-lb, one set of two)	Yes	??
p1_128	Inlet	15-knot headwind	FE-36 (14-lb, one set of two)	Yes	8
p1_129	Inlet	30-knot headwind	Primex CO_2 (one set of two)	No	Not applicable
p1_130	Inlet	30-knot headwind	Primex CO_2 (one set of two)	No	Not applicable
p1_131	Inlet	15-knot headwind	FE-36 (14-lb, one set of two)	Yes	8

TABLE 12 (Continued). Summary of Systems Evaluation Series.

Test	Point of Attack	Wind Conditions	Extinguisher	Fire Extinguished From Initial Point of Attack?	Time From Attack to Extinguishment, seconds [a]
pl_132	Inlet	15-knot headwind	FE-36 (14-lb)	No	Not applicable
pl_133	Inlet	15-knot headwind	FE-36 (14-lb)	Yes	15
pl_134	Inlet	15-knot headwind	FM-200 (20-lb)	No	Not applicable
pl_135	Inlet	30-knot headwind	CO_2 (commercial, one set of four)	Yes	4
pl_136	Inlet	30-knot headwind	Primex CO_2 (one set of four)	Yes	4
pl_137	Inlet	30-knot headwind	CO_2 (commercial, one set of three)	Yes	5
pl_138	Inlet	15-knot headwind	CO_2 (commercial, one set of two)	Yes	17
pl_139	Inlet	30-knot headwind	PKP (18-lb)	No	Not applicable
pl_140	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	Yes	23
pl_141	Inlet	30-knot headwind	FE-36 (14-lb, one set of two)	No	Not applicable
pl_142	Inlet	30-knot headwind	FE-36 (20-lb, one set of two)	Yes	5
pl_143	Inlet	15-knot headwind	FE-36 (14-lb, one set of two)	Yes	8
pl_144	Inlet	15-knot headwind	FM-200 (20-lb, one set of two)	Yes	5
pl_145	Inlet	15-knot headwind	FE-36 (20-lb)	Yes	7
pl_146	Inlet	30-knot headwind	Primex CO_2 (one set of three)	Yes	4
pl_147	Inlet	30-knot headwind	FE-36 (20-lb, one set of two)	No	Not applicable
pl_148	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	No	Not applicable
pl_149	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	No	Not applicable
pl_150	Inlet	30-knot headwind	FM-200 (20-lb, one set of three)	Yes	12
pl_151	Inlet	30-knot headwind	FE-36 (14-lb, one set of three)	Yes	3
pl_152	Inlet	30-knot headwind	FM-200 (20-lb, one set of three)	Yes	4

[a] Time from attack to extinguishment is cumulative from beginning of discharge to extinguishment. If multiple units were discharged individually during a test, the time includes the time to put one down and retrieve another.

The investigators also evaluated a firefighting technique that involved bouncing the streaming agents (FE-36, FM-200, Halotron I) off the roof of the inlet. The hypothesis was that, in this method, the agent had more time to vaporize before passing through the compressor. However, no conclusions were reached regarding the advantages or disadvantages of this process. After pl_118, for consistency, repeatability, and ease when discharging more than two extinguishers simultaneously, the units were mounted on a hydraulic lift and positioned so that the streaming agents bounced off the roof of the inlet.

The systems evaluation series also included assessing the effect on extinguishment of delivering a higher rate of agent. To this end, groups of two, three, or four extinguishers were placed on a hydraulic lift positioned at the inlet of the engine (Figure 9). Mounted across the inlet was a piece of angle iron to which the extinguisher nozzles were tied. This configuration enabled the stream of agent to bounce off the inner roof of the inlet approximately halfway down.

Two tests were conducted at the conclusion of the systems evaluation series to determine if the requirements to extinguish a pan fire were greatly different from those for a pool fire on the bottom of the tailpipe. In both pl_151 and pl_152, the fires were engaged at the inlet under 30-knot headwind conditions. The pool was created by flowing fuel throughout the engine for 60 seconds and allowing it to amass on the bottom of the tailpipe.

Test pl_151 entailed simultaneously discharging three 14-pound FE-36 extinguishers. As in the pan fires in pl_121, pl_122, and pl_140, which were conducted under the same conditions, the firefighting personnel successfully extinguished the pool fire on the bottom of the tailpipe.

In pl_152, three 20-pound FM-200 extinguishers were discharged simultaneously. The results were again successful, as was the case in pl_150, in which a pan fire was extinguished under the same conditions.

FIGURE 9. Four FE-36 Extinguishers Positioned for Inlet Attack.

EXTINGUISHING AGENT RESULTS

This section describes the results of an assessment of various extinguishing agents. The *Agent and Extinguisher Specifications* section provides pertinent information regarding most of the agents included in this effort.

CO_2 Evaluation

The investigators conducted eight tests in which CO_2 was evaluated as an extinguishing agent. Table 13 provides the results.

TABLE 13. Extinguishing Agent Evaluation Results for CO_2.

Test	Scenario	Number of Tests Conducted	Number of Tests in Which Extinguishment Occurred	Flow Rate, lb/s [a]
pl_116	Inlet attack, no wind, two MIL SPEC extinguishers, one at a time	1	1	0.5
pl_126	Inlet attack, 15-knot headwind, two sets of two MIL SPEC extinguishers	1	0	1.0
pl_117	Inlet attack, 30-knot headwind, two sets of two MIL SPEC extinguishers	1	0	1.0
pl_138	Inlet attack, 15-knot headwind, one set of two commercial extinguishers	1	1	2
pl_105, pl_113	Inlet attack, 30-knot headwind, two sets of two commercial extinguishers	2	0	2
pl_137	Inlet attack, 30-knot headwind, one set of three commercial extinguishers	1	1	3
pl_135	Inlet attack, 30-knot headwind, one set of four commercial extinguishers	1	1	4

[a] Flow rates based on 10-second average from Table 5.

Amerex Halon 1211 Evaluation

Three tests were performed in which Halon 1211 was used as the primary extinguishing agent (pl_101, pl_102, and pl_115). All three involved engaging the fire at the inlet under 30-knot headwind conditions and discharging the 20-pound units one at a time. In all three instances, the fire was successfully put out.

Ansul FE-36 Evaluation

Table 14 provides the results of the systems evaluation tests involving Ansul FE-36. The fire was put out during only one of the five exercises in which two 14-pound units were simultaneously discharged into the inlet under 30-knot headwind conditions. In contrast, a successful outcome occurred in all four of the tests in which three 14-pound extinguishers were simultaneously discharged into the inlet under an identical scenario. Discharging three 14-pounds units at a time into the inlet is equivalent to providing an agent delivery rate of approximately 3 lb/s.

Several exercises were conducted with 20-pound prototype FE-36 extinguishers provided by Ansul. The flow rate for these units was higher than that for the 14-pound extinguishers (1.1 lb/s compared to 1.0 lb/s over the first 10 seconds of the discharge). The personnel involved put out the fire during one of the two tests in which two of these units were simultaneously discharged into the inlet under 30-knot headwind conditions. In addition, during the one exercise in which one extinguisher was discharged into the inlet under 15-knot headwind conditions, the fire was successfully extinguished.

TABLE 14. Extinguishing Agent Evaluation Results for Ansul FE-36.

Test	Scenario	Number of Tests Conducted	Number of Tests in Which Extinguishment Occurred	Flow Rate, lb/s [a]
p1_95	Tailpipe attack, no wind, one 14-lb extinguisher	1	1	1
p1_96, p1_108	Inlet attack, no wind, one 14-lb extinguisher at a time	2	1	1
p1_97, p1_98, p1_99	Inlet attack, 30-knot headwind, one 14-lb extinguisher	3	1	1
p1_106, p1_120, p1_123, p1_141	Inlet attack, 30-knot head wind, one set of two 14-lb extinguishers	4	1	2
p1_142, p1_147	Inlet attack, 30-knot head wind, one set of two 20-lb extinguishers	2	1	2.2
p1_121, p1_122, p1_140, p1_151	Inlet attack, 30-knot headwind, one set of three 14-lb extinguishers	4	4	3
p1_118	Inlet attack, 30-knot headwind, one set of four 14-lb extinguishers	1	1	4
p1_132, p1_133	Inlet attack, 15-knot headwind, one 14-lb extinguisher	2	1	1
p1_145	Inlet attack, 15-knot headwind, one 20-lb extinguisher	1	1	1.1
p1_127, p1_128, p1_131, p1_143	Inlet attack, 15-knot headwind, one set of two 14-lb extinguishers	4	4	2
p1_148, p1_149	Inlet attack immediately after windmill, 30-knot headwind, one set of three 14-lb extinguishers	2	0	3

[a] Flow rates based on 10-second average from Table 5.

Metalcraft FM-200 Evaluation

Metalcraft manufactured both 10.75- and 20-pound extinguishers for the FM-200 evaluation. Table 15 provides the results of the applicable tests. The personnel involved failed to put out the fires when using the 10.75-pound units. However, a successful outcome was achieved in both exercises in which three of the 20-pound extinguishers were simultaneously discharged into the inlet under 30-knot headwind conditions. The only other instance in which extinguishment occurred was when two 20-pound extinguishers were simultaneously discharged into the inlet under 30-knot headwind conditions.

TABLE 15. Extinguishing Agent Evaluation Results for FM-200.

Test	Scenario	Number of Tests Conducted	Number of Tests in Which Extinguishment Occurred	Flow Rate, lb/s [a]
pl_107	Inlet attack, no wind, two 10.75-lb extinguishers, one at a time	1	0	1.48
pl_103	Inlet attack, 30-knot headwind, two 10.75-lb extinguishers, one at a time	1	0	0.74
pl_150, pl_152	Inlet attack, 30-knot headwind, one set of three 20-lb extinguishers	2	2	3.6
pl_134	Inlet attack, 15-knot headwind, one 20-lb extinguisher	1	0	1.2
pl_144	Inlet attack, 15-knot headwind, one set of two 20-lb extinguishers	1	1	2.4

[a] Flow rates based on 10-second average from Table 5.

Water Mist Evaluation

The investigators assessed two water mist extinguishers (Amerex and HAI systems) in pl_91 through pl_94, in which the fires were engaged at the tailpipe. The Amerex system was tested in pl_91 and pl_93, and the HAI unit (a modified CO_2 bottle with a Marioff water mist nozzle) was evaluated in pl_92 and pl_94. In pl_91, which was conducted under 30-knot headwind conditions, the personnel involved failed to successfully put out the fire. As a result, the remaining water mist tests were conducted without wind. However, even in this calm environment, the mist had little effect on the fire and extinguishment was not achieved. Therefore, the investigators concluded that water mist discharged from a portable extinguisher is not suitable for this particular application. No further systems evaluation testing of with this type was conducted.

Halotron I Evaluation

While three different companies (Amerex, Badger, and Buckeye) produced the Halotron I extinguishers assessed, the agent volumes and discharge rates were similar. Table 16 provides a summary of the results. As the reader can see, the personnel involved failed to put out the fire in the exercises in which one or two (concurrently) 15.5-pound units were discharged into the inlet under 15- or 30-knot headwind conditions. However, in pl_125, in which three 15.5-pound extinguishers were simultaneously discharged into the inlet under 30-knot headwind conditions, the fire was extinguished. In pl_114, in which two 20-pound Halotron I extinguishers supplied by Buckeye were simultaneously discharged into the inlet, the fire was also successfully put out. Further testing was not feasible because of the limited supply of extinguishers available.

TABLE 16. Extinguishing Agent Evaluation Results for Halotron I.

Test	Scenario	Number of Tests Conducted	Number of Tests in Which Extinguishment Occurred	Flow Rate, lb/s [a]
pl_109	Inlet attack, no wind, two 15.5-lb extinguishers, one at a time	1	0	1.2
pl_110, pl_111	Inlet attack, 30-knot headwind, three and four 15.5-lb extinguishers, one at a time	2	0	1.3/1.2
pl_112, pl_124	Inlet attack, 30-knot headwind, one and two sets of two 15.5-lb extinguishers	2	0	2.4
pl_114	Inlet attack, 30-knot headwind, one set of two 20-lb extinguishers	1	1	3.2
pl_125	Inlet attack, 30-knot headwind, one set of three 15.5-lb extinguishers	1	1	3.9

[a] Flow rates based on 10-second average from Table 5.

Primex Co_2 Gas Generator Evaluation

Four tests were conducted with Primex CO_2 gas generators, which are designed to produce CO_2 at a temperature of approximately 21°C. Each unit expelled 4.1 kg (9 pounds) of CO_2 over a 2-second period. The personnel involved successfully put out the fire in those tests in which three or four gas generators were simultaneously discharged. However, in the exercises in which only two units were simultaneously discharged, the fires were not extinguished.

DISCUSSION OF FINDINGS AND RELATED ISSUES

This section provides a discussion of the findings for this effort, as well as other factors that relate to jet engine fires.

Validity of Test Article

Initially, the engine fueling system was used as part of the test procedure. Once the appropriate fuel quantity and location were determined, test repeatability was substantially improved by eliminating the use of the engine fuel system. Testing with the pan fire ensured that the size of the burning pool was the same during each test.

Making a precise determination of the time of extinguishment proved to be problematic, especially for tests involving CO_2. In many instances, the safety officer's ability to distinguish when the fire was out was impeded because of reduced visibility. Accurately identifying the time of this event was important because the signal indicated to the personnel involved to discontinue discharging agent. As such, this factor had a direct effect on the amount of agent used. For example, if extinguishment was called prematurely, the firefighters stopped applying the agent too soon. As a result, the dying fire began to intensify and additional agent had to be applied. The result was that more agent than necessary was used. Moreover, a late determination also entailed using additional agent. Because all of the extinguishers tested contained ≤9.1 kg (≤20 pounds) of agent, a delay of several seconds could introduce an error as high as

20%. However, the difficulty associated with assessing when fire extinguishment occurred decreased when agents other than CO_2 were evaluated. The safety officer reported increased visibility in tests in which Halon 1211, FE-36, FM-20, and Halotron I were used.

Another factor that influences the repeatability of the tests is the firefighting procedures. In fact, a certain amount of variability is expected in exercises of this type because the results are directly impacted by human involvement. For example, the levels of experience differed for the personnel involved. Many had not fought fires of this type and, as such, were unfamiliar with the doctrinal procedures and tactics required. With variables such as response time and slight tactical differences, an accuracy within a few seconds is the best that can be expected.

Overall, the investigators feel that the test scenario and procedures employed provide an acceptable simulation of actual engine fires.

Wind Effects and Limitations

The intensity and direction of the wind are significant factors when fighting a jet engine fire. For example, wind blowing into the inlet fans the fire, distorts the discharge pattern, dilutes the agent, and increases the velocity of the agent as it passes through the engine. In fact, fires that were easily extinguished under calm conditions required a significantly higher rate of discharge when wind was present. For example (see Table 9), with no wind, an inlet attack on the tailpipe pan fire was successful five out of five times when CO_2 portables were discharged one at a time. In the same scenario with a 30-knot headwind, the personnel involved were unsuccessful in five attempts, even when two extinguishers were simultaneously discharged. Putting the engine fire out when engaged through the tailpipe was also much more difficult because the agent had to be discharged into the wind within that area. As Table 2 shows, windmilling has an even greater impact on wind speed through the engine because this situation can prevent a successful attack with a portable unit while the engine is rotating.

Inherent limitations exist when airboat engines are used to simulate natural wind. For instance, the wind pattern generated is very narrow, extending no more than approximately 10 feet on either side of the propellers. Moreover, an actual crosswind cannot be adequately replicated because air cannot be blown across the engine inlet and outlet at the same time. The conditions generated are also greatly distorted by any ambient crosswinds exceeding 5 knots. Additionally, the airboat propellers generate a vortex pattern rather than a uniform wall of natural wind. This situation can create localized effects on anemometers, a condition that limits the ability to correlate the data captured with the actual air movement through the engine.

Inlet Attack Scenario

As the reader may recall, various scenarios were evaluated. These included varying the point of attack, inlet versus tailpipe; conducting the exercises under head- or crosswind conditions; and performing the tests without wind and with 15- and 30-knot winds. The results showed that extinguishing an engine fire when engaged through the inlet under 30-knot headwind conditions (wind blowing directly into the engine inlet) represented the most difficult scenario. This case is especially representative of the conditions that occur for the typical parking patterns on the flight deck in which the aircraft are positioned with their tails over the edge of the deck while the wind is blowing toward the engine inlet. As such, the investigators feel that this scenario affords the most meaningful benchmark of an agent's effectiveness.

Extinguishment Mechanisms

Several mechanisms contribute to successfully extinguishing an engine fire. The most predominant is smothering, in which the gasified agent displaces or dilutes the air necessary for combustion. To a lesser extent, the agents also provide cooling and, except for CO_2, some chemical suppression via combustion "chain breaking" and free-radical capture. Under very high wind speeds, such as those that occur during engine windmilling, a physical separation of the flame from the fuel, akin to "blowing out a candle," can occur.

Table 17 summarizes the most significant properties relating to fire extinguishment for the agents involved in the test program. Agents discharged from portable fire units are generally considered to be streaming agents, in contrast to total flooding agents, which are typically discharged from fixed systems for fires in enclosed volumes. As such, cup burner values, which are good measures of relative performance in the latter applications, do not provide a meaningful measure of effectiveness for streaming agents. Normally, streaming agents require "throwability" to allow the agent to reach the seat of the fire. Discharge as a liquid stream can provide the reach necessary for most streaming applications, with agent boiling point being a good indicator of this capability (the higher the boiling point, the more liquid the discharge). Because of a low boiling point, very effective total flooding agents, such as Halon 1301, have not typically been employed as streaming agents. Likewise, the low boiling point of CO_2 contributes to its relatively short discharge range.

However, the standard inlet attack against a tailpipe fire adopted in the systems evaluation tests is not a streaming application in the classical sense in which someone utilizes a portable extinguisher to discharge agent directly on the base of the flame. In actuality, the standard scenario is a hybrid of streaming and total flooding systems. For example, during the inlet attack, the personnel involved could not see the fire and, as such, were not trying to aim the discharge onto the base of the flames. The scenario was a streaming application only in that the operator had to aim the agent into the inlet. In essence, the engine fire involved flaming fuel located deep inside a highly cluttered tube containing baffle plates and having small clearances, with the additional complication in most exercises of a high rate of airflow through the tube. Once the agent was discharged into the inlet, the challenge was similar to that when a total flooding agent is used to extinguish a fire in an enclosed volume with a high rate of air fluctuation. The wind passing through the engine not only diluted the concentration of agent but also diminished the time that the agent remained on the fire.

TABLE 17. Agent Characteristics Relating to Fire Extinguishment.

Agent	FE-36	Halotron I	FM-200	CO_2	Halon 1211
Cup burner, %	5.6-6.5	6-7	5.8-6.6	29	3-5
Boiling point, °F	29.3	80.6	2.6	-110	26
Molecular weight	152	150	170	44	165
Specific volume at 70°F, ft^3/lb	2.54	2.57	2.26	8.83	2.34
Portable size, lb	14	15.5	20	15	20
Discharge range, ft	14-16	12-18	10-12	7-10	12-18
UL rating	2A:10B:C	2A:10B:C	N/A	10B:C	4A:80B:C

Extinguishment as a Function of Mass Flow Rate

With a headwind, the agent discharged into the inlet vaporizes, with a resultant slug of mist that passes rapidly through the tube. Successful extinguishment depends on the volume being sufficient to put out the fire. The size is a function of the total vapor generated by each pound of agent, designated as the specific volume in Table 17 (this value is the gas volume per pound of agent at 70°F). All the agents generate approximately 2.2 to 2.6 ft^3 of agent vapor per pound, with the exception of CO_2, which produces four times as much as the others. As a consequence, its minimum extinguishing concentration is also four to six times greater.

Figure 10 depicts the performance of each agent as a function of mass flow rate for inlet attacks with a 30-knot headwind. The values for each agent are categorized into three regimes: (1) an unsuccessful, or partially successful range, (2) a not-tested range for which data are unavailable, and (3) a success point or range above which extinguishment was successful for 100% of the attempts. The following information applies.

1. With FM-200, extinguishment was achieved in two of two attempts when the flow rate was equal to 3.6 lb/s.
2. With Halotron I, the fire was successfully put out in two of two attempts when the flow rate was at least 3.2 lb/s.
3. With CO_2, extinguishment was achieved in two of two attempts when the flow rate was at least 3.0 lb/s.
4. With FE-36, the fire was successfully put out in five of five attempts when the flow rate was at least 3.0 lb/s.

The actual threshold flow rate for consistent success is likely to be below the values stated earlier (i.e., the threshold actually falls somewhere in the not-tested range shown in Figure 10). For example, when FM-200 was used, the personnel involved were successful in both attempts in which the rate was 3.6 lb/s. However, the agent may also be effective at rates of 3.0 lb/s, or even 2.5 lb/s. Similarly, further testing might show that the other agents can consistently extinguish the fire at rates below 3.0 lb/s. A large number of tests encompassing the not-tested range are required to establish the actual statistically valid thresholds to achieve consistent success. However, this level of accuracy is not necessary to form conclusions at this phase of the overall Halon 1211 replacement program. One may conclude that very little difference exists in the agents' performance when based on mass flow rate. In fact, for all the agents tested, a nominal mass flow rate of 3 lb/s should be sufficient to extinguish the worst-case engine fire.

Need for Extinguishers With Higher Flow Rates

In most cases, in order to achieve the mass flow rates required for extinguishment, multiple units had to be simultaneously discharged. For example, consistent success for an inlet attack with a 30-knot headwind necessitated the concurrent application of three or, in some cases, four extinguishers. For actual flight deck use, a doctrine mandating the simultaneous deployment of three or four extinguishers for an engine fire may not be operationally feasible. A more practical approach is to work with the extinguisher manufacturers to develop units that provide higher flow rates. The gross weight of an extinguisher containing 30 pounds of FE-36, FM-200, or Halotron I with a nominal flow rate of 2 lb/s is approximately 45 pounds, about 10 pounds less than the gross weight of existing MIL SPEC 27-pound PKP and 15-pound CO_2 portable handheld units. Moreover, two such extinguishers operating together could successfully combat the established worst-case engine fire.

Effectiveness of CO_2

As Table 13 indicates, based on the mass flow rate, CO_2's performance is comparable to that of the other Halon 1211 alternative agents. However, its disadvantages include the negligible Class A extinguishing capability, the gross weight of the unit, and the limited reach of the stream. For example, the 14-pound FE-36 and the 15.5-pound Halotron I extinguishers both have a UL rating of 2A:10B:C, with a gross weight of 25 pounds. In contrast, the UL rating for a 15-pound CO_2 unit is 10B:C (no A rating), while its gross weight is approximately twice that of the FE-36 or Halotron I units. Moreover, the average discharge range of the FE-36 and Halotron I extinguishers is about twice that of a CO_2 unit.

Additionally, one feature of a military specification (MIL SPEC) 15-pound CO_2 extinguisher (per MIL-E-24269B [Reference 14]) is detrimental to successfully extinguishing a jet engine fire. That unit delivers only about 0.5 lb/s, which is half the nominal flow rate of commercial CO_2 portable extinguishers of the same net weight. The discharge hose connection is 0.25 inch, while that on a commercial unit is 0.375 inch. This configuration extends the discharge time for the MIL SPEC unit, but the flow rate is reduced by half. So, achieving a 3-lb/s discharge of CO_2 (the quantity previously identified as necessary to consistently achieve success in a worst-case standard fire scenario) requires the simultaneous application of six MIL SPEC extinguishers through the inlet. Deploying this number of units at the same time is undoubtedly an operational impossibility. One solution is to designate the use of commercial CO_2 extinguishers with flow rates of at least 1 lb/s for use in engine fires. Another is to change the hose fitting, hose, and horn on MIL SPEC units.

Suitability of PKP

PKP is highly effective in fighting flammable liquid-pool and spray fires. In fact, an 18-pound PKP portable extinguisher has a UL rating of 80B:C, the same B:C rating as a 20-pound Halon 1211 unit. PKP portable extinguishers are commonly found at Navy airfields. They are also widely distributed on carrier flight decks as part of the crash crew tool inventory and as standard equipment at each aqueous film-forming foam hose outlet. While PKP would be effective in extinguishing engine fires, the NATOPS Manual discourages its use for that application because of corrosiveness and the potential to clog engine cooling ports (Reference 4). In those cases in which collateral aircraft damage is the primary concern, Halon 1211 or the "clean" Halon alternative is preferable (Reference 23). However, having PKP available provides a margin of safety. For example, this agent offers an effective stopgap for those fires that grow so large that the need to extinguish them outweighs concerns about the collateral damage that may result.

Firefighting Technique Considerations

The series results clearly emphasize the difficulty of attempting an inlet attack while the engine is turning. Tests p1_148 and p1_149 involved simultaneously discharging three FE-36 portable extinguishers into the inlet immediately after the huffer was secured (i.e., while the engine was still winding down). The fire was not extinguished in either of these instances. However, a successful outcome resulted in four of four attempts when three FE-36 portable units were simultaneously discharged into the inlet 40 seconds after the huffer was secured (p1_121, p1_122, p1_140, and p1_151).

Traditionally, the recommended technique when using Halon 1211 portable units is not to discharge the liquid stream directly on the fire. Instead, operators have been instructed to undershoot or deflect the stream so that the resultant vapor cloud flows into the fire. Such a procedure is implied in Paragraph 3.4.1.2 of Reference 4, which states "Halon 1211 is most effective when reaching the base of the fire in its gaseous form." Representatives of the manufacturer of Halotron I recommend that, because of that agent's high boiling point, the discharge stream should be bounced off the roof of the inlet rather than aiming it directly and horizontally into the inlet. No definitive conclusion can be formed from the test data regarding this application technique. However, based on intuition, adopting a bouncing procedure should facilitate the rapid generation of gaseous agent; and, as a result, the fire should be extinguished in a very expeditious manner. In future testing of vaporizing liquid agents (such as Halotron I, FE-36, or FM-200), structuring some comparative exercises specifically to quantify the merits of such a technique and to definitize tactics may be prudent.

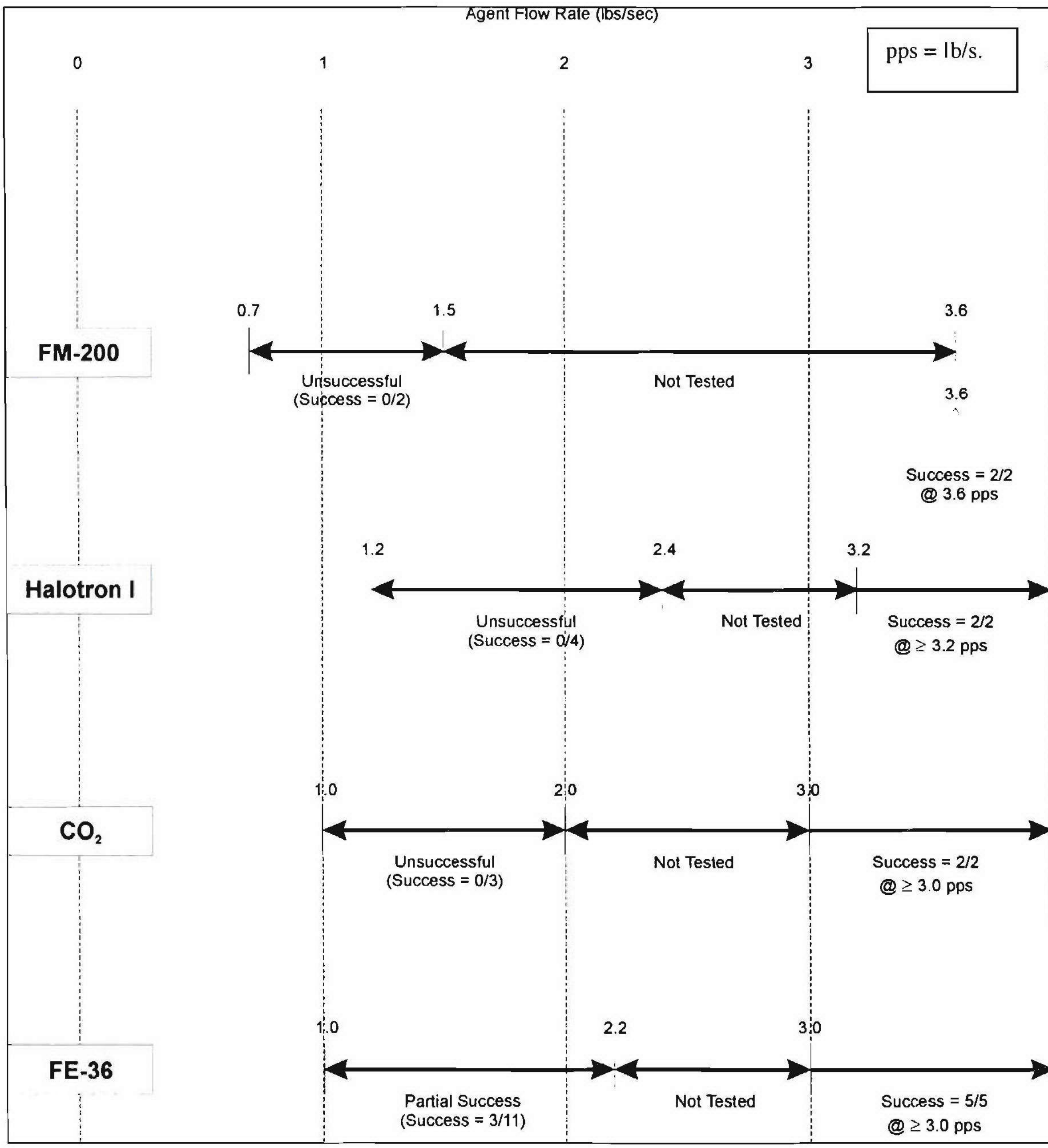


FIGURE 10. Success Regime for Inlet Attack With 30-knot Headwind.

Environmental Considerations

Table 3 includes significant environmental properties for each of the three Halon 1211 alternative agents under consideration, as well as those for Halon 1211 and CO_2. As the information indicates, each agent exhibits some adverse environmental characteristic. While the atmospheric lifetime of Halotron I is relatively short and its GWP is low, its ODP is minimal. Additionally, because its primary constituent is a hydrochlorofluorocarbon (HCFC), Halotron I is defined as a "transitional agent" by the terms of the Montreal Protocol (Reference 24). Under current provisions of that protocol and 1990 amendments to the Clean Air Act (Reference 25), HCFCs are subject to incremental production phaseout indexed to 1989 production levels. Accordingly, in the U.S., HCFCs are subject to a 35% reduction by the year 2004, a 65% decrease by 2010, and total elimination of all production by 2015. While the ODP for both FE-36 and FM-200 is zero, they have a considerably higher GWP and longer atmospheric lifetimes than Halotron I.

Under the existing Environmental Protection Agency (EPA) Significant New Alternative Policy (SNAP) program, FE-36, FM-200, and Halotron I are all approved as streaming agents for "nonresidential use." However an existing caveat is that "discharge testing and training should be strictly limited only to that which is essential to meet safety or performance requirements, and the agents should be recovered from fire protection systems in conjunction with testing or servicing and recycled for later use" (Reference 26). Paragraph 6-5.9.9.1 of OPNAVINST 5090.1B (Reference 27), the Navy's governing policy directive for Halon 1211 alternatives, states that "Navy activities shall select alternatives that are EPA SNAP-approved with an ODP of zero when possible. If no EPA SNAP-approved alternative with an ODP of zero exists, activities shall adopt alternatives with an ODP of 0.05 or less."

Because SNAP-approved alternatives with an ODP of zero do in fact exist (FE-36 and FM-200), this policy would appear to eliminate Halotron I from further consideration. However, it is not inconceivable that international concern over global warming and long atmospheric lifetimes could ultimately lead to future restrictions on FE-36 or FM-200 as well. Before embarking on a major capital investment in any alternative agent delivery system, the Navy would be prudent to undertake an assessment of the possibility of future environmental rules or regulations coming into effect that might hamper long-term availability of the agent.

NACELLE FIRE TESTING

This section summarizes the work completed for the nacelle engine fire series, a description of the tests, and a discussion of the results.

Reference 3 reports that the most common engine fires fought in the past with Halon 1211 are internal (those in the core of the engine, often referred to as tailpipe fires). Though less common, fires have also occurred externally to that core, in the nacelle (the bay consisting of the void space between the engine and the exterior skin of the aircraft). To achieve the realistic conditions required, the investigators used an actual jet engine (constructed at NAWCWD China Lake) as the test article in the simulation of fires that may occur on a flight line or flight deck.

EXPERIMENTAL SETUP

A background survey of aircraft engine and nacelle designs was conducted to aid in the development of the test article. After a review of the information collected, the unit was constructed by using a Pratt & Whitney TF30-P-1 aircraft engine, which is similar to that company's F-14 TF30-P-414A. The same test setup as that for the tailpipe (see Figure 1) was used for this effort.

The investigators determined that the worst threat was presented by the largest nacelle free volume (of those surveyed the F-18C/D [1.3 m^3 {47 ft^3}]) because, in that instance, the most oxygen is present for combustion. As a consequence, extinguishing the fire would require the maximum amount of agent. So, to achieve conservative results, the test unit was designed with a free volume of 1.6 m^3 (55 ft^3). Figure 11 shows the engine with the nacelle in place.

The nacelle was constructed from a 0.32-cm-thick (0.125-inch), 4.5-meter-long (15-foot), 1.1-meter-diameter (3.7-foot) sheet of mild steel. The nacelle incorporated two exhaust openings (each consisting of a series of 1.9-cm-diameter [0.75-inch] holes drilled into the steel sheet). The clear area for the top vent, located in the aft of the nacelle, was approximately 161.2 cm^2 (25 in^2). The clear area for the bottom exhaust opening, positioned directly below the top one, was about 258 cm^2 (40 in^2).

The nacelle also incorporated a 7.6-cm-diameter (3-inch) air inlet scoop to simulate that on the F-14. This scoop (see Figure 12) was located on the starboard side of the nacelle, 0.9 meter (3 feet) aft of the forward edge. A small hole was drilled 30.5 cm (12 inches) aft of the opening to the scoop to accommodate the insertion of a digital anemometer to measure the external wind airflow into the nacelle. This device, a Dwyer Model 471 Digital Thermo Anemometer, is capable of recording velocities up to 70 meters per second.

A 10.1-cm-diameter (4-inch) hole was cut in the port side of the nacelle to replicate the emergency firefighting knock-out panel found on several types of aircraft. The panel for this test series was approximately the same size and in the same location as on the F-14. This configuration provided a second area to attack for the fires. While not in use, the panel was kept covered.

External winds up to 30 knots were generated by three airboat engines, each of which incorporated a 1.8-meter (6-foot) propeller driven by a 5.7-liter (350-in^3) Chevrolet automobile engine. In addition, the revolutions per minute could be adjusted to vary the wind speed and to compensate for ambient conditions. A handheld anemometer (Pacer Industries Wind Speed Indicator Model WSI-66) captured the wind velocity.

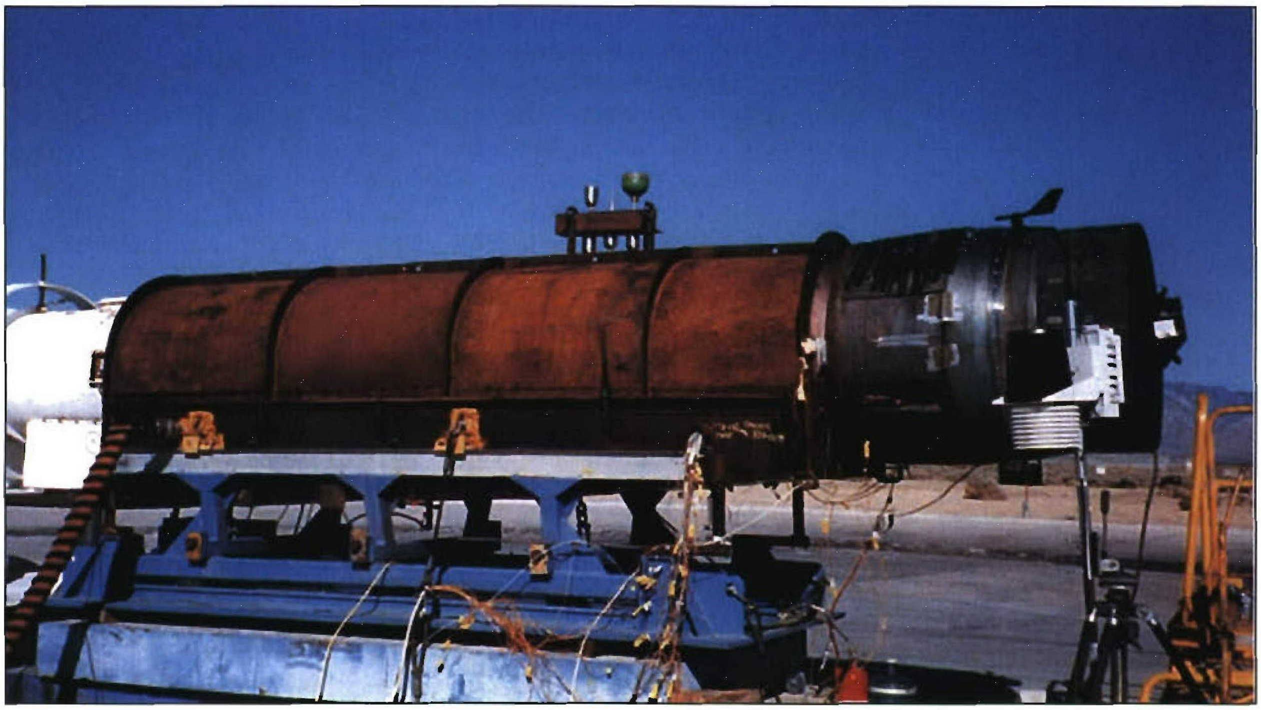


FIGURE 11. Test Article With Nacelle in Place.

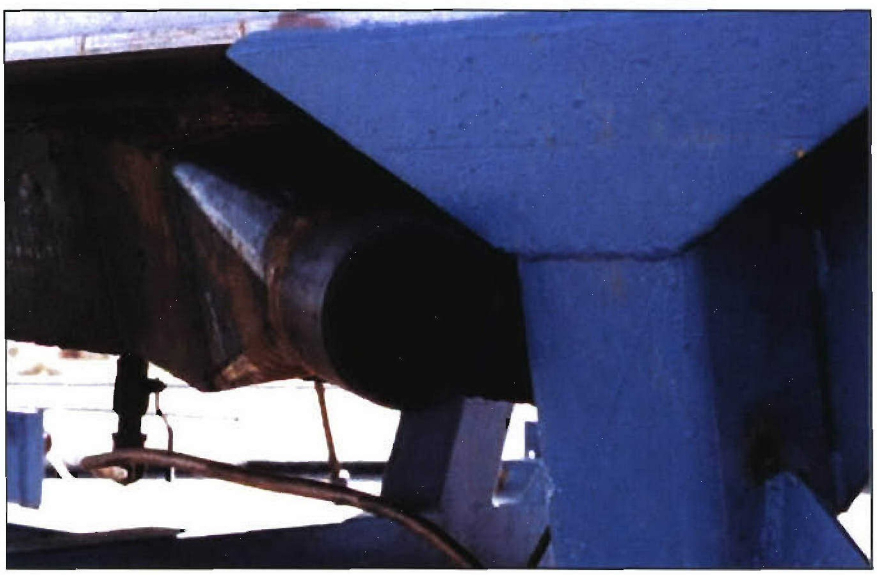


FIGURE 12. Nacelle Inlet Scoop.

AGENT AND EXTINGUISHER SPECIFICATIONS

Table 18 provides a comparison of the physical and chemical properties of the extinguishing agents used in this phase of the evaluation, as well as Halon 1211 for comparative purposes. Table 19 presents the portable extinguisher specifications. For this effort, a full unit was weighed before discharging the agent for 5 seconds and then reweighed, and the data were recorded. Then, the agent was discharged for another 5 seconds, the extinguisher was reweighed, and the data were recorded. The average rates for the first 5 and 10 seconds of flow were computed by dividing the difference in the weights (before and after discharge) by the total discharge time. The total discharge duration and the average flow (based on the former) were derived from manufacturer's specifications. Table 20 provides the results, as well as Halon 1211 for comparative purposes.

TABLE 18. Characteristics of Agents Used in Nacelle Fire Testing.

	CO_2	Halon 1211	FE-36	FM-200
Chemical formula	CO_2	$CBrF_2Cl$	$CF_3CH_2CF_3$	C_3F_7H
Minimum total flooding extinguishing concentration, %	29	3-5	5.6-6.5	5.8-6.6
Boiling point at 1 atmosphere, °F	-110	26	29.3	2.6
Vapor pressure at 77°F, psia	900	38.7	39.5	66.4
Specific volume at 70°F, ft^3/lb	2.54	2.57	2.26	8.83
ODP	0	4	0	0
GWP	1	Not calculated	9400	3800
Atmospheric lifetime, years	N/A	15	226	36.5 [a]
LC_{50}, ppm	70,000 [b]	31,000–100,000	>189,000	>800,000
NOAEL, %	N/A	0.5	10	9
LOAEL, %	N/A	1.0	15	10.5

[a] Weighted average of the constituents.

[b] Threshold level for onset of harmful effects per *NFPA Fire Protection Handbook*, 18th Edition (Reference 17).

TABLE 19. Specifications of Extinguishers Used in Nacelle Fire Testing.

Agent	Manufacturer	Model or Part Number	Gross Weight, lb	Agent Quantity, lb	Operating Pressure, psi	UL Rating
CO_2	Various	Various	42-56	15	900	10B:C
Halon 1211	Amerex	Model 372	37	20	195	4A:80B:C
FE-36	Ansul	CleanGuard 14, Model CA-1481 P/N 422612	26	14	75	2A:10B:C
FM-200	Metalcraft	Prototype	35	20	360	N/A

TABLE 20. Measured Average Discharge Rates of Extinguishers Used in Nacelle Fire Testing.

Agent	Manufacturer/ Model Number, etc.	Agent Quantity, lb	Total Discharge Duration, seconds	Average Flow Rate for First 5 seconds, lb/s	Average Flow Rate for First 10 seconds, lb/s	Average Flow Rate for Total Duration, lb/s
CO_2	Various, MIL SPEC	15		0.54	0.5	0.5
Halon 1211	Amerex	20		1.3	1.2	0.87
FE-36	Ansul CleanGuard 14, Model CA-1481, P/N 422612	14		1.2	1.0	0.96
FM-200	Metalcraft, prototype	20	Not specified	1.3	1.2	Not specified

TESTING EFFORT

The fire scenario developed for the nacelle series involved two steel fuel cups placed in two locations within the nacelle. Both cups were 7.6 cm (3 inches) in diameter, with one 5 cm (2 inches) deep and the other 7.6 cm (3 inches) deep. Table 21 provides a summary of the tests conducted.

In pn_1, which was performed outside of the nacelle to determine the duration of the fire, the cup contained 59 ml (2 ounces) of JP-8. The fire burned for over 28 minutes, longer than that required inside the nacelle. So, for all the subsequent exercises, the cups were filled with 30 mL (1 ounce) of JP-8 and enough water to leave a 1.3 cm (0.5 inch) freeboard in each.

TABLE 21. Summary of Nacelle Tests.

Test	Cup Location	Wind Conditions	Airflow at Nacelle Scoop	Agent Discharge Location	Agent	Time to Extinguish Fire, min
pn_1	None [a]	No wind	None	None	None	27:05
pn_2	Aft	No wind	None	None	None	14:55
pn_3	Forward	No wind	None	None	None	15:32
pn_4	Aft	No wind	None	Inlet scoop	CO_2	0:04
pn_5	Forward	No wind	None	Inlet scoop	CO_2	0:08
pn_6	Forward	No wind	None	Side knock-out panel	CO_2	0:06
pn_7	Forward	No wind	None	Inlet scoop	CO_2	0:05
pn_8	Forward and aft	No wind	None	Inlet scoop	CO_2	0:10
pn_9	Forward and aft	No wind	None	Side knock-out panel	CO_2	0:07
pn_10	Forward and aft	No wind	None	Inlet scoop	FE-36	0:05
pn_11	Forward and aft	No wind	None	Side knock-out panel	FE-36	0:05
pn_12	Forward and aft	12-knot head wind	~500 ft/min	Inlet scoop	FM-200	0:07
pn_13	Forward and aft	15-knot head wind	~500 ft/min	Side knock-out panel	FM-200	0:07

[a] Fire location was outside nacelle to determine size and duration of the fire.

For this evaluation, the investigators chose two locations for the fires. The first site, which was approximately 0.46 meter (1.5 feet) forward of the aft wall of the nacelle on the starboard side, was selected because it is near the exhaust panels but opposite the side knock-out panel. The other, which was in the forward starboard corner of the nacelle, was chosen because its position is farthest from the exhaust vent openings and forward of the inlet scoop. The tests were then conducted with fires in one or both locations.

A 20- by 20-cm (8- by 8-inch) panel was cut into the nacelle at each fire location. The panels were replaced with removable Plexiglas observation windows. These windows were removed to position the cups and then replaced after the fires were ignited. The windows also provided a means of determining when the fires were extinguished. Figure 13 shows the aft fire location with the observation window in place.

During pn_2 and pn_3, the cup was placed in the aft and forward locations, respectively, and the fuel was allowed to burn freely. The resultant fires lasted for approximately 15 minutes in each location. During both tests, smoke emanated from the nacelle inlet scoop and the exhaust openings.

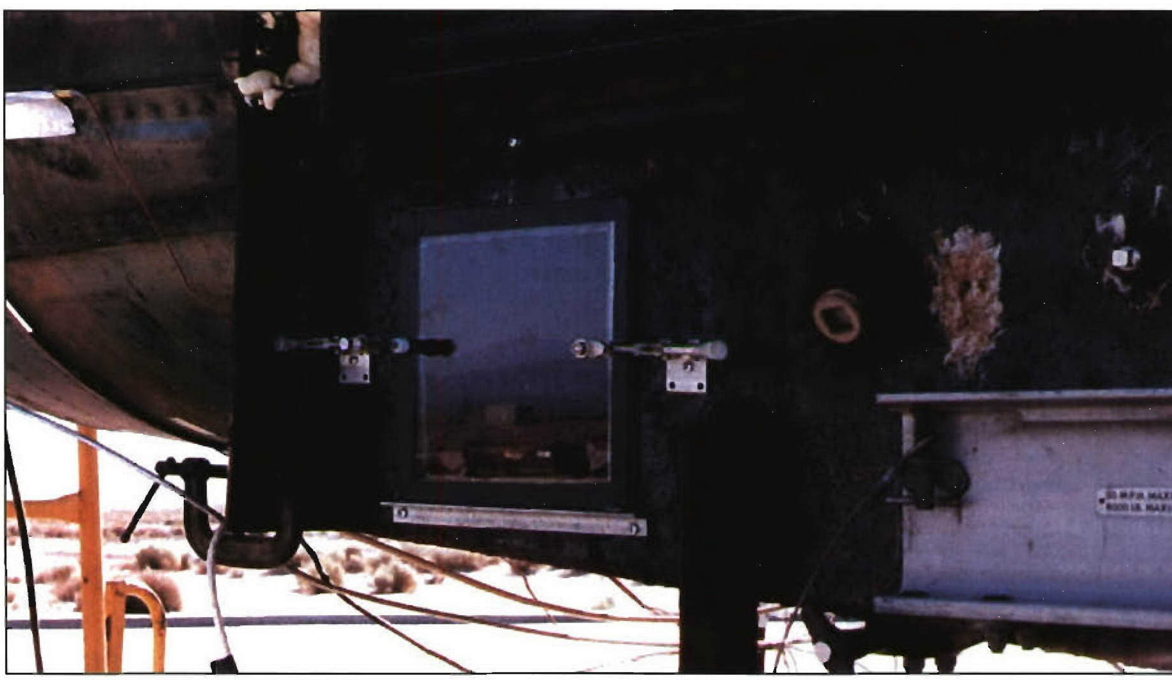


FIGURE 13. Aft Fire Location Observation Window.

In pn_4 through pn_9, CO_2 was applied into either the inlet scoop or the side knock-out panel. The purpose of pn_4 through pn_7 was to evaluate the level of difficulty presented by one fire cup in either location. In those exercises, the fire was put out within 4 to 8 seconds of discharge initiation.

Because successful outcomes were achieved so easily in those tests, fires were simultaneously set in both the forward and aft locations for pn_8 through pn_13. The fuel was ignited and allowed to preburn for 180 seconds, after which the agent (CO_2 [15 pounds], FE-36 [14 pounds], or FM-200 [20 pounds]) was discharged into either the inlet scoop or the side knock-out panel (as determined prior to each test). As Table 21 indicates, the fires were extinguished within 5 to 10 seconds in all of these instances.

Tests pn_12 and pn_13 were conducted with a 12- to 15-knot headwind, which, because there was no obstruction in front of the inlet scoop, created an airflow within of approximately 2.54 m/s (500 ft/min). While the agent was being applied, the scoop was blocked by the firefighter or by the extinguisher discharge horn, actions that effectively prevented the flow of air into the inlet scoop.

ANALYSIS

As Table 21 indicates, all of the fires were quickly extinguished via a single handheld unit. The probable explanation lies in the fact that only small quantities of agent were needed to achieve the minimum total flooding concentration required to extinguish a fire in the nacelle. Table 22 provides these values, which were calculated via Equation 1 (Reference 28).

$$W = (V / S) (C / (100-C)) \tag{1}$$

where:

- W = weight of agent, pounds
- V = volume of space, ft^3
- S = specific volume of agent, ft^3/lb
- C = concentration, %

TABLE 22. Comparison of Minimum Agent Requirements for Fire Extinguishment in Nacelle.

Agent	Minimum Total Flooding Concentration, % (Cup Burner Plus 20%)	Agent Required, lb
Halon 1211	4.8	1.2
CO_2	34.8	3.3
FE-36	7.3	1.7
FM-200	7.4	1.9

CONCLUSIONS, RECOMMENDATIONS, AND FUTURE DIRECTION

In this section, the authors offer their conclusions and recommendations. Also included is the future direction for this effort.

CONCLUSIONS

The following paragraphs provide a summary of the major achievements and conclusions resulting from the jet engine fire testing.

1. The investigators developed a test fixture to assess the agent/system performance for jet engine fires. In addition, a standard scenario was devised that proved to be adequately repeatable and representative of plausible small engine fires (i.e., those in which a concern exists that collateral damage from the firefighting agent may occur to materials not in close proximity to the fire). The apparatus can be used as a standard screening tool or can serve as the baseline for designing a standard surrogate test fixture for future use.
2. The most meaningful benchmark of performance is extinguishing an engine fire through the inlet under 30-knot headwind conditions.
3. For this assumed worst-case scenario, none of the existing handheld COTS units containing FE-36, FM-200, or Halotron I, when discharged one at a time, were successful in putting out the fires. As a consequence, these agents are clearly inferior to Halon 1211 in terms of extinguishing capability.
4. Halon 1211 alternative extinguishers (FE-36, FM-200, Halotron I) exhibited similar performance compared to one another when the agent mass flow rates were the same. The data indicate that a flow rate of approximately 3 lb/s is needed for the worst-case scenario.
5. Existing Halon 1211 alternative COTS extinguishers are too small in terms of agent quantity and flow rate for consistent success against the worst-case engine fire. A unit holding 30 pounds of agent with a flow rate of at least 2 lb/s would be more practical for the specified application. Such an extinguisher for FE-36, FM-200, or Halotron I is estimated to have a gross weight of approximately 45 pounds, which is not excessively heavy for a handheld portable unit. For the worst-case engine fire, simultaneously discharging two such extinguishers provides successful results and affords a considerable factor of safety. The planned strategy is that these larger units be carried on the new P-25 firefighting vehicle or strategically positioned around the flight deck as replacements for Halon 1211.
6. The performance of the CO_2 units was comparable to that of the Halon 1211 alternative extinguishers when the flow rates were the same. However, MIL SPEC CO_2 units flow only at 0.5 lb/s. This factor limits their utility for engine fires because many units must be discharged simultaneously to extinguish the worst-case scenario.
7. Putting out a tailpipe fire through the inlet is extremely difficult when the engine is turning at huffer speed.
8. The three Halon 1211 alternative extinguishers evaluated in this effort exhibited some adverse environmental properties. As a consequence, continued assessment of potential environmental regulations is warranted before undertaking a major capital investment for any alternative agent. (See recommendation 3.)
9. Agent concentrations higher than the minimum required to extinguish a nacelle fire are easily achieved by discharging a single portable extinguisher. In fact, nacelle volumes are so small that even CO_2 is successful. For example, a 15-pound CO_2 extinguisher produces 120 ft^3 of gas, more than twice the volume of the largest nacelle found on flight deck aircraft.
10. Except for aircraft with engines high above the deck (i.e., the V-22 and helicopters), nacelle fires on aircraft flight decks do not present a challenge for any of the Halon 1211 alternatives being considered. The key issue is the application technique, not the inherent capability of the Halon 1211 alternative agent to extinguish the fire.

RECOMMENDATIONS

Based on the findings for this effort, the investigators make the following recommendations.

1. Initiate action with the manufacturers of FE-36, FM-200, and Halotron I handheld portable extinguishers to develop units with a capacity for 30 pounds of agent, a flow rate of at least 2 lb/s, and a maximum gross weight of 45 pounds. The performance of these larger prototypes should be confirmed by retesting them against the standard worst-case engine fire.
2. Continue with the Halon 1211 replacement program effort by developing test plans to evaluate the performance of alternatives against the following fire scenarios: (1) engines mounted high above the deck (helicopters and V-22), (2) engine nacelles, (3) aircraft electronics/avionics bays, and (4) debris piles. Testing for these scenarios should be conducted with the higher flow rate extinguishers developed.
3. Continue to monitor environmental regulations that are applicable to the long-term viability of the Halon 1211 alternatives. Interface as necessary with Department of Defense and Navy environmental authorities to confirm the appropriateness of including Halotron I in the remaining test evolutions.
4. Update References 1 and 30.
5. Consider developing a standard fire simulator modeled after the features of the actual engine used in this program. Such an apparatus could be used to evaluate new agents, equipment, and tactics.
6. Limit additional evaluations of handheld extinguishers for use on nacelle fires to access and application techniques. Pursue a method of introducing the agent into nacelles elevated above the deck as part of the high-mounted engine tests recommended, the next step in the aircraft engine phase of the overall Halon 1211 replacement program.

FUTURE DIRECTION

The effort described in *Internal Engine Fire Testing* section evolved from the engine fire test plan (Reference 3), which was developed in support of the overall Halon 1211 replacement program plan (Reference 2). Additionally, Reference 2 included a graphical representation of the course of action and a suggested decision tree to guide in its implementation.

To complete the engine test sequence, the initial emphasis should be placed on evaluating fires in which access to the inlet or tailpipe is hindered because of the height of the engine above the ground. High engine mounts on helicopters and the unique engine design of the new V-22 may necessitate specific doctrine and equipment, such as extension wands for portable extinguishers. Efforts should proceed to design a suitable apparatus and to develop a test plan.

Planning should proceed to conduct the debris pile fire tests. The investigators anticipate that this effort requires 1 week for the scoping series and 2 weeks for detailed testing. Updating References 1 and 30 may be prudent because both of these reviews are over 5 years old. For example, the fire incident data cited in Reference 1 included information through fiscal year 1995. Similarly, the predictions that apply to the size and the projected drawdown of the Navy Halon 1211 bank should be updated. For example, changes in the drawdown projections and lifetime of the Navy Halon 1211 reserve would influence the focus and schedule of the remaining test effort. Restrictions or bans on Halon 1211 use may occur that affect the scheduling of fielding its replacement systems.

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NOMENCLATURE

CO_2	carbon dioxide
COTS	commercial off-the-shelf
EAPS	engine air particulate separator
EPA	Environmental Protection Agency
gpm	gallons per minute
GWP	global warning potential
HAI	Hughes Associates, Inc.
HCFC	hydrochlorofluorocarbon
JP	jet propulsion
LC	lethal concentration
LOAEL	lowest observed adverse effect level
MIL SPEC	military specification
NATOPS	Naval Air Training and Operating Procedures Standardization
NAWCWD	Naval Air Warfare Center Weapons Division
NFPA	National Fire Protection Association
NOAEL	no observed adverse effect level
ODP	ozone depletion potential
PKP	potassium bicarbonate powder
ppm	parts per millions
pps	lb/s
rpm	revolutions per minute
SNAP	Significant New Alternative Policy

Appendix A
SUMMARY OF SCOPING SERIES

Test	Description
pre1	Experimented with different timing for loading engine and dumping fuel, used igniters to try to light residual fuel after fuel flow secured
pre2	Experimented with different timing for loading engine and dumping fuel, used igniters to try to light residual fuel after fuel flow secured
pre3	Experimented with different timing for loading engine and dumping fuel, used igniters to try to light residual fuel after fuel flow secured
pre4	Experimented with different timing for loading engine and dumping fuel, used igniters to try to light residual fuel while cycling fuel on and off
pre5	Experimented with different timing for loading engine and dumping fuel, used igniters to try to light residual fuel after fuel flow secured
pre6	Dumped fuel for 15 seconds, then tried to ignite with igniters, repeated with additional 15-second fuel flow
pre7	Lit residual pool in tailpipe with torch, used gasoline as an accelerant when JP-8 pool alone would not ignite
pre8	Dumped fuel for 15 seconds with engine loaded, unloaded, dumped gas into tailpipe, lit with torch
pre9	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped gas into tailpipe, lit with torch
pre10	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped gas into tailpipe, lit with torch
pre11	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre12	Dumped fuel for 30 seconds with engine loaded, unloaded, poured 250 ml JP-8 into tailpipe, lit with torch
pre13	Dumped fuel for 15 seconds with engine loaded, unloaded, lit with torch
pre14	Dumped fuel for 15 seconds with engine loaded, unloaded, lit with torch (combustor drain open)
pre15	Dumped fuel for 5 seconds with engine loaded, unloaded, lit with torch
pre16	Dumped fuel for 5 seconds with engine loaded, unloaded, lit with torch
pre17	Dumped fuel for 10 seconds with engine loaded, unloaded, lit with torch
pre18	Dumped fuel for 20 seconds with engine loaded, unloaded, lit with torch
pre19	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre20	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre21	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre22	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre23	Dumped fuel for 30 seconds with engine loaded, unloaded, turned igniters on to try to light (with fuel on)
pre24	Dumped fuel for 30 seconds with engine loaded, unloaded, turned igniters on to try to light (with fuel on)
pre25	Experimented with fuel and igniter to try to light
pre26	Dumped 250-ml JP-8 into turbine section, lit with torch
pre27	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre28	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre29	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre30	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre31	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre32	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre33	Dumped fuel for 15 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre34	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel

Test	Description
pre35	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre36	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre37	Dumped fuel for 20 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre38	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre39	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre40	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre41	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre42	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre43	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre44	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre45	Dumped fuel for 15 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre46	Dumped fuel for 30 seconds with engine loaded, unloaded, energized igniters while cycling fuel
pre47	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre48	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre49	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre50	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre51	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre52	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre53	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch (tried to light turbine)
pre54	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre55	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre56	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre57	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre58	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre59	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre60	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre61	Dumped fuel for 30 seconds with engine loaded, unloaded, lit with torch
pre62	Dumped fuel for 30 seconds with engine loaded, unloaded (two cycles), lit with torch
pre63	Dumped fuel for 30 seconds with engine loaded, unloaded (two cycles), lit with torch
pre64	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre65	Dumped fuel for 30 seconds with engine loaded, unloaded (two cycles), lit with torch
pre66	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre67	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 50 seconds, lit with torch
pre68	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch

Test	Description
pre69	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre70	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch
pre71	Dumped fuel for 30 seconds with engine loaded, unloaded, dumped fuel for 30 seconds, lit with torch

Appendix B
SUMMARY OF AGENT USAGE DURING BASELINE SERIES

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
p1_01	116	39.8	28	11.8
p1_02	51 70	39.2 43.5	32.6 30.6	19.5
p1_03 [a]	67 127	44.2 48.7	36.7 36.3	19.9
p1_04 [a]	66 52 63	39.4 50.5 50.3	30.6 38.6 38.2	32.8
p1_05	45	51.7	43.1	8.6
p1_06	106	49.3	40.2	9.1
p1_07	87	48.5	46.3	2.2
p1_08 [a]	N/A	N/A	N/A	N/A
p1_09 [a]	92	41.8	30.8	11.0
p1_10	53	42.5	38.8	3.7
p1_11	60	49.0	43.0	6.0
p1_12	54	50.7	46.1	4.6
p1_13	72	46.2	38.0	8.2
p1_14	95	49.4	46.9	2.5
p1_15	33	43.5	40.2	3.3
p1_16	65	40.4	36.2	4.2
p1_17	32	41.7	35.6	6.1
p1_18	68	41.5	35.0	6.5
p1_19	56	40.1	35.9	4.2
p1_20 [a]	N/A	N/A	N/A	N/A
p1_21	131	49.3	38.4	10.9
p1_22	97	49.6	46.6	3.0
p1_23	71	50.4	43.6	6.8
p1_24	124	50.5	45.1	5.4
p1_25	94	50.3	40.5	9.8
p1_26	64	45.3	40.8	4.5
p1_27	107	43.3	37.8	5.5
p1_28	44	41.3	37.0	4.3
p1_29	85	47.8	45.3	2.5
p1_30	40	49.4	46.1	3.3
p1_31	81	50.7	49.4	1.3
p1_32 [a]	111 117 49	51.2 49.4 50.6	40.2 40.0 47.8	23.2
p1_33	80 105	42.3 45.4	31.7 40.5	15.5

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
p1_34	62 110 19 119	44.1 49.8 49.3 48.4	32.4 38.1 44.9 45.4	30.8
p1_35	89 123 96	39.8 47.9 48.8	38.4 36.5 38.9	22.6
p1_36	86 50	50.6 50.4	43.3 42.9	14.8
p1_37	38 14	48.0 49.5	38.4 40.6	18.5
p1_38	102 48	46.7 45.8	39.1 39.4	14.0
p1_39 [a]	103 26	48.9 N/A	45.9 N/A	3.0 N/A
p1_40	109 58	45.1 49.4	40.2 45.5	8.8
p1_41	Halon 1	36.9	31.5	5.4
p1_42	Halon 2	37.2	29.8	7.4
p1_43	Halon 3	37.3	31.9	5.4
p1_44 [a]	Halon 4 Halon 5 69	36.6 36.8 43.2	16.6 19.8 38.8	Halon 1211—37.0 CO_2—4.4
p1_45 [a]	Halon 6	36.6	27.7	8.9
p1_46 [a]	55 118 84	49.8 N/A 49.3	37.8 N/A 37.9	23.3
p1_47 [a]	N/A	N/A	N/A	N/A
p1_48 [a]	N/A	N/A	N/A	N/A
p1_49 [a]	N/A	N/A	N/A	N/A
p1_50 [a]	PKP 1	35.6	26.8	8.8
p1_51 [a]	PKP 2	34.7	31.3	3.4
p1_52 [a]	N/A	N/A	N/A	N/A
p1_53 [a]	131 50	49.1 50.3	40.6 50.0	8.8
p1_54 [a]	123 124	46.8 50.1	42.7 47.8	6.4
p1_55 [a]	81	49.9	39.1	10.8
p1_56 [a]	58 109	49.3 45.2	39.1 44.9	10.5
p1_57 [a]	3	40.9	31.9	9.0
p1_58 [a]	18 72	49.4 46.6	38.7 33.5	23.6
p1_59 [a]	156	N/A	39.7	N/A
p1_60 [a]	181	48.6	46.0	2.6

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
p1_61 [a]	87 60 12	48.4 49.1 49.7	41.4 45.0 47.7	13.1
p1_62 [a]	137 76	47.8 50.7	37.2 46.4	14.9
p1_63 [a]	117	50.0	47.6	2.4
p1_64 [a]	11 47 6 82	50.3 42.7 49.6 49.4	41.7 31.1 40.2 40.7	38.3
p1_65 [a]	73 112 94	44.1 52.1 50.2	32.4 39.6 38.7	35.7
p1_66 [a]	46 86 77	45.3 51.1 51.3	33.8 40.2 39.9	33.8
p1_67 [a]	N/A	N/A	N/A	N/A
p1_68 [a]	N/A	N/A	N/A	N/A
p1_69 [a]	N/A	N/A	N/A	N/A
p1_70 [a]	N/A	N/A	N/A	N/A
p1_71 [a]	103 95 92 176 111	48.2 48.7 42.3 42.7 50.8	38.0 38.0 31.0 N/A 50.0	39 [b]
p1_72 [a]	106 182 60 167 128	49.0 39.3 N/A 50.5 50.8	39.0 28.5 39.0 Bad valve 48.0	28.1 [b]
p1_73 [a]	Halon-1	36.7	22.5	15.7 [b]
p1_74 [a]	FE36-1 FE36-2 183 71	27 27.5 50.1 49.9	13.5 14.0 41.0 40.0	FE-36—27.0 CO_2—22.0
p1_75 [a]	122 124	49.5 50.1	45.5 47.0	10.1 [b]
p1_76 [a]	3 129 81 144 143	40.9 40.8 51.0 53.0 49.5	30.0 31.5 40.0 47.0 48.0	41.7 [b]
p1_77 [a]	FE36-4	26.8	19.0	9.3 [b]

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
p1_78 [a]	FE36-3	26.7	13.0	FE-36—30.1 [b] CO_2—10.0
	FE36-5	26.4	13.0	
	142	51.0	45.0	
	57	47.0	43.0	
p1_79 [a]	FE36-6	26.2	14.0	FE-36—28.3 [b] CO_2—4.0
	FE36-8	26.1	13.0	
	136	47.0	43.0	
p1_80 [a]	66	41.0	37.0	7.5
	152	42.0	38.5	
p1_81 [a]	Halon-4	36.9	18.0	Halon 1211—40.5 [b] CO_2—16.5
	Halon-5	36.6	18.0	
	109	47.5	35.0	
	120	52.0	51.0	
p1_82 [a]	N/A	N/A	N/A	N/A
p1_83 [a]	58	N/A	49.0	N/A
p1_84 [a]	48	45.9	41.0	14.3 [b]
	84	49.4	43.0	
p1_85 [a]	120	51.5	46.0	7.0 [b]
p1_86 [a]	8	51.0	44.0	8.5 [b]
p1_87 [a]	156	N/A	41.0	9.3 [b]
	93	47.8	40.0	
	12	N/A	50.0	
Pan1 [a]	132	52.0	50.0	2.0
Pan2 [a]	131	50.0	49.0	1.0
Pan3 [a]	72	49.0	37.0	12.0
Pan4 [a]	50	51.0	42.0	9.0
Pan5 [a]	45	51.0	50.0	1.0
Pan6 [a]	123	48.0	38.0	10.0
Pan7 [a]	89	41.0	30.5	10.5
Pan8 [a]	91	46.0	33.0	57.0
	87	50.0	37.0	
	43	51.5	40.0	
	16	41.0	29.0	
	81	50.0	42.5	
Pan9 [a]	6	53.0	42.0	26.0
	43	51.0	39.0	
	128	52.0	49.0	
Pan10 [a]	124	51.5	41.0	51.0
	63	51.0	40.0	
	76	53.5	50.0	
Pan11 [a]	111	52.5	40.5	61.0
	122	52.5	42.0	
	66	40.0	28.5	
	94	52.0	40.5	
	74	51.5	41.0	
	47	45.0	40.0	

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
Pan12 [a]	46	47.0	35.0	CO_2—62.0 Halon 1211—14.7
	129	43.0	33.0	
	153	49.0	39.0	
	53	43.0	31.5	
	95	50.0	40.0	
	97	51.5	43.0	
	Halon 8	36.7	22.0	
Pan13 [a]	10	47.0	40.0	24.5
	113	43.0	32.0	
	82	50.5	44.0	
Pan14 [a]	3	42.0	30.0	21.5
	183	52.5	43.0	
Pan15 [a]	106	50.5	41.0	58.0
	152	41.5	30.0	
	144	53.0	42.0	
	142	51.0	40.0	
	73	47.0	43.0	
	52	52.0	41.0	
Pan16 [a]	92	44.0	34.0	10.0
Pan17 [a]	109	47.0	35.5	11.5
p1_88 [a]	74	53.0	40.0	70.0
	136	46.0	32.5	
	79	53.0	40.0	
	92	45.0	31.0	
	103	50.0	45.0	
	112	52.0	40.5	
p1_89 [a]	122	52.0	42.0	88.3
	152	41.5	29.0	
	153	50.0	37.5	
	10	50.5	38.5	
	117	51.5	39.0	
	11	49.0	40.5	
	71	51.3	42.0	
	86	52.0	41.0	
	Halon-16	N/A	29.0	
p1_90 [a]	144	53.0	44.2	10.3 [b]
	121	52.0	41.3	12.2 [b]

[a] Indicates data that were not used in analysis summarized in Tables 7 and 8.
[b] Weight adjusted for scale offset of 1.5 lb.

Appendix C
SUMMARY OF AGENT USAGE DURING SYSTEMS EVALUATION SERIES

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
p1_91	W-2 W-1 3	27.6 27.5 41.0	10.0 7.6 35.9	Water mist—37.5 CO_2—6.6 [a]
p1_92	WH 63	31.8 51.5	19.3 47.8	Water mist—12.5 CO_2—5.2 [a]
p1_93	W-2 W-1 156	28.4 28.4 52.0	14.9 17.0 49.2	Water mist—24.9 CO_2—4.3 [a]
p1_94	WH 97	32.2 52	19.3 49.1	Water mist—12.9 CO_2—4.4 [a]
p1_95	FE36-2	27.0	23	4.0
p1_96	FE36-1	26.5	13.2	13.3
p1_97	FE36-3 FE36-4	27.0 27.0	11.8 11.9	30.3
p1_98	FE36-3 FE36-4 89 45 95 118 50 Halon 2	25.3 25.3 42.0 51.3 50.5 52.0 50.7 N/A	11.8 11.9 28.0 38.5 37.2 39.4 37.9 N/A	FE-36—26.9 CO_2—69.9 [a]
p1_99	FE36-6 FE36-5 77 81 54 48 58 Halon	26.6 26.9 51.8 50.8 50.5 47.2 50.3 N/A	11.8 11.8 39.9 38.7 39.3 33.9 38.6 N/A	FE-36—29.9 CO_2—60.3
p1_100	FE36-7 FE36-8 80 66 52 1.1 120 87 Halon	26.3 26.6 43.0 39.0 51.0 50.0 51.8 49.4 N/A	11.9 11.7 31.8 27.4 39.0 38.3 39.6 36.9 N/A	FE-36—29.3 CO_2—71.2
p1_101	Halon 1 Halon 3	36.0 36.8	12.2 11.7	Halon 1211—48.9
p1_102	Halon 8 Halon 5	36.7 36.4	17.3 25.7	Halon 1211—30.1

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
pl_103	FM-2 FM-1 123	15.9 15.7 48.4	5.1 5.5 43.2	FM-200—11.0 CO_2—5.2
pl_104	FE36-3 FE36-4 FE36-1 FE36-2 124 43 Halon 12	25.6 26.5 26.4 26.2 50.3 48.9 36.9	11.7 11.4 12.2 12.0 39.8 38.0 N/A	FE-36—57.4 CO_2—21.8
pl_105	56 90 49 105 147 46 Halon 12 Halon 6	39.4 43.8 49.9 44.5 50.0 45.9 N/A N/A	28.3 32.5 38.4 33.4 38.3 33.4 N/A N/A	CO_2—69.2
pl_106	FE36-7 FE36-8	25.8 26.5	13.5 15.4	FE-36—23.4
pl_107	FM-1 FM-2 73	15.7 15.9 44.7	5.1 5.3 41.3	FM-200—21.2 CO_2—3.4
pl_108	FE36-5 FE36-6 183	26.6 25.4 51.3	11.8 11.8 48.2	FE-36—28.4 CO_2—3.1
pl_109	RONA-1 RONA-2 133	27.3 27.2 49.8	11.8 11.8 45.0	Halotron I—30.9 CO_2—4.8
pl_110	RONB-2 RONB-1 RONB-4	25.0 25.2 25.0	9.9 10.2 17.3	37.8
pl_111	RONC-2 RONC-1 RONC-3 RONC-4 109 94 91 Halon 9	25.1 25.2 25.0 25.0 45.2 50.6 45.9 36.7	9.4 10.7 9.5 9.9 33.9 40.3 34.3 23.2	Halotron I—60.8 CO_2—33.2 Halon 1211—13.5
pl_112	RONC-3 RONC-6 RONC-4 RONC-5 8	26.9 27.3 27.3 27.3 52.1	11.5 11.9 11.7 11.9 44.3	Halotron I—61.8 CO_2—7.8

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
pl_113	68 78 2 85 111	41.1 42.5 44.0 47.4 51.6	29.4 31.1 31.6 36.7 43.8	54.0
pl_114	RONB-7 RONB-8	33.3 33.1	22.9 22.8	20.7
pl_115	Halon 5	36.8	25.2	11.6
pl_116	54 122	50.5 49.2	40.6 49.1	10.0
pl_117	117 121 131 80 79	49.0 51.0 50.2 41.6 51.1	39.6 39.9 39.8 31.6 45.9	46.2
pl_118	FE36-1 FE36-2 FE36-3 FE36-4	26.0 25.6 25.6 25.2	19.5 19.3 19.4 19.4	24.8
pl_119	N/A	N/A	N/A	N/A
pl_120	FE36-5 FE36-6 FE36-7 FE36-8 106	25.9 27.5 25.5 25.8 50.1	12.3 13.1 11.9 12.0 N/A	FE-36—55.4
pl_121	FE36-1 FE36-2 FE36-3	26.8 25.9 25.9	18.8 18.9 17.8	23.1
pl_122	FE36-4 FE36-5 FE36-6	26.5 26.4 26.6	19.9 20.4 20.4	18.8
pl_123	FE36-7 FE36-8 152	26.6 26.3 38.9	11.6 11.7 33.4	FE-36—29.6 CO_2—5.5
pl_124	RONC-5 RONC-6 66	25.5 25.5 38.9	10.1 10.0 34.1	Halotron I—30.9 CO_2—4.8
pl_125	RONB-3 RONB-4 RONB-5	25.4 25.3 25.3	18.0 17.8 17.7	15.5

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
pl_126	92 10 71 143 50	44.2 43.9 50.1 49.3 48.7	40.8 38.8 39.2 37.6 44.5	66.4
pl_127	FE36-1 FE36-2	26.5 26.0	18.3 17.8	16.4
pl_128	FE36-3 FE36-4	26.4 26.7	17.5 18.1	17.5
pl_129	Primex 1 Primex 2	N/A N/A	N/A N/A	N/A N/A
pl_130	Primex 3 Primex 4	N/A N/A	N/A N/A	N/A N/A
pl_131	FE36-1 FE36-2	25.9 26.3	17.0 17.4	17.8
pl_132	FE36-3 120	26.4 51.3	11.5 47.3	FE-36—14.9 CO_2—4.0
pl_133	FE36-4	26.9	13.2	13.7
pl_134	FM20-1 53	34.7 41.0	15.0 37.4	FM-200—19.7 CO_2—3.6
pl_135	28 31 44 61	43.4 44.5 40.8 41.3	39.5 40.6 36.9 38.5	14.5
pl_136	Primex 5 Primex 6 Primex 7 Primex 8	N/A N/A N/A N/A	N/A N/A N/A N/A	N/A N/A N/A N/A
pl_137	62 4 39	44.6 45.4 40.8	39.4 39.9 35.3	16.2
pl_138	70 107	43.8 43.2	31.9 31.5	23.6
pl_139	PKP 1 155	48.0 46.1	30.2 40.8	PKP—17.8 CO_2—5.3
pl_140	FE36-1 FE36-2 FE36-3	26.5 26.5 26.0	15.0 15.0 12.0	37.0
pl_141	FE36-4 FE36-5 136	28.5 26.0 43.3	12.0 12.0 36.0	FE-36—30.5 CO_2—7.3
pl_142	FE36-9 FE36-10	31.5 31.5	22.0 24.0	17.0

Test	Extinguisher Numbers	Pretest Weight, lb	Post-test Weight, lb	Total Usage, lb
pl_143	FE36-1 FE36-2	26.0 25.0	18.5 17.5	15
pl_144	FM20-1 FM20-2	35.0 35.0	28.5 29.0	12.5
pl_145	FE36-9	32.0	22.0	10.0
pl_146	Primex 9 Primex 10 Primex 11	N/A N/A N/A	N/A N/A N/A	N/A N/A N/A
pl_147	FE36-9 FE36-10 CO_2	32.0 31.5 N/A	11.5 11.5 N/A	FE-36—40.5
pl_148	FE36-1 FE36-2 FE36-3 149	26.0 26.0 25.0 49.2	12.0 12.0 11.5 46.0	FE-36—41.5 CO_2—3.2
pl_149	FE36-4 FE36-5 FE36-6 87	26.5 26.0 25.5 43.5	11.5 11.5 11.5 38.0	FE-36—43.5 CO_2—5.5
pl_150	FM20-1 FM20-2 FM20-3	35.0 35.5 35.0	15.0 20.0 22.5	48.0
pl_151	FE36-1 FE36-2 FE36-3	26.0 26.0 26.0	22.0 22.0 22.0	12.0
pl_152	FM20-2 FM20-3 FM20-4	35.5 35.5 35.5	30.5 30.5 30.5	15.0

FM = FM-200 (10.75 lb), FM20 = FM-200 (20 lb), RONA = Amerex Halotron I (15.5 lb), RONB = Buckeye Halotron I (15.5 lb), RONB 7 and 8 = Buckeye Halotron I (20 lb), RONC = Badger Halotron I (15.5 lb).

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