Final Report
for the
Fire Extinguishing Performance Test
of the

Low Global Warming Potential (GWP) Agents

AD No. ________________________________
ATEC Project No. 2016-DT-ATC-RDECO-G5550
Report No. ATC-12480

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TEAT-SLM 13 Jun 19

MEMORANDUM FOR U.S. Army Test and Evaluation Command (ATEC) (CSTE-TM, ATTN: Mr. Gregory Serabo), 6617 Aberdeen Boulevard, Aberdeen Proving Ground, MD 21005-5001

SUBJECT: Final Report for the Fire Extinguishing Performance Test of Low Global Warming Potential Agents, ATEC Project No. 2016-DT-ATC-RDECO-G5550.

1. Subject final report has been approved by this test agency and is submitted for your information and retention.

2. The point of contact for this office is Mr. Daniel Kogut, TEAT-SLM, 410-278-1422, or daniel.t.kogut.civ@mail.mil.

FOR THE COMMANDER:

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SECTION 1. EXECUTIVE DIGEST

1.1 SITUATIONAL DESCRIPTION

The Army relies on Halon 1301 (bromotrifluoromethane, CF_3Br) and two hydrofluorocarbon (HFC) extinguishing agents (HFC-227ea (1,1,1,2,3,3,3-heptafluoropropane, CF_3CHFCF_3) and HFC-125 (pentafluoroethane, CF_3CHF_2)) to provide fire protection for its ground and aviation weapon systems, equipment, and facilities. These deployed fire suppression agents have global warming potentials (GWP) thousands of times that of carbon dioxide (CO_2), which has a defined GWP of one. GWP is a measure of how much heat a greenhouse gas traps in the atmosphere relative to CO_2, with the GWP of CO_2 standardized at 1. Halon 1301 has a GWP of 7,100, HFC-227ea has a GWP of 3,200, and HFC-125 has a GWP of 3,500. This means that when compared to an equivalent mass of CO_2, Halon 1301 will trap 7,100 times as much heat in the atmosphere. Approximately two million pounds of these chemicals are installed in crew, engine, and auxiliary power unit (APU) compartments and portable extinguishers of Army ground vehicles and aviation weapon systems.

Production of Halon 1301 was eliminated in 1994 because of its high ozone depletion potential. Since then, the Army has relied on a strategic reserve and commercial supplies to support a very limited number of critical legacy applications while transitioning to HFCs or other alternatives wherever possible. On 15 October 2016, Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer adopted the "Kigali Amendment". This Amendment added HFCs to the Montreal Protocol and called for the gradual reduction of their consumption (defined as production + imports - exports - destruction). The phasedown schedule for the US and other A2 Parties starts with a 10-percent reduction in 2019 and culminates in an 85-percent reduction by 2036. The intermediate phasedown steps and final allowed consumption levels for all parties are shown in Table 1-1. Note that as of the date of this report, no decisions had been made whether to stockpile HFCs to meet future Army weapon system fire suppression requirements for those systems that have transitioned from Halon. While the Kigali Amendment does not specifically detail the phase down of HCFCs, their production is capped indefinitely at either 65 percent, or 15 percent of the baseline established.

TABLE 1-1. HFC CONSUMPTION PHASE-DOWN SCHEDULE

	A5 Group 1	A5 Group 2	A2
Baseline	2020-2022	2024-2026	2011-2013
Formula	Average HFC Consumption	Average HFC Consumption	Average HFC Consumption
HCFC	65% of baseline	65% of baseline	15% of baseline[a]
Freeze	2024	2028	Not applicable
1st step	2029 - 10% reduction	2032 - 10% reduction	2019 - 10% reduction
2nd step	2035 - 30%	2037 - 20%	2024 - 40%
3rd step	2040 - 50%	2042 - 30%	2029 - 70%
4th step	None	None	2034 - 80%
Plateau	2045 - 80%	2047 - 85%	2036 - 85%

[a]For Belarus, Russian Federation, Kazakhstan, Tajikistan, and Uzbekistan, 25-percent HCFC component of baseline and different initial two steps: (1) 5-percent reduction and (2) 35-percent reduction in 2015.

TABLE 1-1 (CONT)

Note: An Article 5 (A5) country is considered any party that is a developing country with an annual calculated level of consumption of controlled substances as defined by the Montreal Protocol less than 0.3 kg per capita. Article 5 countries are divided into two groups. Group 1: majority of A5 parties not included in Group 2. Group 2: Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates.

As a result of the adoption of the "Kigali Amendment", low GWP chemicals for fire suppression in crew and engine compartments, aviation engine and APU compartments, and portable extinguishers are needed to satisfy these much more stringent environmental restrictions.

Because of the increased global regulatory scrutiny on these materials, the Army established the Low GWP Alternative Fire Suppressants program. The focus of this FY16 - FY18 effort was to evaluate the feasibility of commercially available and emerging chemicals to replace high GWP fire suppressants in Army weapon systems. Continued study of low GWP fire suppression alternatives will be performed to determine the need for regulatory exemptions and/or strategic reserve of HFCs if low GWP chemicals prove not to be feasible alternatives to satisfy military-unique performance requirements including vulnerability to ballistic threats and explosion suppression in occupied areas. Results will guide the direction of future research and procurement activities, as well as offer potential cost avoidance associated with reduced availability and thus higher costs of high GWP agents after phase-down. The focus of this effort was directed at Army applications that do not have any alternatives to the high GWP halons and HFCs as shown in Figure 1-1.

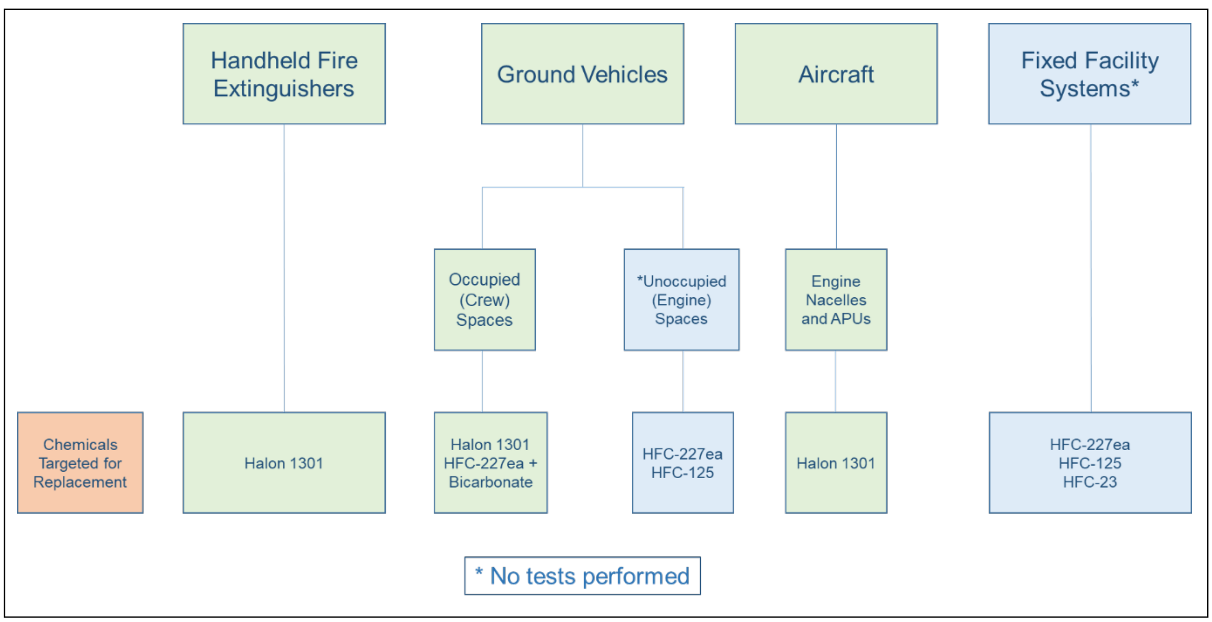


Figure 1-1. Fire protection applications for Army weapon systems. Note: The Army has developed a new aviation weapon system HPFE using HFC-227ea plus small particle bicarbonate, however this has not been fielded at the time of this report.

This effort consisted of the following tasks:

- Market surveys and candidate agent identification
- Cup-burner testing
- Sodium bicarbonate powder assessment
- Hidden fire chamber testing
- Small scale chamber testing
- Toxicology assessments
- Pan fire testing
- Engine nacelle simulator testing and evaluations
- Full-scale explosion suppression testing
- Data analysis and recommendations

Each of these tasks is discussed in detail in the body of this report.

1.2 SUMMARY

Planning between project leads from AMCOM and GVSC initiated the Army weapon systems low GWP fire suppression research planning process in September 2014 to address Army Environmental Requirements and Technology Assessments (AERTA) PP-14-12-01: No/Low Global Warming Potential Alternatives to Ozone Depleting Substances in Army Applications. On 2 March 2016, the U.S. Army Test and Evaluation Command (ATEC) authorized the U.S. Army Aberdeen Test Center (ATC), Aberdeen Proving Ground (APG), Maryland, to plan, conduct, and report the Fire Extinguishing Performance Test of Low Global Warming Potential (GWP) Agents through the establishment of an ATEC project No. 2017-DT-ATC-RDECO-G5550 (app M, ref 1).

Results of this project indicate that the currently available candidate low GWP extinguishing agents that were evaluated:

- Have varying levels of firefighting effectiveness;
- Exhibit more reactivity than currently used HFCs, resulting in elevated byproduct levels;
- May require greater reliance on powder additives than current HFCs to achieve required performance;
- May have performance further improved by delivery system development.

These newly commercialized low GWP developmental alternatives are based on chemicals reactive with atmospheric components (hydroxyl free radicals) and are referred to as tropodegradable compounds. They degrade in the troposphere (the lowest layer of the Earth's atmosphere) and become polar molecules (like water) that are subject to rain-out removal from the atmosphere. Since their atmospheric lifetimes are shorter, these compounds contribute less to global warming.

Alkenes have carbon-carbon double bonds (C=C) and readily decompose in the atmosphere. Structures such as the fluoroalkenes, hydrofluoroalkenes and related compounds are also in general expected to have shorter atmospheric lifetimes than structurally similar alkanes with carbon-carbon single bonds (C-C). In the course of this project, candidate alkenes based on propene and butene structures were obtained from commercial and research sources and evaluated for hand-held fire extinguisher, crew compartment automatic fire extinguishing system

(AFES), engine compartment, and engine nacelle applications for potential aviation and ground vehicle weapon systems.

As the fluoroalkene candidate compounds were expected to be less effective than existing fire suppressants, a performance boosting method previously demonstrated during the development for a new hand-held extinguisher for rotary wing weapon systems was evaluated for select candidates. During the previous development of the new hand-held extinguisher, commercially available United States Pharmacopeia (USP) grade sodium bicarbonate (SBC) was processed using methodology that achieved low micron and nano-sized particles in order to obtain the longest settling times on discharge, and highest amount of particulate surface area. For this effort, the approach utilized blending of newly produced micronized SBC with candidate agents.

The project has identified several promising low GWP candidate agents. Preliminary toxicity reviews and functional fire suppression tests geared to evaluate performance in hand-held, portable fire extinguishers (HPFEs), crew compartment AFES, engine compartment, and engine nacelle applications have been conducted. No comprehensive optimizations of hardware and agent performance, or evaluations of long-term agent stability or material compatibility have been performed under this program. The limited testing performed in each application area shows promise with no "show stopping" results seen.

The fire suppression testing done to date has demonstrated that several of these tropodegradable candidates have potential for use in hand-held fire extinguishers (Section 6), occupied spaces of crew compartments in ground vehicles (Section 8), and in engine nacelle applications (Section 7). Additional testing and development is needed to optimize agent/additive mixture, address hardware optimization, agent and combustion by-product toxicity of optimized systems, and agent stability under accelerated aging conditions. Improvements to the dryness of agents and SBC, and possibly optimization and particle size reduction of larger commercially available SBC also needs further investigation. SBC qualification test methods need development. A summary of testing results and recommendations is located in Section 9.

Additional application specific toxicity evaluations will be required in most cases. Some of the candidates identified are commercialized and have more comprehensive toxicity data available for them. Additional fire suppression testing will be required to optimize hardware, agent fill ratio, and nozzle selection with respect to goals for fire suppression system performance.

Future evaluations will also need to cover the full operational temperature range expected in fielded conditions, accelerated aging and long term stability of the agents/blended agents, and material compatibility with the candidate agents.

The already commercialized low GWP brominated agent 2-bromo-3,3,3-trifluoropropene (2-BTP) was included in the occupied space application testing for performance comparison, as were a limited number of currently commercialized agents.

Candidate compounds were obtained and initially screened to verify flame extinguishment performance in cup-burner and small fire suppression extinguishment. This provided some indication of potential for development to a level of acceptable fire suppression performance in full-scale applications. Candidates that failed to extinguish fires or had other alarming characteristics such as flammability issues were dropped from further consideration. Preliminary evaluation of combustion by-product generation and chemical toxicity were performed.

Extensive appendixes are included with this report to provide an archive of information helpful to any future agent development project. The appendixes include supplementary data and method information of use in testing and agent evaluation efforts.

2.1 INITIAL ASSESSMENT

2.1.1 Background/Objective

GVSC/AMCOM evaluated alternate materials for the high GWP extinguishing agents (HFC-227ea, HFC-125, Halon 1301, etc.) currently, or planned to be, deployed in ground and aviation weapon systems (soon to be in Army heavy fuel engines (HFEs)), Next Generation Combat Vehicle, and Future Lift areas described in Table 2.1-1.

TABLE 2.1-1. AREAS OF USAGE FOR THE HIGH GWP AGENTS TO BE REPLACED

<table>
<tr><th>Weapon System</th><th>Usage Location</th><th>To Be Replaced</th></tr>
<tr><td rowspan="4">Ground vehicles</td><td rowspan="2">Occupied (crew) spaces</td><td>Halon 1301</td></tr>
<tr><td>HFC227-BC (HFC-227ea/Bicarbonate)</td></tr>
<tr><td rowspan="2">Unoccupied (engine) spaces</td><td>HFC-227ea</td></tr>
<tr><td>HFC-125</td></tr>
<tr><td rowspan="2">Aircraft</td><td>Engine nacelles and APUs</td><td>Halon 1301</td></tr>
<tr><td>Handheld fire extinguishers</td><td>Halon 1301</td></tr>
<tr><td rowspan="2">New weapons systems</td><td>Next Generation Combat Vehicle CFT</td><td rowspan="2">--[a]</td></tr>
<tr><td>Future Vertical Lift CFT</td></tr>
</table>

[a]Fire protection capabilities must be maintained and sustainability for these new weapon systems must be ensured as low GWP agents are selected. Army ozone depleting substance (ODS) policy prohibits the use of ODS in new weapon systems and high GWP alternatives are facing increased scrutiny.

CFT = cross-functional team

The objective of this performance testing is to determine possible alternative fire suppressants for select U.S. Army Futures Command (AFC) Combat Capabilities Development Command (CCDC) programmatic areas.

2.1.2 Procedures and Findings

a. The project evaluated several chemicals as possible alternative fire suppressants. Some of these chemicals are being developed or used by industry for other purposes such as foam blowing or as refrigerants. The ultimate goal of demonstrating full compliance for Army weapon system applications (functional, environmental, health, and safety), and meeting or exceeding military unique performance requirements is not addressed in this preliminary survey of chemicals. The environmental policy, law, and international agreements listed below were used as guides in chemical selection and testing:

- AERTA PP-14-12-01: No/Low GWP Alternatives to ODSs in Army Applications, which include fire suppressants.
- The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer will phase down production of hydrofluorocarbons (HFC).

- Federal Acquisition Regulation, High GWP Hydrofluorocarbons states "to procure, when feasible, alternatives to high GWP HFCs".
- Deputy Assistant Secretary of the Army (Acquisition Policy and Logistics) Memorandum SUBJECT: "Ozone Depleting Substances and Their Alternatives", Dated 17 May 2018.
- Title 10 United States Code - Armed Forces § 2302, 16 January 1996. Definitions - Elimination of Use of Class I Ozone-Depleting Substances in Certain Military Procurement Contracts.

b. The project's goals were in support of Next Generation Combat Vehicle and Future Vertical Lift CFTs to maintain fire protection and to ensure sustainability of new weapon systems. The project's initially planned duration was from FY 2016 through FY 2021, however Army priorities for Science and Technology funding dictated an end date through FY2018 and a focus on demonstration and identification of agents with promise as replacements for the application areas listed.

c. The project team included project management team co-leads: one based at GVSC and one based at Redstone Arsenal (AMCOM G-4). The U.S. Army Aberdeen Test Center's (ATC) Intermediate Fire Laboratory supported functional fire suppression testing, materials handling, agent acquisition, and analytical laboratory testing to include chemical evaluations. Contract technical expert consulting support was provided by Alion Science and Technology through their current personnel and a subcontractor. Additional funded and unfunded support was provided in key areas by the Army Public Health Center, ATC's Field Sampling and Analysis Branch, the Naval Research Laboratory, Federal Aviation Administration (FAA) Fire Research Laboratory, and numerous industry and government subject matter experts (SMEs).

d. <u>Benefits of the Project</u>. The expected impacts and benefits of the project include:

(1) <u>Environment, Safety and Occupational Health (ESOH)</u>: The high GWP and ozone-depleting materials used in firefighting applications will be significantly reduced and possibly eliminated. Approximately two million pounds of high GWP extinguishing agents are installed in crew, engine, and APU compartments and portable extinguishers of Army ground vehicles and aviation weapon systems.

(2) <u>Economic</u>: The significant recovery and recycling/disposal costs for high GWP agents will be avoided and a long-term stable supply of agents will be insured. Estimated savings are assumed to be similar or greater than the DoD investment to establish and maintain its Halon stockpile.

(3) <u>Scientific</u>: Advances in materials science (chemical and physical), performance qualification methodology and medical casualty criteria are likely.

(4) <u>Other</u>: The large investments needed to create a reserve of HFCs to support legacy fire protection systems may be avoided. With limited resources, better understanding of the capabilities of available low GWP candidates will be gained so that decision makers understand the capabilities and limitations of available technologies. If suitable alternative fire suppression technologies are identified and implemented, newly produced weapon systems will not require the Halon (Class I ODS) use waiver from the Army Acquisition Executive.

e. The end product of this project is an evaluation of the technical feasibility of emerging low GWP fire extinguishing agents for applicable weapons systems that will guide future research, procurements, and policy decisions.

2.2 CANDIDATE AGENT SELECTION AND EVALUATION STRATEGY

2.2.1 Objective

Determine a list of potential candidate agents, obtain samples, and evaluate for fire suppression related performance.

2.2.2 Procedures and Findings

a. Selection. Non-flammable low GWP chemicals with zero or near zero ozone depletion potential (ODP) were the focus of this project's work. Chemical families with these properties include the fluoroalkenes (Note, the term alkene is interchangeable with olefin), hydrofluoroalkenes, hydrofluoroethers, and fluoro-ethers. Short atmospheric lifetimes have a clear advantage in attaining these two goals as lower atmospheric lifetimes equate to lower GWP values.

Several physical properties that affect functionality and performance in fire suppression, chemical toxicity, and the toxicity of combustion by-products are important factors in the approvals for application areas of fire suppressant chemicals. This project has targeted lower boiling candidate compounds that are commercially available or research chemicals. Operational and storage performance of fire suppressants over broad temperature ranges (-65 °C to +85 °C) is benefited by the use of chemicals with low boiling points.

Formerly, agent development efforts have shown blends of special very finely milled SBC powders and HFC-227ea with optimized hardware to be very effective. These efforts have resulted in the development of an HPFE based on this blend. However, HFCs are now viewed as having GWPs that are too high, in part due to their long atmospheric lifetimes therefore identification of shorter lifetime compounds will be needed. Shorter atmospheric lifetime compounds such as 2-bromo-3,3,3-trifluoropropene (American Pacific 2-BTP) have been identified, patented, have undergone test and evaluation for some applications, and are commercially available. Non-brominated fluoroalkenes have been identified as potential agents, and although these compounds lack the chemical fire suppressing mechanism, they may serve as carriers (blends or suspensions) for fire suppressing powders.

A list of potential agent candidates was identified and samples obtained and evaluated for fire suppression related performance. This list included chemicals currently being developed and some being marketed by The Chemours Company (Chemours) and refrigerant chemicals being commercialized by Honeywell Inc. Dry powder additives were sourced through known suppliers/processors and attempts to obtain powders with particle dimensions in the nanometer range resulted in materials exhibiting physical evidence (scanning electron microscopy photos) of very low nano particle size but with a marked tendency to resist dispersion into suspended individual particles when blended with agents. Improvements were not attempted because of time and funding constraints. Other known commercial and proprietary suppressant powders were also obtained. Development of agents based on these chemicals require functional (fire suppression) testing and optimization, and hardware modifications (including over pressures, cylinder fill ratio, valve head properties, plumbing and nozzle design). Agent boiling points also have a significant effect on cylinder pressurization, discharge rates, and agent dispersion.

In all of this effort, the environmental demands on the extinguishing system and the constraints of the actual application being designed for must be anticipated. In particular, the low temperature performance limits and anticipated high temperature storage and performance limits may be limiting factors. Additionally, the type of discharge needed - fast discharges for high flow applications (i.e. AFES and engine nacelles) and slower flows (those employed by HPFEs) - may preclude the use of some agents not suited to these conditions.

Finally, agent applications in crew compartments require use of lower toxicity compounds that do not affect human health or performance at concentrations required for effective fire extinguishment. Visual obscuration issues also need to be considered and addressed. In a fire scenario where hydrofluoric acid (HF) and/or carbonyl fluoride (COF_2) decomposition product generation is likely, a highly effective suppression agent is needed to limit the amount of byproduct production. Material compatibility with all equipment/instrumentation contained within the vehicle or worn by compartment occupants must also be considered when a candidate agent is tested.

A candidate agent will be down-selected based on fire suppression performance, service life of the agent, chemical stability, and compatibility with optimized powder additives. Once an acceptable agent has been identified, appropriate application specific toxicity clearance(s) would be obtained, and a more concentrated development process for a specific area would occur to support eventual further development/procurement for a specific system.

b. Evaluation. This project focused on identification of candidate chemicals with expected environmental and possible toxicological acceptability, and performed limited fire suppression tests to further assess potential as eventual replacement agents. The project assessed each candidate to demonstrate fire suppression capability under likely areas of application. The project phases were:

(1) Verify non-flammability (cup-burner flame extinguishment, push-back pan fire, pan fires).

(2) Preliminary toxicity assessment (review of available toxicity information, evaluation of Brill Cell combustion by-products.)

(3) Identify manufacturing methods with the potential to prepare low micron (< 2 μm) - and lower nano (< 500 nm) particle SBC, and obtain samples for evaluation.

(4) Identify and construct fixtures for initial hardware/agent performance testing in various fire suppression applications. These include hidden fire test fixture, FAA engine nacelle test fixture, AFES crew compartment test fixture, pan-fire test facility, and 8 ft^3 test chamber.

(5) Perform selected application specific testing of agents based on preliminary toxicity and fire extinguishment performance using engine nacelle, crew compartment, and HPFE test fixtures.

c. The overall objective was to develop effective acceptable replacement fire suppression agents and hardware with distribution systems for specific applications. To this end, an agent candidate development and evaluation project effort is suggested. Once optimal candidates are identified, a more focused effort in which tightly controlled discharge times in concert with hardware, nozzle, and pressurization optimization will need to be performed.

2.3 TROPODEGRADABLE AGENT CANDIDATES AND SODIUM BICARBONATE POWDER ADDITIVES

2.3.1 Objectives

Select agent candidates and SBC additives, and determine acquisition strategies of materials for use in testing.

2.3.2 Procedures and Findings

a. Agent candidates. Chemours, Honeywell, and SynQuest Laboratories were sources of fluoroalkenes with known or potentially short atmospheric lifetimes.

(1) Some of the Chemours chemicals were experimental and available only in small quantities (a few liters). Chemours initially supplied laboratory experimental chemicals identified as TF-1, SC-1, SC-2 (withdrawn from consideration in this project because of very limited availability), and later provided two newly commercialized chemicals: Opteon 1100 and Opteon 1150. Opteon 1100 proved to be the formerly supplied experimental TF-1 candidate.

(2) Honeywell candidates were already commercialized for other applications. Honeywell supplied two newly commercialized chemicals: Solstice PF (also referred to as Solstice ZD and Solstice 1233zd in this report) and Solstice ZE. Solstice ZE performed poorly in early cup-burner and 8 ft^3 chamber testing and was therefore dropped from further testing. No testing of blended agent (SBC additive) was performed; however Solstice ZE was included because blending with advanced nano SBC could make a difference in performance. Because Solstice ZE is the lowest boiling commercial option of those considered, the potential for use exists over the broad range of fielded operational temperatures encountered.

(3) SynQuest Laboratories candidates were research chemicals with attractively low boiling points. These unproven candidates, with scant toxicity data, were studied to evaluate fire extinguishment and potential suitability, and to serve as a guide in directing future interests in chemicals for evaluation. Several very low boiling potential candidate compounds were identified from the SynQuest Laboratories research chemicals catalog (Table 2.3-1). Only one of those identified, hexafluoropropene (perfluoropropene), was selected for very limited cup-burner testing because of the cost of acquiring sufficient materials (estimated in the 10's of thousands of dollars for several kilograms) needed to test in pan fires or cup-burner evaluations.

TABLE 2.3-1. SYNQUEST LABORATORIES RESEARCH CHEMICALS FOR POTENTIAL EVALUATION

Chemical Name	Chemical Structure	Molecular Weight	Boiling Point, °C
Hexafluoropropene	CF_3-CF=CF_2	150	-29
2-chloro-3,3,3-trifluoropropene	CF_3-CCl=CH_2	130	14
2,3,3,3-tetrafluorpropene	CF_3-CF=CH_2	114	-28
1-chloro-1,3,3,3-tetrafluoropropene	CF_3-CH=CFCl	148	19
1,2,3,3,3-pentafluoropropene	CF_3-CF=CHF	132	-18
Octafluoro-2-butene	CF-CF=CF-CF_3	200	1

Note: Octafluoro-2-butene was studied previously (NIST HOTWC report R0000270): cup-burner extinguishment 4.9%, boiling point = 0.8 °C.

(4) The acquired commercially available chemicals and their physical properties are summarized in Table 2.3-2.

TABLE 2.3-2. FINAL COMMERCIALLY AVAILABLE CANDIDATE AGENTS LIST

Agent and CAS No.	Chemical Name and Structure	Molecular Weight	Boiling Point, °C	ODP	GWP
2-BTP, 1514-82-5	2-bromo-3,3,3-trifluoropropene, CF_3-CBr=CH2	174.9	34	0.0028	0.02
Opteon 1100, 692-49-9	1,1,1,4,4,4-hexafluoro-2-butene, CF_3-CH=CH-CF_3	164	33	0	2
Opteon 1150, 66711-86-2	1,1,1,4,4,4-hexafluoro-2-butene, CF_3-CH=CH-CF_3	164	7.5	0	2
Solstice ZD, 102687-65-0	Trans 1-Chloro-3,3,3-trifluoropropene; CF_3-CH=CHCl	130	19	0	1
Solstice ZE, 29118-24-9	Trans-1,3,3,3-tetrafluoroprop-1-ene, CF-CH=CHF	114	-19	0	<1

CAS - Chemical Abstract Service
GWP - global warming potential
ODP - ozone depletion potential

b. SBC Additives.

(1) Past work with the development of a non-ODS HPFE successfully demonstrated the use of SBC powders with particle sizes in the low micron range and needle-like particles in the high nanometer range as fire suppression performance enhancers. The specific SBC powders employed were products of particle size reduction processes and a proprietary process based on a new cryogenic particle formation method.

(2) Two sources of dry SBC powder were selected for evaluation. SBCs with particle sizes in the low micron range were sourced from Fluid Energy, a previously used vendor. The source of high nanometer range particles used in past blended agent development was no longer in

business. An unproven alternate method based on a California Nanotechnologies Corporation (Cal-Nano) cryogenic-milling process (SBC slurried in liquid nitrogen) was selected.

SBC powders were obtained from both for use in this testing. Acquired micron-sized particle SBC powder from Fluid Energy performed satisfactorily in early testing. The new cryogenic-milling process generated SBC powders that were in the nanometer range, but unfortunately the initially prepared material, tended to clump. A second attempt to employ a method of separating the milled product from the liquid nitrogen failed to resolve the clumping problem. No attempt to further refine the cryogenic-milling process was made and this approach was not pursued further. Therefore, due to the clumping issue, the unrefined Cal-Nano SBC was not tested in HPFE or engine nacelle applications. Additional exploration into improving the cryogenic-milling process could prove to be beneficial in producing smaller particle sized SBC.

(3) Analytical reports and scanning electron photographs of the generated powder for both the Fluid Energy and Cal-Nano materials are provided in Appendix B.

(4) KSA, a finely ground SBC powder from Kidde Aerospace and Defense was also included in this testing. The Kidde powder is coated with anticaking compounds and is generally of a larger particle size than Fluid Energy, though much finer than standard commercial bicarbonates.

2.4. TROPODEGRADABLE FLUOROALKENE CANDIDATE INITIAL EVALUATIONS

2.4.1 Objective

Use a combination of three methods to establish a preliminary ranking of fluoroalkene candidates.

2.4.2 Procedures and Findings

a. Initial comparative evaluations of expected toxicity, chemical stability, and flame extinguishment performance were needed to identify problematic candidates. Two methods, Brill Cell thermal breakdown and cup-burner flame extinguishment, were selected to address the chemical stability, and cup-burner testing was used to evaluate flame extinguishment. A review of each candidate's toxicity was also conducted.

b. The Brill Cell thermal breakdown by-product characterization provided comparative information on the rate at which by-products were generated and the rate at which each by-product accumulated on exposure to a heated metal surface. The cup-burner flame extinguishment method generally requires several liters of agent, and therefore only those candidate compounds sufficiently available as commercialized products or laboratory samples were tested.

c. An example of the comparisons generated using the Brill Cell and associated instrumentation is presented in Figure 2.4-1, where the time dependency of by-products (HF, HCl, CO_2 and COF_2) is shown. From a practical stand point, a fast fire extinguishment leads to lower levels of by-products. This drives the need to enhance agent performance with SBC or, as in the past, the use of brominated and chlorinated chemical suppressants (i.e., Halon 1301 and Halon 1211). The Brill Cell method allows for a qualitative "first-look" at candidate materials and an opportunity to assess potential thermal decomposition by-products and the hazards to be encountered in scenarios where the agent fails to extinguish a fire in an occupied space.

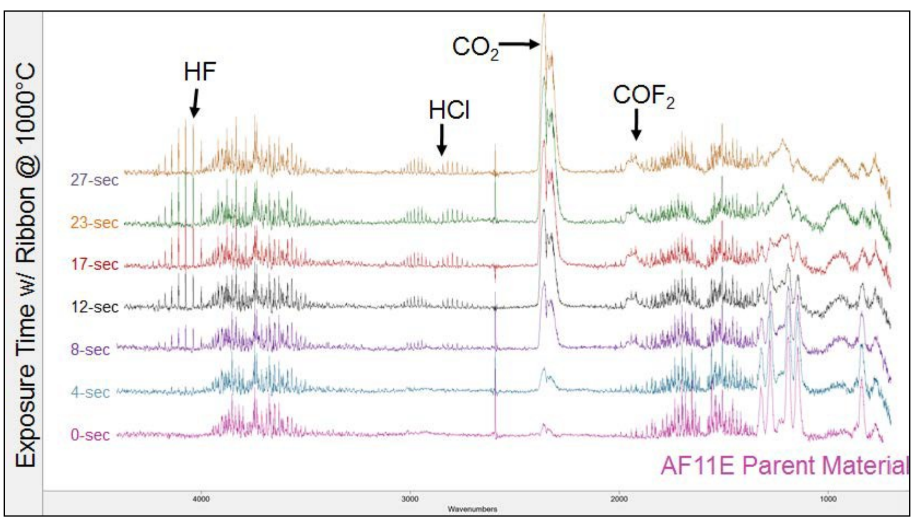


Figure 2.4-1. Example of a by-product analysis (CO_2, HF, HCl, COF_2) - Brill Cell.

d. By-product generation was also studied using an 8-ft^3 test chamber (fig. 2.4-2).

Figure 2.4-2. The 8-ft^3 test chamber employed in by-product testing.

e. Representative plots (fig. 2.4-3) from the 8-ft^3 by-product tests show the type and concentration of acid gas production over a given sampling duration. Note the effect of employing a chemically active agent 2-BTP compared to non-chemically active agents (HFC-227ea and Solstice ZD) on by-product levels. Using the 8-ft^3 chamber for by-product analysis allowed for comparison of by-product generation when the extinguishing agent was applied at, below, or above, the minimum design concentration or observed cup burner extinguishment concentration.

f. A toxicological data review of chemicals with available data (MSDS/SDS) was conducted early in the project to identify optimal chemicals for occupied space applications and to establish guidelines for handling in testing. This initial toxicity review was later extended in a comprehensive review of available data included in Appendix C. Halon 1301, HFC-227ea (FM-200), and HFC-125 (FE-25) were included for comparison. AF11e was included for comparison purposes, however it is comprised mainly of HCFC-123, a chemical also being phased out of production. Candidates SC-1, SC-2, TF-1, and FC-1 are laboratory test identifiers that either were dropped or became commercially available as Opteon 1100 and 1150. Of these, Opteon 1150, because of other factors, was the only commercial agent candidate whose toxicity was judged low enough to warrant consideration for use in occupied crew spaces.

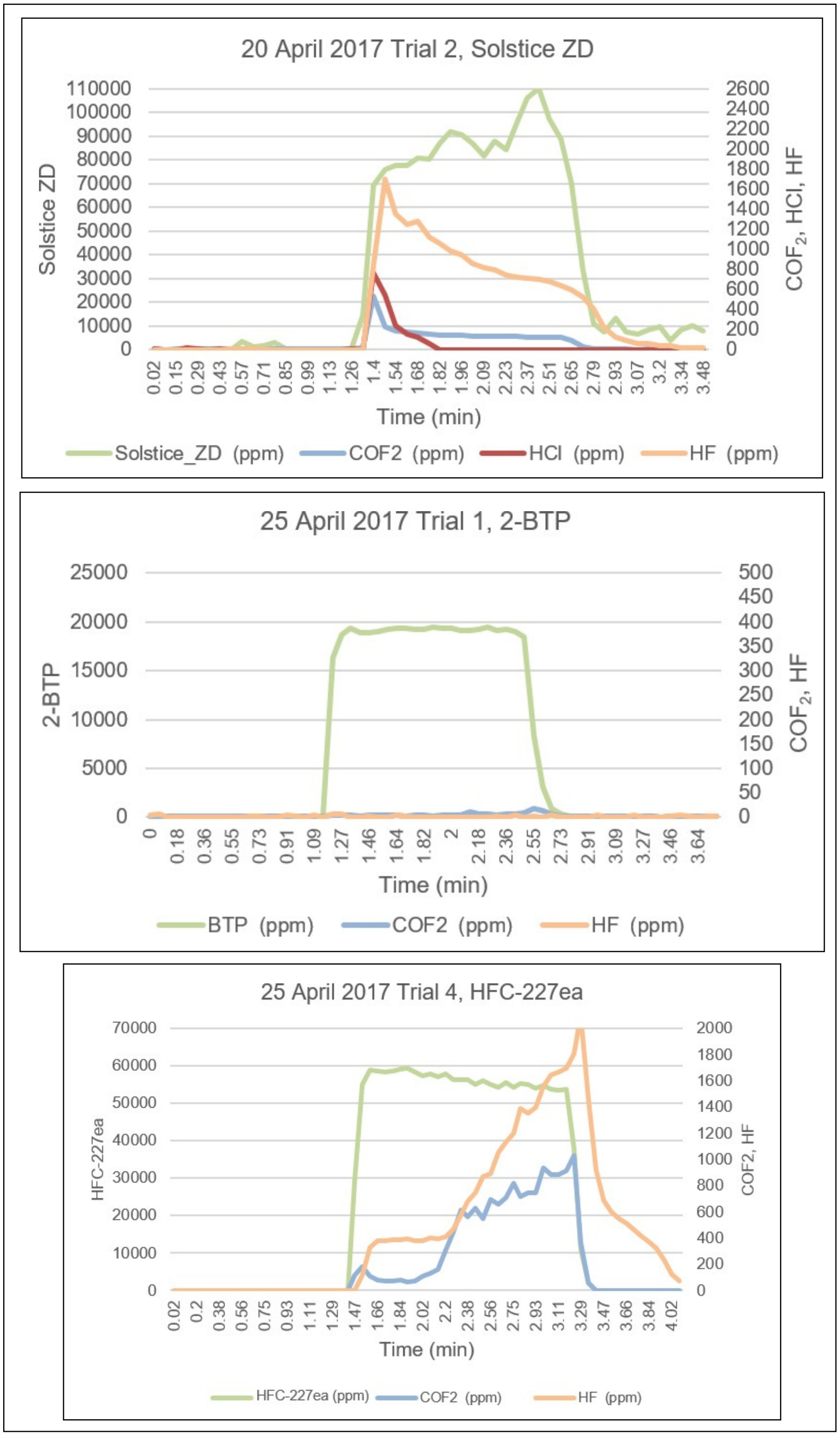


Figure 2.4-3. By-product testing results for Solstice ZD, 2-BTP, HFC-227ea.

g. Cup-burner testing was performed at the Naval Research Laboratory. Because of limited candidate compound availability, a reduced scale cup-burner modeled after the New Mexico Engineering Research Institute's 5/8 scale cup-burner design (fig. 2.4-4) was used. The smaller cup-burner enabled testing where only small quantities of a candidate chemical were available. The results provided a means to rank flame extinguishment performance of candidate chemicals, and an opportunity to observe flame/agent interaction characteristics. The characterization results are shown in Table 2.4-1. The cup-burner values all demonstrate acceptable levels of performance and are comparable to those of existing extinguishing agents like HFC-227ea.

Figure 2.4-4. Sub-scale (5/8) experimental setup to quantify agent extinction concentrations.

TABLE 2.4-1. CUP-BURNER EXTINGUISHMENT DATA
FOR SELECT CANDIDATE COMPOUNDS

Agent	Average Extinguishment Concentration, vol %
Opteon 1100	7.43
Opteon 1150	3.60
Solstice ZD	5.80
Solstice ZE	6.40
2-BTP	4.63
Hexafluoropropene	5.17

2.4.3 Modeling of agent discharge material needs

Preparations for the use of NIST PROFISSY and REFPROP modeling software, which employ thermodynamic and physical properties to better estimate needed agent quantities for spaces (occupied and unoccupied) in planned and potential future application tests were initiated. An extensive compilation of all known thermodynamic properties was assembled for selected agent candidates. The collection of candidate agent physical and thermodynamic properties was pursued to facilitate the ease of scaling to larger volumes and test fixtures. The data collected for all candidate agents and comparison data for select currently fielded agents are located in Appendix D.

2.5. PRELIMINARY BLENDED AGENT CHARACTERIZATION, FIRE SUPPRESSION AND VOLUME FILLING INERTION APPARATUS

2.5.1 Objective

Use initial testing and development to determine the preliminary optimization of the suspendability of SBCs in each candidate agent, agent fire interaction, and to perform agent hardware evaluations.

2.5.2 Procedures and Findings

a. Suspensions. The development of methods to create stable suspensions of SBCs in each fluorocarbon candidate for use in fire suppression testing in HPFE applications employed ultra-sonication and specialized pressure-rated glassware. The glassware allowed visual observation of the degree of SBC suspension in the fluorocarbon liquid. The goal of agent composition from the start to the end of discharge in HPFE applications assures that the fire suppression performance stays approximately consistent. If the SBC is all discharged at the beginning of the discharge and only fluorocarbon is discharged for the remainder of the time, the fire suppression effectiveness will be significantly diminished compared to a well suspended blend of SBC and fluorocarbon. The results of testing of various SBC fluorocarbon suspensions are shown in Figure 2.5-1. A summary of extensive evaluation and optimization of the use of ultrasonic equipment to re-suspend dry SBC in fluorochemical agents is located in Appendix E.

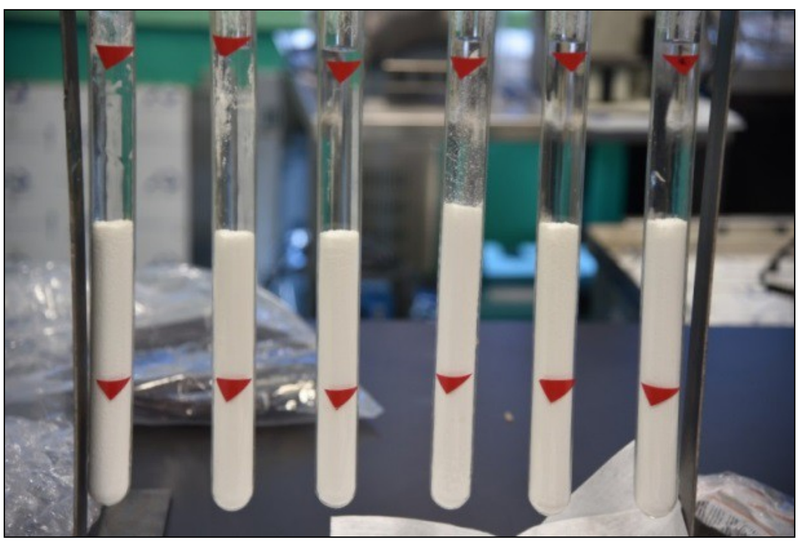


Figure 2.5-1. Ultra-sonicated samples of Fluid Energy and Cal Nano SBC suspended in HFC-227ea after sonication under a range of conditions (lower red markers indicate initial SBC levels).

b. Agent - fire interaction. Fluorocarbon agents were tested in simple fire pushback tests where a narrow pan was employed to evaluate heptane fire response to a discharged agent. A range of observations included failure to clear the front edge of the pan of fire to full clearance and possible extinguishment. This is a basic indicator and useful for selecting agents with more optimal performance. An example of good push back is shown in Figure 2.5-2 (left). The push back test gives a first look at agent performance in the larger standard UL-711 pan-fire extinguishment test and non-standard UL-711 pan-fire extinguishment tests with JP-8 fuel (fig. 2.5-2, right) which is used to assess an extinguisher's performance.

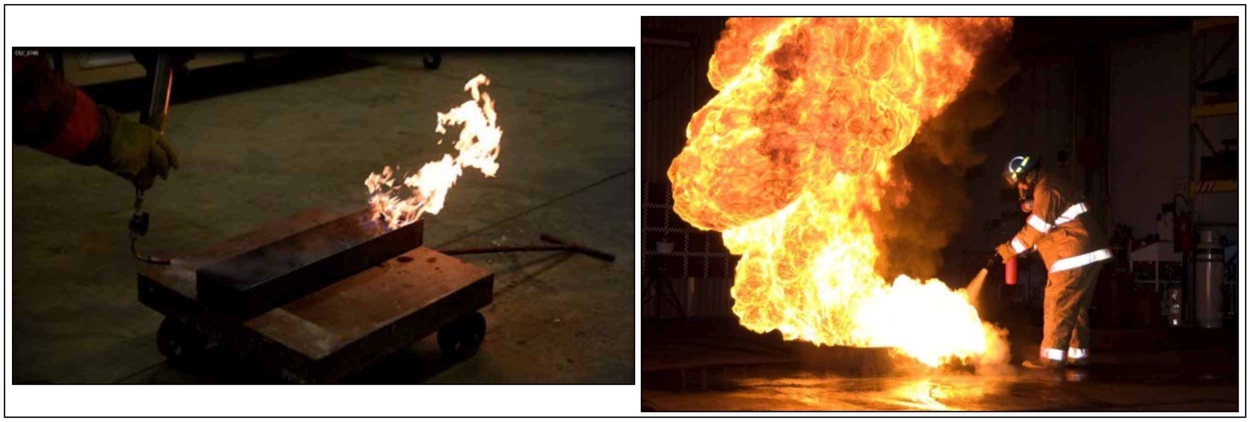


Figure 2.5-2. Pan fire push-back test (left) and large pan fire extinguishment test (right).

c. Agent hardware evaluations. The FAA developed a Hidden Fire test chamber for the purpose of evaluating fire suppression agent effectiveness in challenging fire suppression scenarios such as the hard to access cluttered spaces and "cheek" areas of commercial jet aircraft. This test fixture allows discharge of extinguishers into a closet-like chamber in which small cup fires burn. The test fixture measures the ability of an agent and hardware configuration to extinguish the maximum number of cup fires. Agent and hardware developers are then provided a means to measure, by numbers and patterns of extinguished burning cups, performance dimensionality. Repeated testing and modification of extinguisher nozzle fill pressures and valve assemblies optimizes the potential ease with which the agent can extinguish fire in cluttered or obstructed areas.

A test fixture (fig. 2.5-3) was constructed using FAA specifications provided in Appendix F. The planned use was to enable optimization of extinguisher hardware configurations such that extinguishment of the largest number of burning fuel cups was achieved. Limited testing was conducted with the agents on hand. The Hidden Fire Test chamber was expected to be an effective means of optimizing agent hardware configurations. Documents describing this test fixture can be found in DOT/FAA/AR-01/37: Development of a Minimum Performance Standard for Hand-Held Fire Extinguishers as a Replacement for Halon 1211 on Civilian Transport Category Aircraft and are also summarized in Appendix F.

Figure 2.5-3. ATC hidden fire test chamber.

2.6. HPFE FULL SCALE PAN FIRE PERFORMANCE TESTING OF AGENT AND AGENT COMBINATIONS

2.6.1 Objective

Identify the agents that performed the best in extinguishing fires.

2.6.2 Procedures and Findings

a. Four of the candidate agents were selected for testing in pan-fire HPFE applications. The fuel employed in this testing was JP-8. The results of this limited initial testing are presented below. In all cases the hardware was not fully optimized. A very limited range of nozzles, horns and valves were tested. Attempts were made to maintain a discharge duration of approximately 8 - 10 seconds for all candidate agents at ambient temperature, which is typical of ground vehicle or aviation HPFEs. The goal was to identify those agents that performed the best in extinguishing fires. Measures of effectiveness are success in fire extinguishment, discharge duration, remaining undischarged agent, agent blending with SBC powder or not, and size of fire extinguished. Testing included firefighter technique development trials which varies with pans sizes as well as equipment configuration and agent composition (i.e., pure fluorocarbon or blended fluorocarbon and SBC).

b. Limited testing was conducted with Opteon 1100. The results are displayed in Table 2.6-1. Of eight attempts only one pan fire of 5 ft^2 was successfully extinguished with a considerable amount of agent remaining in the bottle. None of the tests performed included the use of SBC additive which would likely have improved performance.

TABLE 2.6-1. PAN-FIRE TESTING OF OPTEON 1100

Cylinder Size, in^3	Agent Weight, g	Nozzle	Pressure, psi	Pan Size, ft^2	Discharge Duration, s	Fire Out, Yes/No	Agent Remaining, g
97	1504	1211 Amx	130	5	8.8	No	0
97	1490	1211 Amx	130	5	5.9	No	0
97	1508	1211 Amx	130	5	7.5	No	0
97	1492	1211 Amx	130	5	6.5	No	0
97	1510	1211 Amx	130	5	7.5	No	0
97	1502	1211 Amx	130	5	3.3	Yes	411
80	1006	SS H6.5	250	5	10.2	No	0
80	1007	SS H6.5	250	5	11	No	0

c. Opteon 1150 was tested a total of 28 times. The results are presented in Table 2.6-2. Of 27 attempts, the fire was extinguished three times with substantial amounts of agent remaining undischarged in the extinguisher bottle. In 12 tests of Opteon 1150 blended with KSA using the Amx 1211 nozzle, an additional four fires were extinguished with substantial amounts of agent remaining. The maximum pan fire size extinguished was 7.5 ft^2 and considerable SBC blended agent remained in the bottle suggesting that further optimization of the combined agent and hardware is likely to see acceptable performance at larger pan sizes.

d. Solstice ZD was tested 33 times. The results are presented in Table 2.6-3. The pan- fire was extinguished five times, with four at pan fire sizes of 7.5 ft^2. The blended SBC fluorocarbon agent that remained undischarged in the extinguisher bottle was substantial. Further optimization of the combined agent/hardware configuration could lead to successful performance at a larger pan size.

e. Results of the 2-BTP testing are presented in Table 2.6-4. Of fourteen attempts the fire was extinguished 11 times with substantial amounts of agent remaining undischarged in the extinguisher bottle. In a single test of 2-BTP blended with KSA, the test resulted in no extinguishment - a result that was possibly attributable to nozzle plugging. The maximum pan fire size extinguished was 12.5 ft^2 and considerable agent remained in the bottle. This was the largest pan fire extinguishment out of all tested agents, suggesting that further optimization of 2- BTP and the extinguisher hardware could likely result in acceptable performance at larger pan sizes.

2.6.3 Pan fire testing results and conclusions

a. By far the most effective agent as measured by size of fire extinguished (12.5 ft^2) and the consistency with which test fires were successfully extinguished, is the brominated agent, 2-BTP. None of the other three candidates came close to this level of performance. (Note: 2-BTP would only be considered for use in large spaces or outdoors, with no plans for use in HPFEs due to cardio-toxicity in smaller occupied spaces.)

b. The performance of Opteon 1100 as an unblended, unenhanced agent was not as good as the performance of unblended, unenhanced Opteon 1150. Opteon 1150 without additive extinguished the same size fires as Opteon 1100 but with more agent remaining in the bottle. Once combined Opteon 1150 and SBC blends were tested, performance improved substantially and the substantial amounts of remaining agent suggest that, with optimization, the firefighting performance of Opteon 1150/SBC may be increased further. Solstice ZD (with no added SBC) performed similarly to Opteon 1100 in this testing. The addition of SBC to Solstice ZD enabled pan-fire extinguishment performance at the 7.5 ft^2 level and left significant amounts of remaining agent in the bottle.

c. Low boiling HPFE agents employed in windy conditions are more easily deflected away from targeted fire hot spots. Streaming candidates benefit from a marginally higher boiling point. They “stream” better and are not as easily deflected or diluted before arriving at the fire threat.

TABLE 2.6-2. PAN-FIRE TESTING OF OPTEON 1150

Cylinder Size, in.^{3}	Agent Weight, g	SBC Type	SBC Weight, g	SBC %	Nozzle	Pressure, psi	Pan Size, ft^2	Discharge Duration, s	Fire Out, Yes/No	Agent Remaining, g
80	1660	-	-	-	SS H6.5	240	10	17	No	481
80	1518	FE-1	70	4.6	16 hole	230	5	6.9	No	0
80	1216	FE-1	70	5.8	16 hole w/ horn	230	5	6.2	No	0
80	1379	-	-	-	16 hole	230	5	6.9	No	0
80	1417	-	-	-	BETE P190	230	5	7.8	No	0
97	1624	-	-	-	1211 Amx	130	5	4.5	Yes	756
97	1620	-	-	-	1211 Amx	130	5	2.3	Yes	914
97	1602	-	-	-	1211 Amx	130	7.5	2.9	Yes	740
97	1604	-	-	-	1211 Amx	130	10	6.2	No	0
97	1620	-	-	-	1211 Amx	130	10	6	No	0
97	1628	-	-	-	1211 Amx	130	7.5	6.9	No	0
97	1538	FE-1	80	4.9	1211 Amx	130	7.5	8.4	No	0
97	1490	FE-1	80	5.1	1211 Amx	130	7.5	6.3	No	0
97	1520	FE-1	80	5.0	1211 Amx	130	7.5	6.8	No	0
97	1528	FE-1	80	5.0	16 Hole	130	7.5	5.6	No	0
97	1520	FE-1	80	5.0	1211 Amx	130	7.5	6	No	0
97	1500	KSA	75	4.8	1211 Amx	130	5	10.1	No	0
97	1490	KSA	75	4.8	1211 Amx	130	5	10	No	0
97	1515	KSA	75	4.7	1211 Amx	130	5	9	No	0
97	1505	KSA	75	4.7	1211 Amx	130	5	10.3	No	0
97	1515	KSA	75	4.7	1211 Amx	130	5	5	Yes	497
97	1515	KSA	75	4.7	1211 Amx	130	5	4.5	Yes	511
97	1525	KSA	75	4.7	1211 Amx	130	7.5	2.2	Yes	1031
97	1515	KSA	75	4.7	1211 Amx	130	7.5	8.4	No	0
97	1505	KSA	75	4.7	1211 Amx	130	7.5	11	No	0
97	1500	KSA	75	4.8	1211 Amx	130	7.5	3.1	Yes	701
97	1500	KSA	75	4.8	1211 Amx	130	7.5	10	No	0

TABLE 2.6-3. PAN-FIRE TESTING OF SOLSTICE ZD

Cylinder Size, in.[3]	Agent Weight, g	SBC Type	SBC Weight, g	SBC %	Nozzle	Pressure, psi	Pan Size, ft^2	Discharge Duration, s	Fire Out, Yes/No	Agent Remaining, g
80	1320	KSA	65	4.9	SS H6.5	230	5	12.2	No	0
80	1320	KSA	65	4.9	16 hole	230	5	6.2	No	0
80	1297	-	-	-	16 hole	230	10	7.4	No	0
80	1330	-	-	-	SS H6.5	230	10	12	No	0
80	1328	-	-	-	16 hole	230	5	7.9	No	0
80	1076	-	-	-	16 hole	80	5	8.7	No	0
80	1031	FE-1	45	4.4	16 hole	80	5	8.1	No	0
80	1066	-	-	-	BETE P190	230	5	N/A	No	0
80	1020	FE-1	42	4.1	BETE P190	230	5	4.1	No	900
97	1550	-	-	-	1211 Amx	130	5	7.4	No	0
97	1525	-	-	-	1211 Amx	130	5	6.7	No	0
97	1520	-	-	-	16 Hole	130	5	4.1	Yes	328
97	1506	-	-	-	16 Hole	130	7.5	8	No	0
97	1520	-	-	-	16 Hole	130	7.5	8.1	No	0
97	1510	-	-	-	16 Hole	130	7.5	6.5	No	0
97	1422	FE-1	75	5.0	16 Hole	130	7.5	3.6	Yes	454
97	1456	FE-1	75	4.9	16 Hole	130	7.5	4.5	Yes	222
97	1410	FE-1	75	5.1	16 Hole	130	10	6.6	No	0
97	1408	FE-1	75	5.1	16 Hole	130	10	6.2	No	0
97	1400	FE-1	75	5.1	1211 Amx	130	10	6.7	No	0
97	1405	FE-1	75	5.1	1211 Amx	130	10	6.2	No	0
97	1454	KSA	76	5.0	16 Hole	130	7.5	7.5	No	0
97	1416	KSA	77	5.2	16 Hole	130	7.5	7.3	No	0
97	1420	KSA	75	5.0	1211 Amx	130	7.5	7	No	0
97	1420	KSA	77	5.1	1211 Amx	130	7.5	7.9	No	0
97	1420	KSA	76	5.1	1211 Amx	130	7.5	5.9	No	0
97	1420	KSA	77	5.1	1211 Amx	130	7.5	6.4	No	0
97	1420	KSA	150	9.9	1211 Amx	130	7.5	3.8	Yes	452
97	1420	KSA	150	9.8	1211 Amx	130	7.5	4.7	Yes	225
97	1420	KSA	150	10.0	1211 Amx	130	10	7.2	No	0
97	1420	KSA	150	10.0	1211 Amx	130	10	7.4	No	0
97	1420	KSA	150	10.0	1211 Amx	130	10	8.1	No	0
97	1420	KSA	150	10.0	1211 Amx	130	10	7.5	No	0

TABLE 2.6-4. PAN-FIRE TESTING OF 2-BTP

Cylinder Size, in.[3]	Agent Weight, g	SBC Type	SBC Weight, g	SBC %	Nozzle	Pressure, psi	Pan Size, ft^2	Discharge Duration, s	Fire Out, Yes/No	Agent Remaining, g
80	1431	-	-	-	16 hole	80	5	1.8	Yes	904
80	1434	-	-	-	SS H6.5	240	5	4	Yes	867
80	1450	-	-	-	16 hole	80	7.5	4.3	Yes	410
80	1420	-	-	-	SS H6.5	240	7.5	6.3	Yes	517
80	1439	-	-	-	SS H6.5	240	7.5	3.8	Yes	891
80	1421	-	-	-	16 hole	80	10	4.6	Yes	271
80	1395	-	-	-	SS H6.5	240	10	3.2	Yes	940
80	1425	-	-	-	SS H6.5	240	12.5	12.7	No	17
80	1460	-	-	-	SS H6.5	240	12.5	10	No	24
80	1190	-	-	-	16 hole	80	10	2.8	Yes	417
80	1420	KSA	70	4.9	16 hole	230	12.5	5.8	No	0
97	1944	-	-	-	1211 Amx	130	10	3.3	Yes	844
97	1950	-	-	-	1211 Amx	130	12.5	3.8	Yes	669
97	1954	-	-	-	1211 Amx	130	12.5	2.7	Yes	846

2.7 FAA ENGINE NACELLE 2-BTP TESTING

2.7.1 Objective

Investigate potential solutions to re-ignition audible events experienced when using 2-BTP in an engine nacelle. Determine if the fire extinguishment performance of 2-BTP could be increased through use of dry chemical additives and/or by simulating the use of a solid propellant gas generator (SPGG).

2.7.2 Background Information

a. In 2004, several months of industry-led testing were performed at the U.S. Federal Aviation Administration (FAA) Hughes Technical Center in Atlantic City, NJ. This testing was unreported and employed a generic nacelle fire simulator (gNFS) (fig. 2.7-1). In this testing, 2-BTP (discharged at 38 °C) was evaluated as a replacement for Halon 1301 in commercial aviation engine nacelle fire suppression. Testing of 2-BTP performance in spray fire extinguishment under "low air flow" and high temperature fire suppression conditions was done in this apparatus. The "low air flow" configuration has been identified as the most difficult fire suppression condition in this test apparatus because of the higher surface temperatures that are encountered.

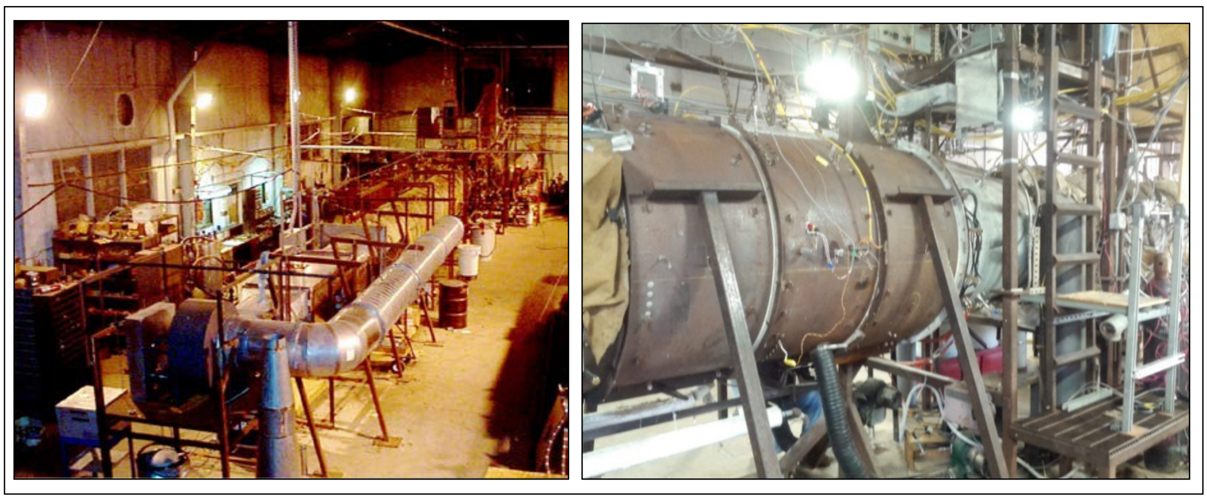


Figure 2.7-1. FAA Atlantic City Technical Center: gNFS (left) and spray fire section (right).

b. Testing of 2-BTP as a halon replacement for this application was discontinued after observations of unexpected fireballs and clear audible sounds downstream of the fire zone. These events were believed to be due to rapid re-ignition of the accumulated mixture of hot air, fuel from the continuing fuel spray, and residual 2-BTP inside the gNFS, downstream toward the air gap and exhaust intake (fig. 2.7-2). The fireball and audible event was so frequent and remarkable in its atypical energy release in the testing performed that testing of 2-BTP for this application was not pursued further.

c. A review of the four fuel spray tests performed in 2004 showed re-ignition audible events in most tests. It should be pointed out that the audible event associated with the 2-BTP testing at the FAA Technical Center had never been observed in tests of Halon 1301 or any other agents, including HFC-125, CF3I, and FK-5-1-12. The re-ignition of the spray fire in all cases failed to produce a rapid burning of residual air, fuel, and agent downstream in the test fixture. However, each halon-replacement candidate had liberated effluent from the gap in the gNFS, whether aerosol, flame or both, in varying rates of frequency and magnitude, although none doing so like that observed with 2-BTP.

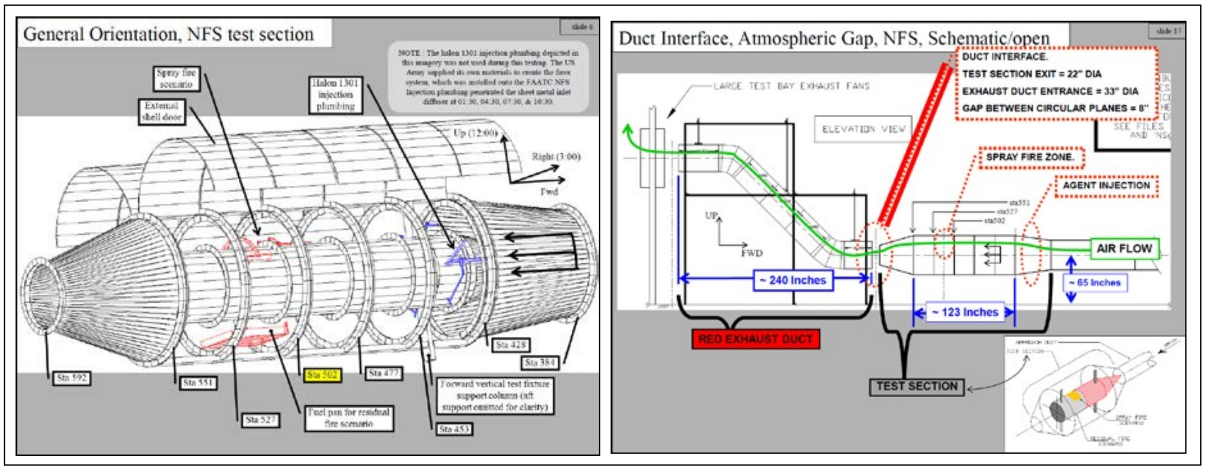


Figure 2.7-2. FAA supplied schematic of gNFS air flow, agent nozzles and spray fire location (left) and duct interface gap site of post re-igniting audible event (smoke, fireball and audible event).

d. Causes of the audible event in 2-BTP testing under low airflow and high temperature conditions were not explored in the intervening years. The higher boiling point of 2-BTP was thought to result in slower evaporation of this agent following discharge, resulting in a reduced air concentration and a more spread out air concentration profile compared to that of Halon 1301. To overcome the issues with the higher boiling point, the 2-BTP was pre-heated to 85 °C to simulate discharge by a SPGG, which simultaneously heats and pressurizes the agent during discharge. Heating of 2-BTP and co-discharges with SBC were expected to aid extinguishment performance and vaporization of the agent and to alleviate concern with its ability to perform in low temperature environments. The addition of SBC to 2-BTP was also tested to assess the possible elimination and/or reduction of the audible re-ignition event observed in the 2004 testing. The testing reported here undertook a preliminary evaluation of the effects of employing:

- Preheated 2-BTP agent discharge with and without SBC
- Simultaneous discharge of room temperature 2-BTP and SBC powders from separate pressurized cylinders injected into a “Tee” distribution system
- Discharge of room temperature 2-BTP and SBC blended together

e. The effects on extinguishment of the gNFS spray fires and on the audible event noted earlier were monitored, as well as a wide array of gNFS conditions of local temperature, pressure, and airflow. Video recording with sound served to document each discharge and its re-ignition events if any.

f. Air flow in the nacelle test fixture, the location of the duct interface through which visual signs accompanying the audible events could be seen, and some of the internal design features are depicted in Figure 2.7-2.

g. The internal locations of the spray fire nozzles and agent discharge nozzles are shown in Figure 2.7-3.

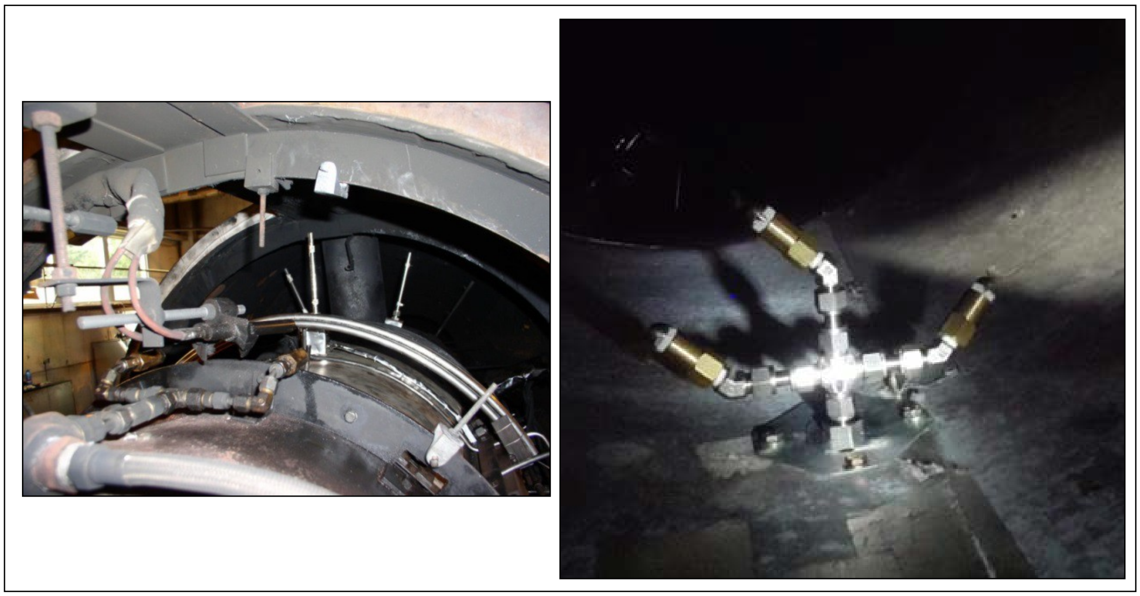


Figure 2.7-3. Interior of the gNFS showing fuel spray nozzles (left, FAA supplied photo) and one of four sets of fire suppression nozzle assemblies (right) used in this testing.

h. A close-up of the air gap at the exit end of the gNFS test fixture is shown in Figure 2.7-4.

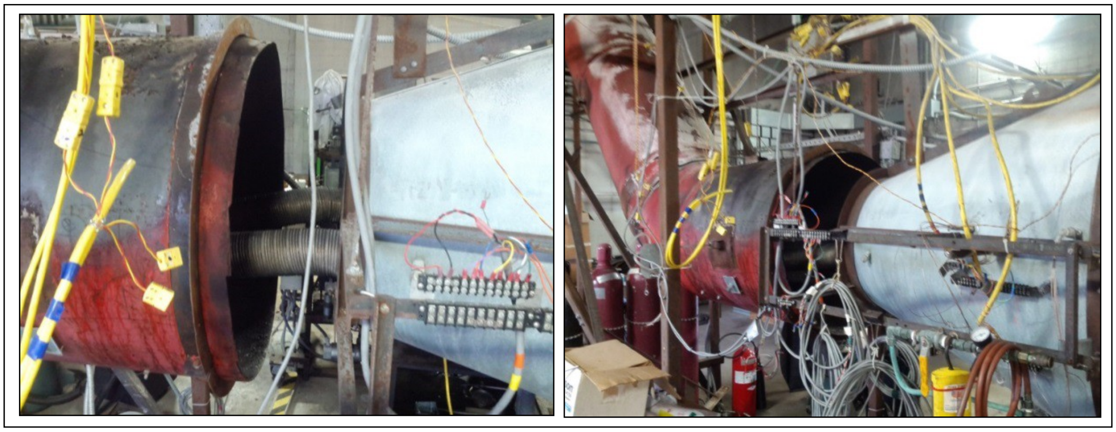


Figure 2.7-4. The gNFS duct interface gap - location of post re-ignition events (if any).

i. Video still of a test showing the airgap and spray fire from 2004 testing is provided in Figure 2.7-5.

Figure 2.7-5. FAA supplied video stills from 2004 testing of gNFS duct interface gap (left) and spray fire (right) during testing [typical].

j. A screen capture of the atypical release from the gNFS gap during 2004 testing is shown in Figure 2.7-6. It was accompanied by an audible cue.

Figure 2.7-6. FAA supplied photo of post extinguishment re-ignition event from 2004 testing showing smoke ejected during audible event.

2.7.3 Procedures and Findings

a. Testing of 2-BTP in combination with SBC from Fluid Energy (a jet-mill processed product) employed AFES high pressure rapid discharge hardware, a custom agent transfer line, and oil spray nozzles from Monarch Manufacturing. The 12 individual nozzles were arrayed at four points around the inner test fixture circumference equally spaced with two of three individual nozzles pointed roughly in opposition and one nozzle (the center nozzle) directed slightly up stream (with respect to the air flow) (fig. 2.7-3). This arrangement is comparable to that employed in the 2004 testing (note: previously tested nozzles were identified, but specific details regarding modifications to the nozzles were not available). A comprehensive description of the testing, prepared by the FAA, is included with this report in Appendix L. The results of that report are summarized in Table 2.7-1.

b. Eighteen nacelle fire suppression tests were conducted. Of these, only one heated 2-BTP discharge evidenced an audible signal. No audible signals were detected for the 2-BTP co-discharges with SBC or the blended 2-BTP + SBC discharge. These results, though limited, suggest that further study of 2-BTP and 2-BTP blends for use in engine nacelle applications may be warranted with improvements to the methods to disperse agent and other parameters.

Table 2.7-1. SUMMARY gNFS TESTING AT THE FAA TECHNICAL CENTER

Configuration	SBC Type	SBC Weight, g	2-BTP Weight, g	Shell Temperature, °F	Discharge Time, s	RTD, s	SBC Remaining, g	Audible re-ignition? Y/N
Heated BTP + SBCs	FE-1	199.6	2,032	141	2.5	2.4	35	No
Heated BTP + SBCs	FE-1	199.6	1,996	148	2.5	3.41	34	No
Heated BTP + SBCs	FE-1	199.6	2,018	148	2.7	3.7	32	No
Heated BTP No SBCs	-	N/A	1,982	145	2.9	2.2	N/A	No
Ambient BTP + SBCs	FE-1	199.7	2,009	91	-	2.9	30	No
Heated BTP No SBCs	-	-	1,991	156	2.6	3	N/A	No
Heated BTP No SBCs	-	-	1,987	152	2.5	2.3	N/A	No
Heated BTP No SBCs	-	-	1,991	155	2.4	2.37	N/A	Yes
Ambient BTP No SBCs	-	-	2,005	84	2.6	3.94	N/A	No
Heated BTP + SBCs	FE-1	199.6	1,991	146	2.5	1.56	20	No
Heated BTP + SBCs	FE-3	199.6	1,991	155	2.7	2	39	No
Heated BTP + SBCs	FE-3	199.6	2,009	157	2.7	2.34	47	No
Heated BTP + SBCs	FE-3	199.6	1,991	159	2.2	2.73	43	No
Ambient BTP Slurry	FE-3	199.6	199.6	84	2.5	1.93	0	No
Ambient BTP Slurry - Increased SBCs %	FE-3	300	300	87	2.4	2.43	0	No
Ambient BTP Slurry - Increased SBCs %	FE-3	300	300	91	2.4	2.93	0	No
Ambient BTP Slurry - Increased SBCs %	FE-3	300	300	86	2.4	2.03	0	No
Ambient BTP Slurry - Increased SBCs %	FE-2	300	300	90	1.7	1.77	0	No

RTD = re-ignition time delay

Note: Shell temperature refers to the agent cylinder temperature (ambient temperature during testing was in the 85 to 90°F range) and RTD is the time to re-ignition following extinguishment.

2.8. CREW COMPARTMENT TESTING

2.8.1 Objectives

Evaluate gaseous low GWP agents which were identified as having the best fire extinguishing performance based on previous smaller scale testing when combined with different SBC based dry chemicals. Determine if there were noticeable differences between the different SBCs when used alone.

2.8.2 Procedures and Findings

a. A total of four gaseous, low GWP agents (Opteon 1100, Opteon 1150, Solstice 1233zd, and 2-BTP) all mixed with various types and amounts of SBC dry chemicals were evaluated in a larger scale, simulated crew compartment application. A high GWP agent (HFC-227ea and SBC) was also tested for baseline and chamber verification purposes. Prior tests using the smaller 8-ft^3 chamber indicated a high probability that all but Opteon 1150 would not be suitable candidates for crew compartment applications because of a number of factors. However, these other agents were tested in a limited capacity to compare to the previous results, and to see if there were any differences due to delivery method or interaction within the larger chamber. In addition to the gaseous agents, two different commercial dry chemical agents, KiddeX and KSA, and an experimental SBC from Cal-Nano were also evaluated individually and when blended with the gaseous agents. Even though the Cal-Nano SBC exhibited signs of clumping, it was still included for comparison purposes in the crew compartment testing. Further testing with improved SBCs would be advisable.

b. The tests were conducted in a 172-ft^3 chamber (fig. 2.8-1 and 2.8-2). The chamber was instrumented with two pressure transducers to measure the blast overpressure (BOP) within the chamber, temperature probes, sampling lines for measuring byproducts, high-speed cameras (top and side) for video capture, and an infrared (IR) sensor to establish when the fire was initiated. The chamber had provisions for agent delivery via two extinguishers and two nozzle outlets located on the opposite wall from the fireball initiation.

c. A total of 80 trials were completed, including 16 daily fireball generator (FBG) warm-up shots and three no-tests due to FBG or fire suppression equipment malfunction. Trials were conducted at a range of different concentrations as described below, with different SBC additives, both with and without clutter in the test chamber.

d. SBC dry chemical evaluation. Nine trials were conducted with KSA (dataset nomenclature: KSA) at a range of concentrations: 160 g/m^3 (1 trial), 120 g/m^3 (5 trials), 80 g/m^3 (2 trials) and 40 g/m^3 (1 trial). A similar set of nine trials was conducted with KiddeX (currently used in fielded extinguishers) (dataset nomenclature: KX) at a range of concentrations: 160 g/m^3 (1 trial), 120 g/m^3 (4 trials), 80 g/m^3 (3 trials) and 40 g/m^3 (1 trial). Two trials were conducted with Cal Nano (dataset nomenclature: Nano), both at concentrations of 80 g/m^3. KiddeX and KSA showed similar performance, however KSA seemed to perform slightly better with reflash in 2 of 9 trials, where KiddeX had reflash in 4 of 9 trials. Cal Nano had reflash in both trials and was determined not feasible for further evaluation. See Appendix I for a summary of the test results and Appendix J for the gas sampling measurements.

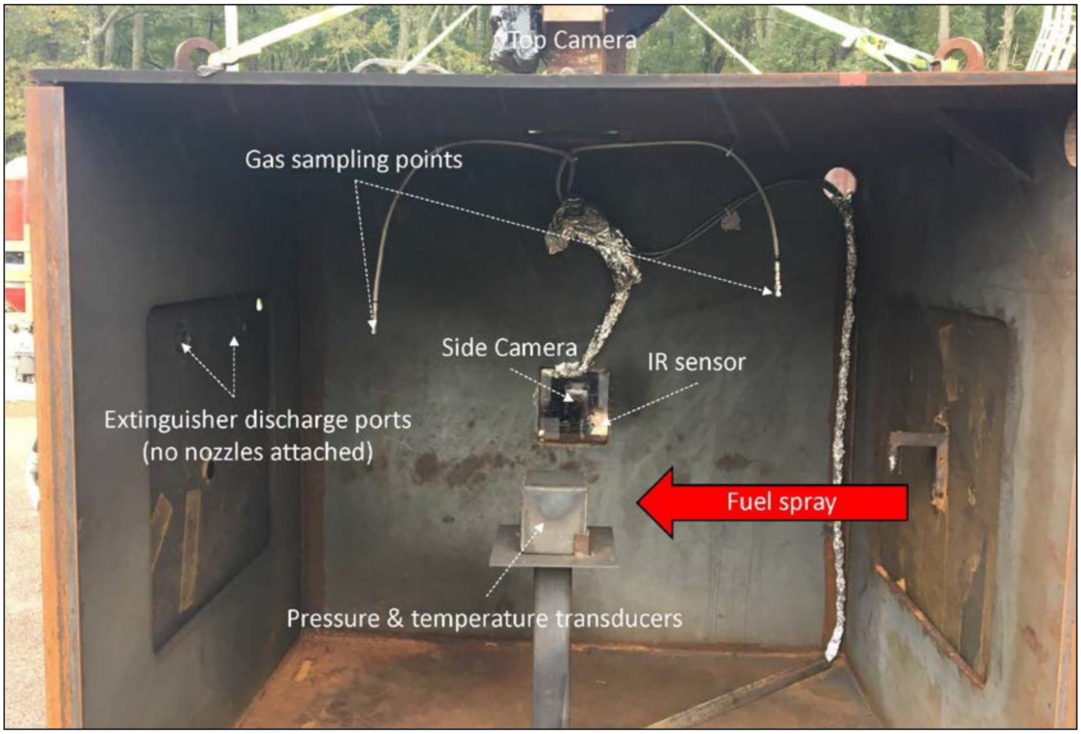


Figure 2.8-1. Test chamber (172 ft^3) with no clutter (side panel removed for photo).

Figure 2.8-2. Test chamber (172 ft^3) with clutter (simulated with ammo cans) and side panel removed.

e. Candidate agent with SBC additive evaluation. With SBC dry chemical evaluation results in mind, the candidate agents were evaluated with both KiddeX and KSA as an additive.

(1) Opteon 1100 was evaluated in four trials: two with KiddeX SBC additive (dataset nomenclature: 1100BC), and two with KSA SBC additive (dataset nomenclature: 1100KSA). Three of the four trials were conducted at the full minimum design concentration (MDC) of 9.7 percent, and showed effective fire extinguishment with low byproducts produced. The remaining trial was conducted at two-thirds MDC and, while still extinguishing the fire, had very high byproducts of COF_2 and HF. Because of the generation of very high byproducts, over five times the no-observed-adverse-affect-level (NOAEL) for Opteon 1100 (1.25%), it cannot be considered for a crew compartment application. While future work on the use of Opteon 1100 for unmanned compartments may be feasible, other agents have shown more promise in this area.

(2) Solstice 1233zd was evaluated in three trials all with KiddeX SBC (dataset nomenclature: 1233BC). Each trial was conducted at a design concentration equal to the NOAEL of 10 percent. At the time of testing, the NOAEL of Solstice 1233zd was still under discussion and thought to be as low as 2.5 percent which would be more detrimental as to the feasibility for a crew compartment application, given its MDC of 8.5 percent. Of the three trials conducted, one failure was observed with reflash, resulting in high levels of COF_2, HF, and hydrochloric acid (HCl) byproducts. The remaining two trials passed marginally with elevated levels of HF. Because of these byproduct results and the since confirmed NOAEL of 2.5 percent, Solstice 1233zd cannot be considered for a crew compartment application. Other agents have shown more promise for unmanned applications. No further evaluation is being considered at this time.

(3) The agent 2-BTP was evaluated in three trials, all with KiddeX SBC (dataset nomenclature: 2BTPBC). Previous testing and toxicology analysis has shown that 2-BTP is not suitable for a crew compartment application because of its NOAEL of 0.49 percent. Testing of 2-BTP was primarily to ensure that results were consistent with those from the smaller 8-ft^3 chamber testing. In those tests, 2-BTP showed the most promise of all agents being evaluated for fire extinguishing performance and possible unmanned compartment applications. Two trials were conducted at the full MDC of 6.2 percent which showed effective fire extinguishment with low levels of byproducts produced, consistent with previous testing. The third trial evaluated the agent at 3.1 percent (1/2 its MDC). This trial also showed effective fire extinguishment and low byproduct levels. While unsuitable for crew applications, 2-BTP remains the most promising agent of all of the low-GWP agents that have been evaluated thus far for normally unoccupied applications.

(4) Opteon 1150 showed the most potential, prior to the simulated crew compartment testing, as a replacement crew agent when mixed with SBC. This is because of its 7 percent NOAEL and lower 4.7 percent MDC, combined with performance in previous testing that showed low to moderate byproduct levels. This resulted in Opteon 1150 being closely looked at and used in significantly more trials than the other agents. Opteon 1150 was evaluated in 18 trials, eight were conducted with KiddeX SBC (dataset nomenclature: 1150BC) and 10 were conducted with KSA SBC (dataset nomenclature: 1150KSA). Agent concentrations used in the trials ranged from the NOAEL of 7 percent, down to 1.75 percent which is less than half the MDC.

(a) When mixed with KSA, Opteon 1150 showed positive results for fire extinguishment and byproduct levels in eight of ten trials. The two failures were because of reflash and resultant high byproducts during tests below the MDC (38 and 75 percent of the MDC).

(b) In trials conducted with KiddeX, failures due to reflash, high byproducts, or extended fire-out times were observed in six out of eight trials. While two of these failures were encountered with a lower concentration of SBC, the results indicate that use of KSA had a significant positive impact on the performance of the agent versus trials conducted with KiddeX.

(c) One observation to note was that during trials No. 69 through No. 71, which were the last Opteon 1150 tests conducted, significant caking of the KSA was found during post-discharge examination of the extinguishers. At this time, why this caking was observed during these tests is unknown; one possible reason is a lower ambient temperature compared to when the other tests were conducted, however this cannot be confirmed. Additional testing in high and low environmental conditions would be required to further validate Opteon 1150 mixed with SBC, in addition to testing in full-up vehicle applications.

(d) The BOP for a baseline test using HFC227-BC and one of the 1150BC tests where a reflash occurred is shown in Figure 2.8-3. Overall, the results shown during these trials warrant additional testing of Opteon 1150 as a possible crew compartment agent.

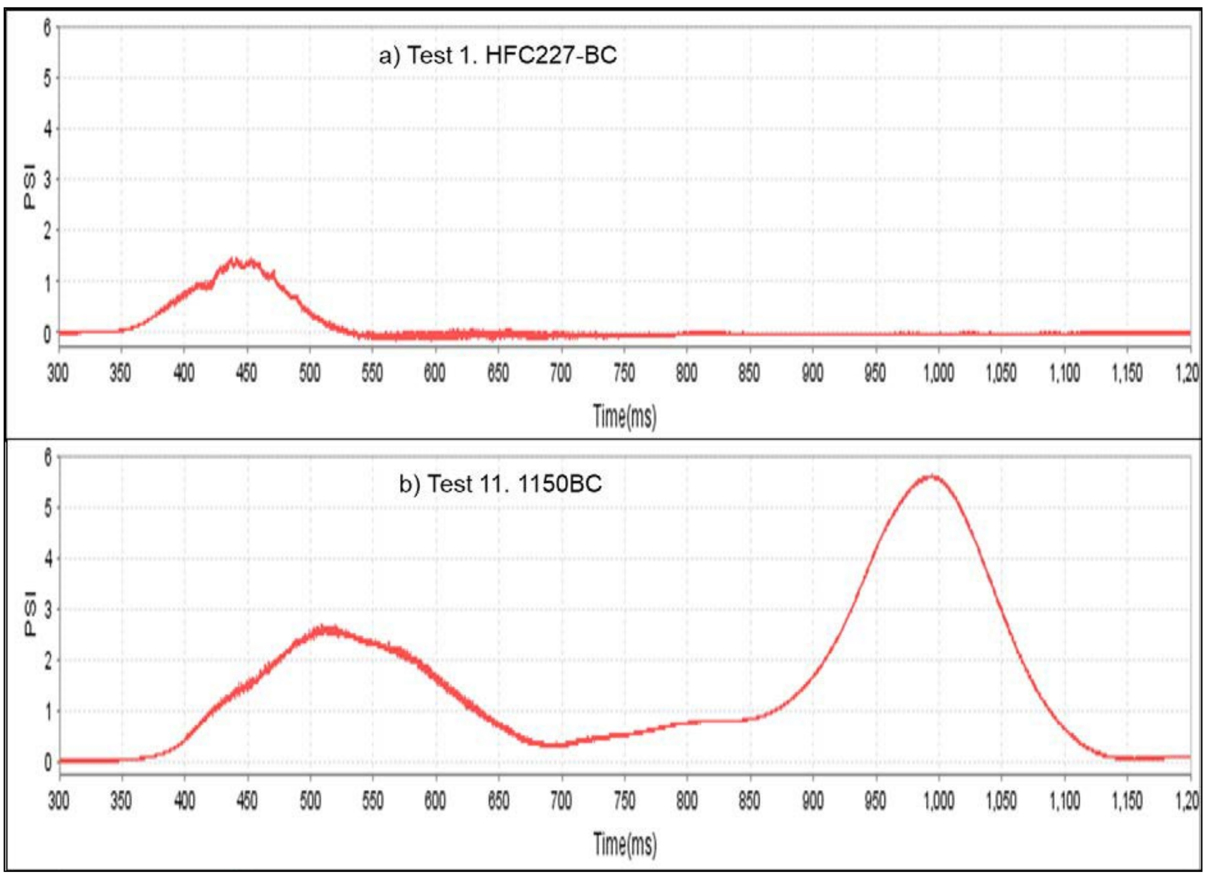


Figure 2.8-3. BOP: a) Test 1 - HFC227-BC with no reflash, b) Test 11 - 1150BC with reflash.

f. HFC-227ea with powder was evaluated as both a baseline to ensure the results that were being collected are representative of known HFC227-BC performance as well as to see if performance could be enhanced when used with KSA versus KiddeX (fine and normal grinds of sodium bicarbonate dry chemicals). HFC227-BC was evaluated in twelve trials: five were conducted with KiddeX SBC (dataset nomenclature: 227BC) and seven were conducted with KSA SBC (dataset nomenclature: 227KSA). Designed agent concentrations in the trials ranged from 10 percent (near the lowest-observed-adverse-affects-level (LOAEL) of 10.5 percent) down to less than 1/6 of the 8.7 percent MDC (1.4 percent). As expected, HFC227-BC showed strong performance with successful extinguishment, low byproducts, and no reflash in 11 of 12 trials. The single failure was due to reflash and byproducts when at 1.4 percent concentration with KiddeX. No failures were shown with KSA at this concentration level, which indicated again that KSA exhibits higher performance when mixed with gaseous agents than KiddeX.

g. As in previous full-scale crew compartment test programs, the observation was made that chemicals designed to be more reactive, thus yielding shorter atmospheric lifetimes and therefore lower GWPs, tend to generate much higher byproduct levels during the fire suppression process than more stable, and thus likely higher GWP, compounds (see Appendix K).

h. Two major conclusions were brought to light as a result of this simulated full-scale crew compartment testing. First, from an SBC standpoint, KSA appears to be superior to KiddeX by enhancing the performance of gaseous agents, indicated by successful performance with an extinguishing concentration below the MDC of the neat agent, thereby giving an increased safety margin for the AFES. Second, Opteon 1150 showed better-than-expected performance as a potential crew compartment agent replacement. While there are certainly questions that need to be answered (e.g., the potential long-term compatibility of SBC and Opteon 1150 when stored together in a compressed gas cylinder) before using it as a potential replacement, Opteon 1150 has shown promise that no other agent evaluated has shown thus far. However, sufficient amounts of FE-1 were not available for evaluation during this testing, therefore no conclusions can be drawn regarding the performance of FE-1.

i. Based on the positive initial results of Opteon 1150 blended with KSA, the extinguishing blend was tested in a full-up vehicle configuration in May 2019. At the time of publication of this report, the crew compartment FSAB report was not available. Full details of this testing will be published in three separate reports: Stryker Low Global Warming Potential Automatic Fire Extinguishing System Performance Test Events 1 and 2 (2019-FSAB-058), Events 3 and 4 (2019-FSAB-059), and Events 5 and 6 (2019-FSAB-060).

2.9 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

a. This project has assembled a suite of test methods, test fixtures, and test facilities suitable for the testing, identification of promising candidates and optimization of candidate low GWP chemicals for use in HPFE (pan-fire), aviation engine nacelles, vehicle crew compartments, and related applications.

b. Several non-occupied space and HPFE agent candidates have been identified. Only one low-GWP agent has been identified as a possible candidate for use in occupied crew areas: Opteon 1150 mixed with SBC.

c. The research chemicals identified and their status in screening tests are listed in Table 2.9-1. As noted, the only research chemical tested was hexafluoropropene. The other chemicals were identified as possible candidates, but were not available in quantities large enough for testing at the time of this effort. The identified chemicals have been included for reference for possible inclusion in future testing.

TABLE 2.9-1. RESEARCH CHEMICAL (SYNQUEST LABORATORIES) TESTING SUMMARY

Chemical Name and Structure	Acquired, Y/N	Testing
Hexafluoropropene, CF3-CF=CF2	Y	Cup-burner
2-Chloro-3,3,3-Trifluoropropene, CF3-CCl=CH2	N	None
2,3,3,3-Tetrafluorpropene, CF3-CF=CH2	N	None
1-Chloro-1,3,3,3-Tetrafluoropropene, CF3-CH=CFCl	N	None
1,2,3,3,3-Pentafluoropropene, CF3-CF=CHF	N	None
Octafluoro-2-butene, CF-CF=CF-CF3	N	None

Note: Octafluoro-2-butene was studied previously (NIST HOTWC report R0000270): cup-burner extinguishment 4.9%, boiling point = 0.8 °C.

d. The testing status of all commercially available chemicals and their physical properties is summarized in Table 2.9-2.

TABLE 2.9-2. COMMERCIALLY AVAILABLE CANDIDATE AGENTS TESTED AND EVALUATED

Agent CAS No.	Chemical name and structure	Cup-Burner	Pan Fire	Engine Nacelle	Crew Compartment
2-BTP, 1514-82-5	3,3,3-Trifluoropropene, CF3-CBr=CH2	Y	Y	Y	Y
Opteon 1100, 692-49-9	1,1,1,4,4,4-Hexafluoro-2-Butene, CF3-CH=CH-CF3	Y	Y	N	Y
Opteon 1150 66711-86-2	1,1,1,4,4,4-Hexafluoro-2-Butene, CF3-CH=CH-CF3	Y	Y	N	Y
Solstice ZD, 102687-65-0	Trans 1-Chloro-3,3,3-Trifluoropropene, CF3-CH=CHCL	Y	Y	N	Y
Solstice ZE, 29118-24-9	Trans-1,3,3,3-Tetrafluoroprop-1-ene, CF-CH=CHF	Y	N	N	N

[a]All crew compartment agents were mixed with various types and amounts of SBC when tested.

Note: The agent 2-BTP was tested in pan fire tests and in crew compartment tests even though it is unlikely to be fielded in either configuration in an Army application. While 2-BTP is being used commercially in limited larger volume crew space applications, it would most likely not be an acceptable candidate for Army crew space applications because of cardio-toxicity concerns and the NOAEL of 0.49 percent. However, 2-BTP was evaluated in this program's pan fire tests and crew space tests for reference purposes.

e. Overall performance of agents tested and related discussion on areas of application:

(1) <u>Portable fire extinguishers (HPFEs)</u>

(a) By far the most effective agent, as measured by size of fire extinguished (12.5 ft^2) and the consistency with which test fires were successfully extinguished, is the brominated agent 2-BTP. This is a higher boiling agent and will likely stream well in windy or high air flow conditions.

(b) The performance of Opteon 1100 as an unblended, unenhanced agent was not as good as the performance of unblended, unenhanced Opteon 1150. Opteon 1150 extinguished fires of the same size extinguished by Opteon 1100 but with considerably more agent remaining in the extinguisher. Opteon 1150 has a lower boiling point and would be expected to perform better than Opteon 1100 in lower temperature conditions.

(c) Once blended with SBC, performance of Opteon 1150 improved considerably and the substantial amounts of remaining agent post fire extinguishment suggest that with further optimization, the performance of blended Opteon 1150/SBC could be increased further.

(d) Solstice ZD (with no added SBC) performed similarly to Opteon 1100 in this testing. Addition of SBC to Solstice ZD enabled pan-fire extinguishment performance at the 7.5 square foot level and left significant amounts of remaining agent.

(e) Further testing of Opteon 1150 and 2-BTP and optimization of the agent hardware configurations both with and without the addition of SBC would likely yield further improvements in agent performance in both cases.

(2) Aviation engine nacelle and auxiliary power unit (APU) compartments

(a) One heated 2-BTP trial evidenced a minor audible event. No audible events were detected for the 2-BTP co-discharged with SBC or the blended 2-BTP SBC discharge.

(b) These results, although limited, suggest that further study of 2-BTP and 2-BTP blends for use in engine nacelle applications may well be warranted.

(c) The noticeable lack of a post re-ignition audible event for 2-BTP when discharged in conjunction with SBC opens an opportunity for further consideration of this agent as an engine nacelle agent for replacement of Halon 1301. Blending or co-discharge configurations employing SBC could be further tested. Use of solid propellant gas generators (SPGG) to heat the 2-BTP could possibly eliminate all audible events as the agent temperatures reached would be considerably higher than those tested here. While not developed for this project, it is understood that SPGG technology is available to adjust heat transfer thus providing a means to adjust and control the temperature of the agent at the time of discharge. A key reason for introducing heated 2-BTP was to evaluate its performance/feasibility to possibly overcome low temperature extremes by introducing a SPGG technology.

(3) Crew compartment of ground vehicles. Four gaseous agents (Opteon, 1100, Opteon 1150, Solstice 1233zd and 2-BTP), in addition to three SBC dry chemicals (KiddeX, KSA, Nano) were evaluated in a simulated crew compartment application (172-ft^3 test chamber). The chamber used a FBG as the fire threat that is similar in size and intensity to a threat seen in a combat situation. The results from this testing are summarized in Table 2.9-3 and showed the following:

(a) Opteon 1150 demonstrated the most potential as a replacement crew agent when mixed with a dry chemical agent (KSA). Further evaluation is recommended for continued consideration as a replacement crew agent.

(b) KSA dry chemical showed a noticeable improvement over KiddeX dry chemical, by enhancing the performance of the gaseous agents evaluated with respect to fire suppression performance.

(c) Promising fire performance was shown by 2-BTP, however toxicology results limit this agent to unoccupied compartments.

(d) Opteon 1100 and Solstice 1233zd showed acceptable fire suppression performance, however only at concentrations that far exceed the maximum safe concentration for occupied spaces.

(e) Dry chemical agents when tested without being mixed with gaseous agents were prone to reflash at the concentration levels evaluated.

TABLE 2.9-3. CREW COMPARTMENT PERFORMANCE SUMMARY

Agent	Maximum Safe Concentration	Minimum Success		Successes[a]		Estimated Margin[b]
		Concentration	Powder Weight, lb	At Minimum Weight	In All Tests	
227KSA	9 % (7.73 lb)	1.4 % (1.1 lb)	0.44	2/2	7/7	>7
227BC	9 % (7.73 lb)	1.4 % (1.1 lb)	0.88	2/3	4/5	7
1150KSA	7 % (5.76 lb)	1.9 % (1.44 lb)	0.88	1/2	8/10	4
KSA	300 g/m^3 (3.22 lb)	80 g/m^3 (0.88 lb)	0.88	1/2	5/9	3.7
BC	300 g/m^3 (3.22 lb)	80 g/m^3 (0.88 lb)	0.88	1/3	2/9	3.7
1150BC	7 % (5.76 lb)	7 % (5.76 lb)	0.88	2/3	2/8	1
2BTPBC	0.49 % (0.4 lb)	3.2% (2.65 lb)	0.88	1/1	3/3	>0.15
1233BC	2.5 % (1.55 lb)	10 % (6.73 lb)	0.88	2/3	2/3	0.23
1100KSA	1.25 % (0.96 lb)	9.7 % (8.1 lb)	0.88	2/2	2/2	>0.12
1100BC	1.25 % (0.96 lb)	9.7 % (8.1 lb)	0.88	1/1	1/2	0.12
Nano	300 g/m^3 (3.22 lb)	-	NA	0/3	0/3	TBD[c]

[a]Based on current crew casualty criteria.
[b]Ratio of maximum safe agent weight/lowest successful agent weight.
[c]Agent quality issues observed.

(4) Recommendations for future testing and agent development and qualification needs:

f. Fire suppression agents must perform over a wide operational temperature range. Lower boiling agents are inherently better at rapid space filling over a wide temperature range and an emphasis on testing of lower boiling point candidates is stressed.

(a) Lower boiling agents may be required and some chemicals with low boiling points have been identified though not tested. Work with these compounds would require additional resources and planning.

(b) To achieve comparable performance to current HFCs blended with SBCs or Halon 1301, SBCs will have to be added to the non-brominated agents.

(c) SBC powders in the low micron range can be prepared by jet milling methods. To achieve nano particle size powders, cryo-milling and cryo-crystallization methods could possibly be used. New sources and methods will have to be identified. Suggested approaches to further development of methods for generating free flowing SBC powders of low micron and nanometer sizes are provided in Appendix H.

(d) In addition to Solstice ZD other low boiling chlorinated chemical agent options (Table 2.9-1) may be promising areas for future testing as they might perform sufficiently well as to avoid the need for SBCs as additives and due to their low boiling points provide better low temperature performance.

g. Note that non-brominated streaming and flooding agents are not as effective as Halon 1301, and SBC addition will most likely be required to achieve successful extinguishment, as was the case with HFC-227ea used to protect the crews of combat vehicles. This will be critical to meet low temperature performance requirements. Higher boiling candidates for engine nacelle applications would most likely require the development of SPGG technology for effective fire suppression especially to meet low temperature requirements. Note also that preliminary full-scale crew compartment testing results support the previously hypothesized result that chemicals that are designed to be more reactive, thus yielding shorter atmospheric lifetimes and therefore lower GWPs, tend to generate higher byproduct levels during the fire suppression process than more stable, and thus likely higher GWP, compounds.

h. Finally, the development of suitable application-specific qualification test methods for SBC agent mixtures entails measures of SBC concentrations within spaces and must define acceptable concentrations for application acceptance. The characterization tools available for micron sized particles are likely adequate for evaluating particle air concentrations over time. Tools for nano particle air concentration characterization likely will require source identification. The identified technology will require further development, pretesting and evaluation to characterize accuracy, repeatability and reliability for use in engine nacelle and other applications for qualification purposes. Lastly, performance of heated 2-BTP (simulated SPGG) with an optimized SBC powder could be enhanced by improvements to the agent dispersion method (plumbing, nozzles, solenoid valves, etc.).

SECTION 3. APPENDIXES

APPENDIX A. TEST CRITERIA

Not used.

APPENDIX B. SBC POWDER CHARACTERIZATION TEST DATA FROM GALBRAITH LABORATORIES, INC.

Fluid Energy (FE) samples are shown as FE-1 through FE-3 and Cal Nano (CN) samples are shown as CN-1 through CN-3 with the corresponding Galbraith sample ID in Table B-1.

TABLE B-1. NUMBERING SCHEME OF NEI CORPORATION SAMPLES

U.S. Army ATC	Galbraith Laboratories, Inc.
FE-1 Sample 7	D-4636
FE-2 Sample 8	D-4638
FE-3 Sample 9	D-4640
CN-1 Sample 10	D-4642
CN-2 Sample 11	D-4644
CN-3 Sample 12	D-4646

TABLE B-2. WATER CONTENT FOR CAL NANO (CN) AND FLUID ENERGY (FE) SBC POWDERS

Sample No.	Sample ID	Water Content, ppm
1	FE-1	1,582
2	FE-2	1,680
3	FE-3	1,782
4	CN-1	2,802
5	CN-2	2,594
6	CN-3	949

Laboratory test results for a typical Fluid Energy jet-milled product are shown below. Samples of powder are re-suspended in isopropyl alcohol using ultrasonic agitation. Note some evidence of nanometer-sized particles though bulk composition cannot be inferred from this result alone.

Figure B-1. Sample D-4636.

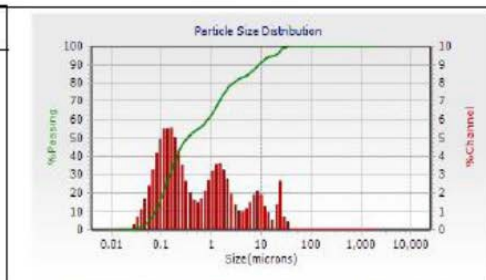
Microtrac

- Particle Size Analysis -

C:\Microtrac\FLEX 11.0.0.4\Databases\MTDatabase.MDB

-Tabular Data -

Size(um)	%Chan	%Pass	Size(um)	%Chan	%Pass
2000	0.00	100.00	4.63	0.96	83.63
1674	0.00	100.00	3.89	1.02	82.67
1408	0.00	100.00	3.27	1.37	81.65
1184	0.00	100.00	2.750	1.97	80.28
995.6	0.00	100.00	2.313	2.74	78.31
837.2	0.00	100.00	1.945	3.28	75.57
704.0	0.00	100.00	1.635	3.58	72.29
592.0	0.00	100.00	1.375	3.55	68.71
497.8	0.00	100.00	1.156	3.20	65.16
418.6	0.00	100.00	0.972	2.66	61.96
352.0	0.00	100.00	0.818	2.10	59.30
296.0	0.00	100.00	0.688	1.66	57.20
248.9	0.00	100.00	0.578	1.48	55.54
209.3	0.00	100.00	0.486	1.59	54.06
176.0	0.00	100.00	0.409	1.99	52.47
148.0	0.00	100.00	0.344	2.65	50.48
124.5	0.00	100.00	0.2890	3.46	47.83
104.7	0.00	100.00	0.2430	4.31	44.37
88.00	0.00	100.00	0.2040	5.05	40.06
74.00	0.00	100.00	0.1720	5.55	35.01
62.23	0.00	100.00	0.1450	5.48	29.46
52.33	0.00	100.00	0.1220	5.49	23.98
44.00	0.00	100.00	0.1020	4.94	18.49
37.00	0.44	100.00	0.0860	4.16	13.55
31.11	0.67	99.56	0.0720	3.27	9.39
26.16	2.61	98.89	0.0610	2.42	6.12
22.00	1.37	96.28	0.0510	1.67	3.70
18.50	0.54	94.91	0.0430	1.08	2.03
15.56	0.94	94.37	0.0360	0.66	0.95
13.08	1.23	93.43	0.0300	0.29	0.29
11.00	1.90	92.20	0.02550	0.00	0.00
9.25	2.11	90.30	0.02150	0.00	0.00
7.78	1.91	88.19	0.01810	0.00	0.00
6.54	1.51	86.28	0.01520	0.00	0.00
5.50	1.14	84.77	0.01280	0.00	0.00



- Measurement Info -

Title	
D4646	
Identifiers	
ultrasonicated 15 min	
-	
Database Record	464
Run Number	Avg Of 3
Date	2/8/2017
Time	3:30 PM
Acquired Date	2/8/2017
Acquired Time	3:30 PM
Serial Number	S5418
Sample Cell ID	0139
Calculated Data	
Above Residual	0
Below Residual	0
Loading Factor	0.0145
Trans. L1:L2:	0.969:0.939
RMS Residual	0.269%
Recalculation Status	
Live-Meas : : Original :	

-SOP Info-

LAST USED(*)	
Timing	
Setzero Time	10 (sec)
Run Time	10 (sec)
Number of Runs	3
Multi-Run Delay	0 (min)
Delay First Meas.	Disabled
Analysis	
CURRENT PARTICLE	
Refractive Index	1.33
Transparency	Transp
Shape	Spherical
IPA	
Refractive Index	1.38
Options:	
Filter	Enabled
Analysis Gain	Default(2)
Analysis Mode	BLUEWAVE
Perspective	
Progression	Standard
Distribution	Volume
Upper Edge(um)	2000
Lower Edge(um)	0.0107
Residuals	Disabled

Summary	
Data	Value
MV(um):	2.830
MN(um):	0.0570
MA(um):	0.1920
CS:	31.18
SD:	2.410
Mz:	1.780
si:	4.05
Ski:	0.936
Kg:	4.37

Percentiles	
%Tile	Size(um)
10.00	0.0740
20.00	0.1070
30.00	0.1470
40.00	0.2040
50.00	0.332
60.00	0.859
70.00	1.463
80.00	2.673
90.00	9.03
95.00	18.82

Peaks Summary		
Dia(um)	Vol%	Width
23.33	5.6	7.31
7.66	12.7	6.51
1.27	29.2	1.431
0.131	52.5	0.171

2/8/2017 3:31 PM

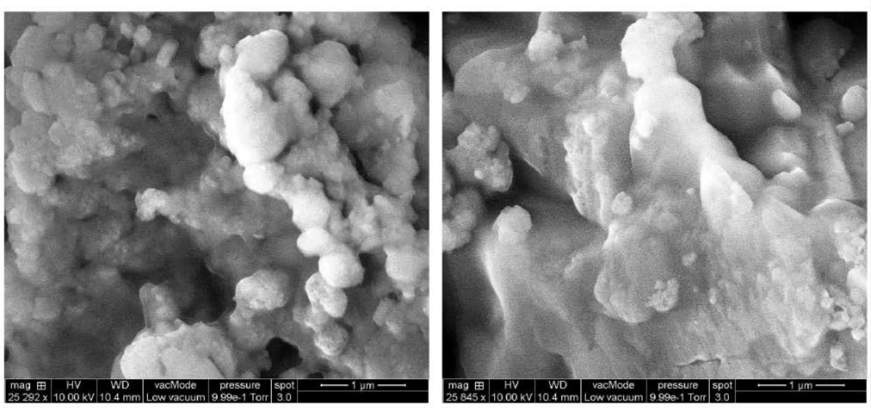
FLEX

11.0.0.4

-

Sample System(Wet)	
Number of Rinses	2
Flow Rate (%)	55%
Deaeration Cycles	3

Sample ID: D4646 **SEM** **Magnification: 25,292 x 25,845 x**



NEI
NEI Corporation

37

Figure B-2. Sample D-4646.

APPENDIX C. CANDIDATE TOXICITY PRELIMINARY EVALUATION

DEPARTMENT OF THE ARMY
US ARMY PUBLIC HEALTH CENTER
BUILDING 5158
8252 BLACKHAWK ROAD
ABERDEEN PROVING GROUND MARYLAND 21010-5403

MCHB-PH-TEV

04 January 2019

MEMORANDUM FOR Commander, U.S. Army Tank Automotive Research, Development and Engineering Center, ATTN: AMSRD-TAR-R (Steven J. McCormick), 6501 E. Eleven Mile Road, Warren, MI 48397-5000

SUBJECT: Toxicity Evaluation for Low Global Warming Fire Suppressants

1. References (see enclosure).

2. The Army Tank Automotive Research, Development and Engineering Center (TARDEC) and Army Aviation and Missile Command (AMCOM) are evaluating alternative materials for the high Global Warming Potential (GWP) fire suppressants currently deployed in ground and aviation weapons per AERTA PP-14-12-01: No/Low GWP Alternatives to Ozone Depleting Substances (ODSs) in Army Applications – Fire Suppressants. Toxicology support for the project was provided by this Center (reference 1). The Materiel Solution addresses evaluation of alternative fire suppressants being developed by industry or the military to reduce health, safety, and environmental concerns while meeting or exceeding military unique performance requirements. The scope includes ground vehicle crew and engine compartments, aviation engine and Auxiliary Power Unit (APU) compartments, and portable extinguishers.

3. Toxicity Evaluation is only one aspect of the down selection process. Other factors include ozone depletion potential (ODP) and GWP, fire extinguishing performance, physical properties, flammability, storage/equipment requirements, compatibilities, and pyrolysis and combustion by-products. These factors are assessed through small-scale and large-scale testing and optimization. In support of this effort, Toxicity Evaluation Division personnel reviewed the manufacturer information, exposure guidance, and available toxicological information for each of the candidate agents identified by the work group.

4. The information on each agent was used to rank the chemicals primarily by ODP, Cardiac Sensitization (CS) levels, and other reported health effects. Cardiac sensitization is the primary endpoint for assessing brief, high concentration halocarbon exposures. It is a condition in which the heart may become sensitized to catecholamines (i.e., adrenaline) and increase the risk of cardiac arrhythmia. The rat 4-hour inhalation LC_{50} values provide another measure of acute toxicity when CS levels are not available.

5. A comparison of the 3 currently deployed agents and 15 ranked replacement candidates is provided as Appendix 1. The degree of available information varies for the replacement candidates depending upon their phase of research. Although the manufacturers may have provided toxicology data for some agents, the chemical formulation and physical properties may have been withheld due to proprietary concerns. This information would be required at a later date if a Toxicity Clearance for use of the chemical by the Army was requested. Other chemicals that were identified solely based upon their physical/chemical properties had no available toxicity data and would require toxicity studies to fill the data gaps if performance testing indicated that they could be viable options. Parameters with no available data are identified as To Be Determined (TBD).

6. While a candidate may be highly ranked in Appendix 1 by the No Observed Adverse Effect Level (NOAEL), it may not be a suitable candidate for use in crew compartments if the margin of safety is too narrow between CS levels and the design concentration required to extinguish the fire and prevent reflash. Inherent trade-offs exist for specific applications in regard to physical properties, performance, toxicity, environmental impact, cost, combustion by-products, and reactivity. A candidate that performs well for streaming or engine applications may not be appropriate for use in the crew compartment and vice-versa.

7. The top 4 candidates based upon zero OPD, low GWP, and high thresholds for CS NOAELs (range 12 to 7%) were Solstice HFO-1234ze, HFO-1234yf, Chemours TF-1, and Opteon 1150. Occupational exposure limits (OELs) have not yet been determined for the TF-1 and Opteon 1150. The OELs for 8- and 12-hour daily exposures are typically based upon endpoints other than CS as identified in the 4-hour and 90-day rat inhalation tests, or reproductive studies if deemed necessary.

8. The next 6 middle ranked candidates had low thresholds for CS NOAELs (range 2.5 to 0.49%). In the case of HFO-1233zd, no cardiac sensitization in dogs was identified up to 35,000 ppm (3.5%), though general toxicity was noted in the animals resulting in a no observed effect level of 25,000 ppm (2.5%) (reference 2). The 8-hr TWA of 800 ppm for HFO-1233zd was based upon adverse changes in cardiac tissue observed in rats (reference 2). The candidate 2-BTP has a uniquely low recommended OEL based upon reproductive endpoints observed in rats (references 3 and 4).

9. The 5 remaining experimental candidates had little or no toxicity data available. In the case of hexafluoropropene, kidney effects may present a limiting factor with an ACGIH Threshold Limit Value (TLV) of 0.1 ppm (reference 5). It has a reported 4-hour rat LC_{50} of 3,060 ppm and a 30-minute LC_{50} of 15,750 ppm (reference 5). If

hexafluoropropene appears to be a viable candidate based upon performance, additional toxicity studies could be performed to assess safe exposure levels in the 5 to 10-minute exposure timeframe.

10. E-Octafluoro-2-butene has a reported 4-hour rat LC_{50} of 81 ppm (reference 6). Based upon this single data point, this candidate should be considered highly toxic. Additional toxicity testing would not be likely to provide any additional refinement for its possible use.

11. Past work developing non-ODP agents for vehicle crew compartments and handheld fire extinguishers has demonstrated the utility of combining sodium bicarbonate based dry chemicals with gaseous agents for enhanced fire extinguishing performance and possible reduction of hazardous combustion by-products (references 7, 8). Approved dry chemicals for use in crew compartments are primarily sodium bicarbonate with low concentrations of amorphous silica to prevent clumping and aid flow (reference 9). A nano-sized sodium bicarbonate powder has also been approved for use in handheld extinguishers (reference 10). Dry chemical formulations can vary significantly in regard to the additives and particle size. Selection of the appropriate dry chemical is a critical aspect of the optimization process. The toxicity of specific sodium bicarbonate dry chemicals and allowable concentrations have been extensively reviewed and assessed by the Toxicity Evaluation Division (references 11, 12). Any new dry chemical formulations identified during the optimization process that have not been previously assessed will require a Toxicity Clearance prior to use.

12. The potential of certain aqueous-based agents as zero-ODP and zero-GWP alternatives to fluorinated agents for vehicle crew compartments and handheld fire extinguishers has also been demonstrated (references 7, 13). A 50/50 (percent mass) blend of water and potassium acetate is presently deployed as a replacement for Halon 1301 in handheld extinguishers on ground vehicle platforms (reference 14). The Toxicity Evaluation Division has evaluated several aqueous agents for Army ground vehicle applications (references 15, 16, 17). Although not part of the most recent study described in paragraph 1, it is anticipated that future work in this area will include consideration of aqueous agents. Past work on aqueous agents has identified pyrolysis and combustion by-products such as acetone, acetic acid, methane, carbon dioxide, and carbon monoxide (reference 18). Depending upon future aqueous formulations and applications, the development of additional acute chemical exposure criteria and thermal injury criteria may be necessary (references 19, 20).

13. Conclusions.

a. As observed between the deployed agents and replacement candidates, inherent trade-offs exist between ODP, GWP, toxicity, and performance characteristics for these chemicals. Toxicity evaluation is only one aspect of the down selection process.

b. Based upon a review of the available literature and manufacturer information, the 15 proposed candidate replacements were ranked by ODP and cardiac sensitization NOAELs. Data gaps and possibilities for additional toxicity testing have been identified to aid the selection process.

14. Point of contact for this action is Mr. Matthew Bazar who can be reached at DSN 584-3980, commercial 410-436-3980, or via e-mail at usarmy.apg.medcom-phc.mbx.tox-info@mail.mil.

FOR THE DIRECTOR:

JOHNSON.MARK.STEVEN.1229380717 Digitally signed by JOHNSON.MARK.STEVEN.1229380717 Date: 2019.01.08 11:05:59 -05'00'

Encl

MARK S. JOHNSON
Director, Toxicology

REFERENCES

1. Military Interdepartmental Purchase Request, #11057946, PHC MEDCOM – ETAP Support, 29 Aug 2017.

2. Technical Document, trans-1-Chloro-3,3,3-Trifluoropropene (1233zd(E)) WEEL Documentation, OARS, 2300 Montana Avenue, Suite 409, Cincinnati, OH 45211, 2013.

3. Technical Document, Skaggs SR, Derivation of a Proposed Occupational Exposure Limit for 2-Bromo-3,3,3-Trifluoropropene, Universal Technical Services, Inc., 05 Dec 2014.

4. Memorandum, Army Public Health Center, MCHB-IP-TEP, 19 Aug 2015, subject: Occupational Exposure Limit Review for 2-Bromo-3,3,3-Trifluoro-1-Propene.

5. Technical Document, Hexafluoropropylene Emergency Response Planning Guideline, AIHA Guideline Foundation, Falls Church, VA 22042, 2009.

6. Safety Data Sheet (SDS), Octafluoro-2-butene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 03 Dec 2015.

7. Hodges SE and McCormick SJ., 2010, Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles, Suppression & Detection Symposium (SUPDET), National Fire Protection Association (NFPA).

8. Memorandum, US Army Institute of Public Health, MCHB-IP-TEP, 6 Mar 2012, subject: Toxicity Clearance for HFC-227ea with Sodium Bicarbonate (SBC-1) Powder in Handheld Fire Extinguishers for Army Aviation Rotary Aircraft.

9. Memorandum, US Army Center for Health Promotion and Preventive Medicine, MCHB-TS-TTE, 14 Dec 2001, subject: Request for Toxicity Clearances for Use of HFC-227ea Plus Dry Powder in Interim Armored Vehicle (IAV) Crew Compartment Fire Extinguishing System.

10. Memorandum, US Army Institute of Public Health, MCHB-IP-TEP, 18 May 2012, subject: Toxicity Clearance for HFC-227ea with Sodium Bicarbonate (SBC-2) Powder in Handheld Fire Extinguishers for Army Aviation Rotary Aircraft.

11. Memorandum, US Army Public Health Command (Provisional), MCHB-TS-TTE, 28 Jan 2010, subject: Sodium Bicarbonate Based Dry Powder Agents in Armored Vehicle Automatic Fire Extinguishing Systems.

12. Memorandum, US Army Institute of Public Health, MCHB-IP-TEP, 17 Mar 2015, subject: Revised Toxicological Assessment of Sodium Bicarbonate Based Dry Powder Agents in Armored Vehicle Automatic Fire Extinguishing Systems.

13. Technical Document, US Army Aberdeen Test Center, Dec 2005, Final Report for the Technical Feasibility of the Hand-held Fire Extinguisher on the M1A1, Special Evaluation of Potassium Acetate/Water Agent, Report No. ATC-8867.

14. Technical Document, Fire Extinguisher Assembly, TACOM Drawing 12994293.

15. Technical Document, US Army Center for Health Promotion and Preventive Medicine, Dec 1994. Toxicity Profile: Water Mist Spray with Additives.

16. Technical Document, US Army Public Health Command, MCHB-IP-TEP, Nov 2012, Acute Inhalation Toxicity in Rats Exposed To Aqueous Agents (Cryotech E36®) Used For Automatic Fire Extinguishing Systems, Toxicology Study No. 85-XC-0FMJa-12.

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18. Technical Document, US Army Aberdeen Test Center, 31 Jul 2012, Analysis of Environmentally Friendly Fire Extinguishing Agents, Report No. 2012-CC-663.

19. Memorandum, US Army Institute of Public Health, MCHB-IP-TTE, 24 Jan 2011, Review of Thermal Injury Criteria for the OSHKOSH Medium Tactical Vehicle Replacement (MTVR) and Logistics Vehicle System Replacement (LVRS) Automatic Fire Extinguishing System (AFES).

20. Memorandum, US Army Institute of Public Health, MCHB-IP-TTE, 28 Nov 2011, subject: Stage 2 Automatic Fire Extinguishing System Risks and Thermal Injury Criteria.

Trade Name	Chemical Name	CAS#	MW	ODP	GWP (100yr)	LC_{50} 4-hr (ppm)	CB Values (%)	CS NOAEL (%)	CS LOAEL (%)	8-hr TWA (ppm)
	Deployed Agents									
Halon 1301	Bromotrifluoromethane	75-63-8	148.91	16	7,100	>770,000[2]	4.10[1], 3.04[32]	5.0[1]	7.5[1]	1000[2]
HFC-227ea	1,1,1,2,3,3,3-Heptafluoropropane	431-89-0	170.03	0	3,200	>788,000[3]	6.70[31]	9.0[3]	10.5[3]	1000[3]
HFC-125	1,1,1,2,2-Pentafluoroethane	354-33-6	120.02	0	3,500	>769,000[4]	8.70[31]	7.5[4]	10.0[4]	1000[4]
	Replacement Candidates*									
Solstice HFO-1234ze	Trans-1,3,3,3-tetrafluorop-1-ene	29118-24-9	114.00[5]	0	<1	>207,000[5]	6.40[32]	12.0[5]	NA	800[6]
HFO-1234yf	2,3,3,3-tetrafluoropropene	754-12-1	114.00[7]	0	4	>405,800[7]	NT	12.0[7]	NA	500[8]
TF-1 / FC-1	Proprietary	NL	Proprietary	0	2	>231,000[9]	5.69[32]	10.0[9]	12.5[9]	TBD
Opteon 1150	E-1,1,1,4,4,4-hexafluoro-2-butene	66711-86-2	164.05[10]	0	2	>17,000[11]	3.60[32]	7.0[12]	7.0[12]	TBD
Solstice HFO-1233zd	Trans-1-chloro-3,3,3-trifluoropropene	102687-65-0	130.50[13, 14]	0	1	120,000[13,]	5.80[32]	2.5[13, 14]	2.5[13, 14]	800[13, 14]
SC-2	Proprietary	NL	Proprietary	0	5	120,000[9]	NT	2.5[9]	>2.5[9]	TBD
SC-1	Proprietary	NL	Proprietary	0	<10	>102,900[9]	6.74[32]	1.25[9]	2.5[9]	TBD
Opteon 1100	Z-1,1,1,4,4,4-hexafluoro-2-butene	692-49-9	164.00[15]	0	2	>102,900	7.43[32]	1.25	2.5	500[15]
2-BTP	2-Bromo-3,3,3-trifluoro-1-propene	1514-82-5	174.95[16]	0.003	0.02	>11,700[17]	4.63[32]	0.49[18]	1.0[18]	11[19, 20]
AF11E[20] / R-123	2,2,-Dichloro-1,1,1-trifluoroethane	306-83-2	152.93[21]	0.02	93	32,000[22]	NT	1.0[22]	2.0[22]	50[22]
	Hexafluoropropene	116-15-4	150.03[23]	TBD	TBD	3,060[23]	5.17[32]	TBD	TBD	0.1[23]
	E-Octafluoro-2-butene	360-89-4	200.03[24]	TBD	TBD	81[24]	NT	TBD	TBD	TBD
	1,2,3,3,3-Pentafluororopene	2252-83-7	132.03[25]	TBD	TBD	TBD	NT	TBD	TBD	TBD
	2-Chloro-3,3,3-trifluoropropene	2730-62-3	130.50[26]	TBD	TBD	TBD	NT	TBD	TBD	TBD
	1-Chloro-1,3,3,3-tetrafluoropropene	460-71-9	148.48[27]	TBD	TBD	TBD	NT	TBD	TBD	TBD

*** Replacements candidates sorted by ODP and the CS NOAEL**

MW= Molecular Weight; ODP=Ozone Depletion Potential; GWP=Global Warming Potential; LC_{50}= Lethal Concentration 50%; CS= Cardiac Sensitization; NL= Not Listed; NT= Not Tested; NOAEL= No Observed Adverse Effect Level; LOAEL= Lowest Observed Adverse Effect Level; TWA= Time Weighted Average; TBD= To Be Determined; CB= Cup Burner average

APPENDIX 1 REFERENCES:

1 Technical Document, NFPA 12A, Halon 1301 Fire Extinguishing Systems, National Fire Protection Association, One Batterymark Park, Quincy, MA. 2018.

2 Safety Data Sheet (SDS), Halon 1301 (Fire Extinguishing Agent), Kidde-Fenwal, 400 Main Street, Ashland, MA 01721, 09 Feb 2012.

3 Safety Data Sheet (SDS), FM-200® (Fire Extinguishing Agent with Expellant), Kidde-Fenwal, 400 Main Street, Ashland, MA 01721, 10 Apr 2015.

4 Safety Data Sheet (SDS), Genetron® 410A, Honeywell, 115 Tabor Road, Morris Plains, NJ 07950, 10 Apr 2010.

5 Technical Document, trans 1,3,3,3-Tetrafluoropropylene (HFO-1234ze) Emergency Response Planning Guideline, AIHA Guideline Foundation, Falls Church, VA 22042, 2012.

6 Safety Data Sheet (SDS), Solstice® 1234ze, Honeywell, 115 Tabor Road, Morris Plains, NJ 07950, 02 May 2016

7 Technical Document, 2,3,3,3-Tetrafluoropropene (HFO-1234yf) Emergency Response Planning Guideline, AIHA Guideline Foundation, Falls Church, VA 22042, 2010.

8 Safety Data Sheet (SDS), Solstice® yf Refrigerant (R-1234yf), Honeywell, 115 Tabor Road, Morris Plains, NJ 07950, 03 Aug 2018

9 Presentation, ARL-TARDEC Fire Protection Information Exchange Meeting, US Army Research Laboratory, Aberdeen Proving Grounds, MD, Oct 14-15, 2015, Robin ML, Chemours, Development of Zero ODP Low GWP Clean Agents.

10 Safety Data Sheet (SDS), (E)-1,1,1,4,4,4-Hexafluoro-2-butene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 28 Oct 2015.

11 Safety Data Sheet (SDS), Opteon™ 1150 Research Sample, Chemours, 1007 Market Street, Wilmington, DE 19899, 15 Dec 2016.

12 Estimated from cardiac sensitisation threshold limit: 469,670 mg/m^3 reported in reference 11.

13 Safety Data Sheet (SDS), Solstice® ZD, Solstice® 1233zd (E), Honeywell, 115 Tabor Road, Morris Plains, NJ 07950, 31 May 2016.

14 Technical Document, trans-1-Chloro-3,3,3-Trifluoropropene (1233zd(E)) WEEL Documentation, OARS, 2300 Montana Avenue, Suite 409, Cincinnati, OH 45211, 2013.

15 Brochure, Opteon™ 1100 Foam Blowing Agent, Chemours, 2016.

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17 Report, Hoffman GM, 2-Bromo-3,3,3-Trifluoropropene, E-1-Bromo-3,3,3-Trifluoropropene and 1-Bromo-2-Triflouromethyl-3,3,3-Trifluoropropene: An Acute (4-Hour) Inhalation Toxicity Study in the Rat Via Nose-Only Exposure, Huntingdon Life Sciences, Cambridgeshire, UK 02-5449, 14 Jan 2004.

18 Report, Horrel PJ et al. Agent 873: An Inhalation Study to Investigate the Cardiac Sensitization Potential in the Beagle Dog, Huntingdon Life Sciences, Cambridgeshire, UK, AAS 001/014630, 12 Sep 2002.

19 Report, Skaggs SR, Derivation of a Proposed Occupational Exposure Limit for 2-Bromo-3,3,3-Trifluoropropene, Universal Technical Services, Inc., 05 Dec 2014.

20 Memorandum, Army Public Health Center, MCHB-IP-TEP, 19 Aug 2015, subject: Occupational Exposure Limit Review for 2-Bromo-3,3,3-Trifluoro-1-Propene.

21 Brochure, Freon™ 123 Refrigerant (R-123) Properties, Uses, Storage, and Handling, Chemours, 2016.

22 Safety Data Sheet (SDS), Freon™ 123 (R-123) refrigerant, 2,2-Dichloro-1,1,1-trifluoroethane, Chemours, 1007 Market Street, Wilmington, DE 19899, 17 Oct 2018.

23 Technical Document, Hexafluoropropylene Emergency Response Planning Guideline, AIHA Guideline Foundation, Falls Church, VA 22042, 2009.

24 Safety Data Sheet (SDS), Octafluoro-2-butene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 03 Dec 2015.

25 Safety Data Sheet (SDS), 1,2,3,3,3-Pentafluoropropene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 28 Oct 2015

26 Safety Data Sheet (SDS), 2-Chloro-3,3,3-trifluoropropene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 10 Jul 2017

27 Safety Data Sheet (SDS), 1-Chloro-1,3,3,3-tetrafluoropropene, SynQuest Laboratories, P.O. Box 309 Alachua, FL 32615, 30 Nov 2017

28 Per ref. 29-30, AF11E is 99.5% R-123 with a proprietary additive. MW is the same but tox is very different with a reported NOAEL of 9% and rat LC50 >750,000 ppm.

29 Safety Data Sheet (SDS), Hartindo AF11E, Newstar Chemicals, 47500 Petaling Jaya, Selangor Darul Ehsan, Maylasia, 28 Dec 1994.

30 Brochure, AF11E, M-Fire Suppression, 19300 S. Hamilton Ave. #270, Torrance, CA 90248, http://www.mfiresuppression.com

31 Technical Document, NFPA 2001, Standard on Clean Agent Fire Extinguishing Systems, National Fire Protection Association, One Batterymark Park, Quincy, MA. 2018.

32 Naval Research Lab data, present report.

APPENDIX D. CANDIDATE AGENT THERMODYNAMIC, ENVIRONMENTAL, FIRE SUPPRESSION AND PHYSICAL PROPERTY DATA FOR USE IN PROFISSY AND REFPROP AGENT CALCULATIONS

	Halon 1301	HFC-227ea (FM200)	HFC-125 (FE-25)	2-BTP	Solstice PF[a] (Solstice 1233 zd)	Chemours TF-1 (FC-1)	Chemours SC-1	Chemours SC-2	Opteon 1100 (HFO-1336mzz-Z)	Opteon 1150 (HFO-1336mzz-E)
ODP	16	0	0	0.0028	0	0	0	0	0	0
GWP (100 year ITH)	6900	3350	2800	0.02	1	2	TBD	TBD	2	2
Flammability	Non	Non	Non	Non	Non	Non	Non	Non	Non	Non
Storage compatibility with $NaHCO_3$	Yes	Yes	Yes	No			Yes			
Molecular weight, g/mol	149	170	120	174.9	130	proprietary	proprietary	proprietary	164	164
Empirical formula	$CBrF_3$	C_3HF_7	CF_3CHF_2	$C_3H_2BrF_3$	$C_3H_2ClF_3$	proprietary	proprietary	proprietary	$C_4H_2F_6$	$C_4H_2F_6$
Boiling point, °C	-58	-16	-48	34	19	31	31	18	33	7.5 (Chemours) 8.5 (Synquest)
Heat of vaporization, J/g	117	133	164		194	122.1	165.7	195.3	165.7	152.4
Liquid density, g/mL	1.56	1.39	1.19 @ 25 °C	1.65 @ 25 °C	1.296	1.3 @ 25 °C	1.38	1.3	1.41 @ 4 °C	1.36 @ 20 °C
Cup burner value, %	3.04 (NRL) 4.2 (NFPA 12A)	6.51 (NRL) 6.7 (NFPA 2001)		4.63 (NRL) 4.8 (Kidde, 2014)	5.80 (NRL) 6.5 (NFPA 2001)	5.69 (NRL) 5.3 (Chemours)	6.74 (NRL) 5.6 (Chemours)	4.8 (Chemours)	7.43 (NRL)	3.60 (NRL)
Class A MDC, %		6.7	8.7		6.5	5.6	5.6	4.8		
Class B MDC, %	5.0	8.7	11.3	6.2	8.5	6.9	7.3	6.2	9.7	4.7
Class C MDC, %		7.0	9.0		6.5	6.3	6.3	5.0		
LOAEL, %	7.5	10.5	10.0	1 (Madden, 2014)	>10 → 2.5	12.5	2.5	>2.5	2.5	7.0
NOAEL, %	5.0	9.0	7.5	0.49 (Huntington, 2002)	10 → 2.5	10	1.25	2.5	1.3	7.0
Max 5-min exposure, %	7 (15 min)	10.5	11.5	1 (Madden, 2014)						
Specific volume a:	0.147810	0.126865	0.182600	0.122650	0.162769	0.097430	0.128906	0.162854	0.130841	0.128906
$S(m^3/kg) = a + bT(°C)$, b:	0.000567	0.000517	0.000700	0.000494	0.000692	0.000416	0.000539	0.000697	0.000528	0.000539
CAS	75-63-8	431-89-0	354-33-6	1514-82-5	102687-65-0	proprietary	proprietary	proprietary	692-49-9	66711-86-2
IUPAC name and structure	Bromo (trifluoro) methane ($CBrF_3$)	1,1,1,2,3,3,3-Heptafluoro-propane (CF_3-CHF-CF_3)	1,1,1,2,2-pentafluoro-ethane (CH_3-CHF_2)	2-Bromo-3,3,3-trifluoro-1-propene ($CF_3CBr{=}CH_2$)	Trans-1-chloro-3,3,3-trifluoropropene ($CF_3CH{=}CHCl$)	proprietary	proprietary	proprietary	(Z)-1,1,1,4,4,4-Hexafluoro-2-butene ($CF_3CH{=}CHCF_3$)	(E)-1,1,1,4,4,4-Hexafluoro-2-butene ($CF_3CH{=}CHCF_3$)
Feasibility - agent conc[b]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- cylinder size[c]	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	No
- stored energy[d]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[a]Solstice PF is “Solstice Performance Fluid” as well as Solstice 1233 zd.
[b]Agent concentration calculations require: MDC, L/NOAEL, specific volume formula (e.g., S=a+bT; NFPA 2001).
[c]Cylinder size calculations require: Thermodynamic and N_2 solubility properties versus temperature (e.g., PROFISSY), or laboratory measurements, as well as storage compatibility with $NaHCO_3$.
[d]Stored energy (nominal discharge effectiveness) calculation requires: liquid density (pressurized).

CAS = Chemical Abstract Services
GWP = global warming potential
ITH = integration time horizon
IUPAC = International Union of Pure and Applied Chemistry
LOAEL = lowest observed adverse effect level
MDC = minimum design concentration ODP = ozone depletion potential
NFPA = National Fire Protection Association
NOAEL = no observed adverse effect level
NRL = Naval Research Lab
ODP = ozone depletion potential
PROFISSY = properties of fire suppression systems
REFROP = reference fluid properties

Note:
Website references:
https://www.honeywell-solvents.com/resources/product-literature/
https://www.honeywell-refrigerants.com/india/?document=solstice-ze-hfo-1234ze-brochure-2012&download=1
http://msds-resource.honeywell.com/ehswww/hon/result/result_single_main.jsp?P_LANGU=E&P_SYS=1&C001=MSDS&C997=C100;E%2BC101;SDS_US%2BC102;US%2B1000&C100=E&C101=SDS_US&C102=US&C005=000000012546%20&C008=&C006=HON&C013=&
NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems

APPENDIX E. CANDIDATE ULTRASONIC SUSPENSION TESTING OF BLENDED FLUOROCARBON WITH SBCS

Ultrasonic and Suspension Evaluation

The purpose of the ultrasonic and suspension evaluation was to determine which unit was most effective for suspending the SBC slurry, and if different watt densities and frequencies affected the SBC slurry differently. If different watt densities and frequencies produced different results, the best combination was desired.

Initial testing was conducted using the BlueWave and the Advanced Sonics units for a quick visual assessment. For this test, 9 g of Cal Nano SBC was blended with 188 g HFC-227ea (~4.6 % w/w) in the Andrews Glass 24-in. Pressure Reaction Vessel (PRV). This slurry was ultrasonicated at full power in the BlueWave unit for 30 minutes. Initial findings were:

- 2x suspended height vs non-sonicated SBC, ~60 % overall suspension
- Re-suspends/blends easily
- Flows freely
- Still has visible particles and clumps/clusters

The same tube was then processed in the Advanced Sonics unit for progressively longer durations. After 20 minutes

- Less visible ultrasonication
- Not much change from BlueWave

After 30 minutes:

- Small amount of caking in bottom of tube (not in direct Sonics-path)

After 45 minutes:

- Settling with less ultrasonic cavitation in top half of tube
- Moderate settling/sediment in bottom of tube

This led to the belief that perhaps more/longer ultrasonic duration may not be better. An updated approach was planned for the following day.

Samples from the driest batches from Fluid Energy and Cal Nano were chose to be included in the expanded ultrasonic evaluation. Samples from Fluid Energy Bag 1 (FE1) and Cal Nano Jar 3 (CN3) were used. A similar 4 - 5 % w/w concentration was planned for use. In this test, both Honeywell agents were used (an ample supply was available), and a tube with HFC-227ea for easier comparison. Fill details for the test tubes are included Tables E-1 and E-2.

TABLE E-1. FILL INFORMATION, BLUEWAVE

Tube	SBC	Agent	Weight, g			%w/w
			SBC	Agent	Total	
1	FE1	ZE	9	186	195	4.8
2	CN3	ZE	12	199	211	5.6
3	FE1	FM200	10	205	215	4.6
4	FE1	PF	10	212	222	4.5
5	CN3	PF	12	182	194	6.1

TABLE E-2. INITIAL SBC SUSPENSION HEIGHTS AND LIQUID LEVELS

Tube	Height, mm	
	SBC	Liquid
1	95	370
2	50	395
3	105	310
4	95	340
5	90	395

The 5 tubes were then ultrasonicated using the BlueWave unit for incremental durations, starting with 1 minute. The blended agent was allowed to settle in the tubes after each ultrasonication and the new height was recorded. The tubes continued to be ultrasonicated until the heights began to decrease, which could indicate the maximum suspendability for that particular blend. Ultrasonication results are presented in Table E-3.

TABLE E-3. SBC HEIGHT (mm) AFTER ULTRASONICATION IN BLUEWAVE UNIT

Tube	BlueWave Ultrasonic Duration, min						
	0	1	2	3	4	5	10
1	95	165	225	210	N/A	N/A	205
2	50	80	80	85	N/A	N/A	85
3	105	210	230	230	235	225	225
4	95	175	210	215	230	225	210
5	90	185	240	250	260	255	235

Testing in the BlueWave unit showed that peak suspension occurred after approximately 4 minutes, and that extended exposure to the ultrasonics seemingly degraded the material.

Next, each Chemours agent was blended with a sample from FE1 and CN3. These agents were blended in the Andrews Glass 8-in. PRV to conserve material. Fill information is presented in Table E-4.

TABLE E-4. CHEMOURS FILL INFORMATION

Tube	SBC	Agent	Weight, g			%w/w
			SBC	Agent	Total	
1	CN3	SC1	5	100	105	4.8
2	FE1	SC1	5	100	105	4.8
3	FE1	TF1	5	100	105	4.8
4	CN3	TF1	5	100	105	4.8

A similar procedure was conducted with incremental ultrasonic testing in the BlueWave unit (table E-5).

TABLE E-5. CHEMOURS AGENTS - SBC HEIGHT (mm)
AFTER ULTRASONICATION IN BLUEWAVE

Tube	BlueWave Ultrasonic Duration, min					
	0	1	2	3	4	5
1	26	70	91	100	103	102
2	28	84	116	126	130	126
3	28	80	105	117	120	115
4	23	85	80	96	105	91

A set of 24-in. PRV tubes were prepared for Crest Testing. For this comparison test, HFC-227ea + SBCs was used since there is more information from past blending at ATC using HFC-227ea. All six tubes were filled with the same ratio of 10 g SBC (FE-1) and 200 g HFC- 227ea. FE-1 SBC was chosen because of the low moisture content and quantity available. For these measurements, the SBC height was measured in inches (table E-6).

TABLE E-6. CREST ULTRASONIC TESTING FILL INFORMATION

Tube	SBC	Agent	Weight, g			%w/w	Initial Height, in.
			SBC	Agent	Total		
1	FE1	FM200	10	200	210	4.8	4
2							4.375
3							4
4							4.5
5							4.5
6							4.375

Crest had multiple ultrasonic units available for use in the lab with a variety of frequencies and power densities. The test unit specifications are listed in Table E-7.

TABLE E-7. CREST ULTRASONIC SPECIFICATIONS

Unit	Frequency, kHz	Power, w/gal.
1	40	100
2	132	100
3	58	85
4	470	160
5	25	100
6	58/132 (dual)	200
7	40/58/132/192 (quad)	200

Testing was conducted with short exposures to the ultrasonics with time to settle prior to measurement. After exposure to the 470 kHz unit, the test tube did not show any noticeable change, so that tube was set aside and reused for the final test. Ultrasonic exposure continued until the SBC height stayed the same or decreased. Details of testing are described in the Table E-8.

TABLE E-8. SBC HEIGHT (in.) AFTER ULTRASONIC EXPOSURE, CREST

Tube	Unit	Ultrasonic exposure, s						24 hr rest	Change
		0	30	60	90	120	Final		
1	1	4	5.5	7.625	7.625	7.375	7.375	7.125	3.125
2	2	4.375	7.875	8.875	9	8.625	8.625	8.5	4.125
3	3	4	7.5	9.625	9.125	8.875	8.875	8	4
4	4	4.5	4.5	NA	NA	NA	4.5	NA	NA
5	5	4.5	7.75	9.625	10.5	10	10	8.625	4.125
6	6	4.375	9.875	9.75	NA	NA	9.75	8.125	3.75
4	7	4.5	9.5	9.125	NA	NA	9.125	8.625	4.125

This testing showed that the best suspension was achieved using either the 132 kHz unit, 25 kHz unit, or quad frequency (40/58/132/192) unit, but that all of the tubes achieved similar suspension with different exposure durations.

APPENDIX F. FIRE SUPPRESSION PERFORMANCE SCREENING METHODS AND MATERIALS COMPATIBILITY EVALUATION

Test summaries for ATC's initial evaluation of the newly constructed Hidden Fire Test Chamber and testing performed in the 8-ft^3 test chamber.

1. Hidden Fire Test Chamber

Six tests have been conducted using the Hidden Fire Test Chamber constructed at ATC based on the FAA/Kidde drawings. Initial testing has been used to compare validity and assess any shortcomings of the ATC fixture.

Initial tests show that the test fixture functions comparably to the FAA/Kidde fixture, and that going forward the ATC fixture should produce useful and valid test data. Details of testing are shown in Table F-1.

TABLE F-1. HIDDEN FIRE TESTING

Test	Agent	Total Weight, g	Empty Weight, g	Agent Weight, g	Discharge Time, s	Cups Extinguished
1	1301	2900	1700	1200	12	11
2	1301	3000	1700	1300	13.3	11
3	2-BTP	2745	1306	1430	8.9	6
4	1211	1658	524	1134	7.8	8
5	1211	1684	506	1178	8.1	7
6	HFC-227ea	3424	2040	1384	11.8	6

In both agent 1211 tests, a small amount of agent did not discharge from the bottle after the pressurization gas had evacuated. The 2-BTP extinguisher was put together using materials on hand at ATC and with the recommended fill ratios per AmPac (~65 % fill ratio). Test 4 was negligible, but in Test 5, 132 g did not discharge. The HFC-227ea unit was a non-SBC HPFE that was developed previously at ATC. Extensive hidden fire chamber testing was not conducted during the initial no/low GWP evaluation since the handheld extinguisher configurations were not optimized, and therefore likely not directly representative of realistic agent performance. The fixture can be utilized for comparison testing during future development work.

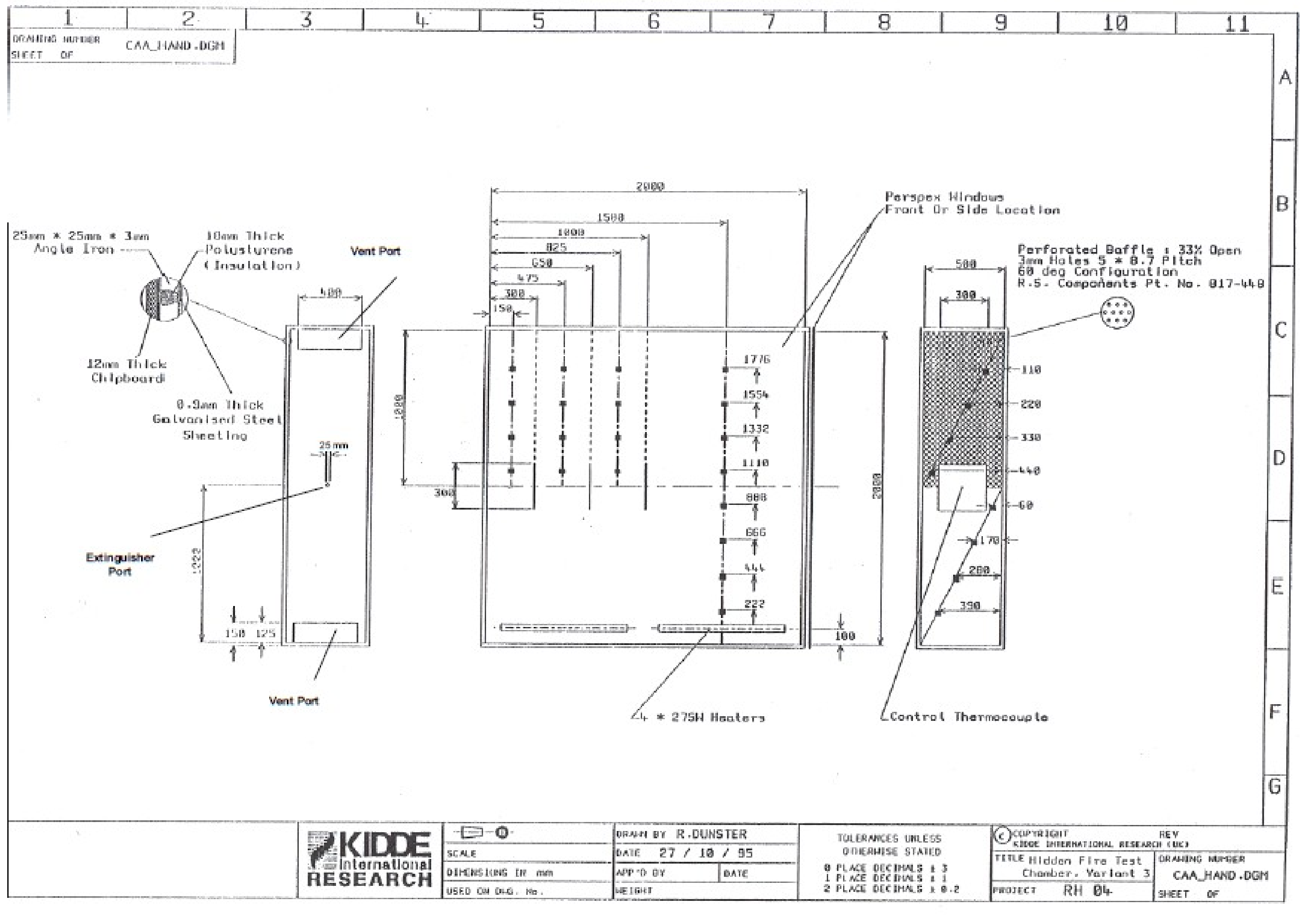

FIGURE A-3. HIDDEN FIRE TEST APPARATUS PLANS AND DIMENSIONS

Figure F-1. Drawing taken from DOT/FAA/AR-01/37 - Development of a Minimum Performance Standard for Hand-Held Fire Extinguishers as a Replacement for Halon 1211 on Civilian Transport Category Aircraft.

2. 8-ft^3 Chamber Testing

Preliminary testing was conducted to develop a repeatable method of discharging into the 8-ft^3 test chamber. The test setup consisted of a 500 ml Swagelok stainless pressure vessel plumbed to an inlet port on the test chamber. On the other side of the inlet port was a Swagelok tube that ran to the centerline of the chamber with a discharge nozzle on the end.

Using neat HFC-227ea with no pressurization gas, a repeatable setup was identified using a Spraying Systems 5.6W nozzle. This allowed for a ~10 sec discharge using 200 g HFC-227ea. This configuration easily extinguished the small cup fire but created a 12-percent HFC-227ea concentration in the chamber. Multiple tests were run using the FTIR to monitor agent concentration in the test chamber with the intention of finding a point where the amount of agent introduced can barely extinguish the fire, or has a ~50-percent success. With the amount of agent introduced at the edge of pass/fail, this should allow for a noticeable improvement in extinguishing ability once the SBC is added. Preliminary fire tests used a 1.5-in. round cup with 5-mL n-heptane and 10-ml water. Information from the initial testing is detailed in Table F-2.

TABLE F-2. INITIAL TESTING WITH HFC-227ea - 8-ft^3 CHAMBER

Test	Type	Agent Weight, g	Nozzle	Discharge Time, s	Fire Out, Y/N	Fire Out Time, s	FM-200 Conc, %
1	Discharge	200	ATC	3.3	NA	NA	NA
2	Discharge	200	SS	8.8	NA	NA	NA
3	Discharge	200	SS	6.7	NA	NA	NA
4	Fire	200	SS	9.5	Y	3.0	NA
5	FTIR	200	SS	10.1	NA	NA	12
6	FTIR	170	SS	7.7	NA	NA	10
7	Fire + FTIR	170	SS	8.4	Y	0.9	11
8	Fire + FTIR	140	SS	5.3	Y	2.0	8
[a]9	Fire + FTIR	140	SS	7.5	Y	5.8	8.6
[b]10	Fire + FTIR	140	SS	5.7	Y	3.7	8.4
[b]11	FTIR	110	SS	3.9	NA	NA	7.2
[b]12	FTIR	110	SS	4.1	NA	NA	7.1
[b]13	FTIR	80	SS	2.8	NA	NA	5.9

[a]Beginning in Test 9, the fire cup was elevated to approximately 9 in. from the base of the chamber.
[b]Beginning in Test 10, the FTIR sampling line was moved lower to the same height as the fire cup.

NA = not applicable

Following the chamber setup testing, multiple tests were conducted using the no/low GWP candidate agents. Additional modifications were made to the chamber since some of the no/low GWP agents had a higher boiling point and therefore were introduced as small liquid droplets. It was noted that if the liquid droplets fell directly into the fire cup, the amount required for extinguishment (g) would result in an artificially low extinguishing concentration (%). To prevent this, the fire cup remained 9 in. above the base of the chamber, but was moved to the corner of the chamber so it was not directly in the discharge path of the nozzle. Also, a perforated stainless baffle was constructed and placed over the cup. This allowed the cup to burn freely, but prevented liquid extinguishing agent droplets from landing directly in the fire cup. This setup is referred to as "NEW FIRE SETUP" in Table F-3. The details of the additional tests are presented in Table F-3.

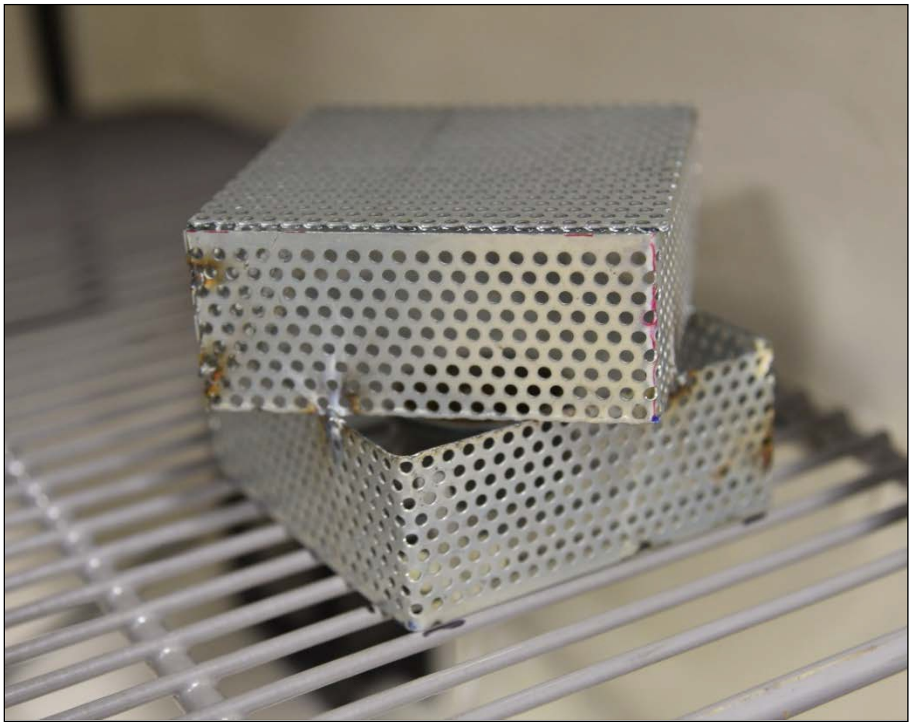

Figure F-1. Perforated stainless baffle constructed and placed over the fire cup in 8-ft^3 chamber testing.

TABLE F-3. DETAILS OF 8-ft^3 CHAMBER TESTING

Test Type	Agent	Agent Weight, g	SBC	SBC Concentration, % w/w	Discharge Time, s	Fire Out Time, s	Agent Concentration, %	HF Concentration	COF_2 Concentration	Note
								ppm		
Fire	FM200	90	-	-	7	NO	5.7	3800	N/A	
Fire	FM200	90	-	-	3.9	NO	6	3400	NA	
Fire	FM200	90	-	-	3.5	NO	5.9	3000	NA	
Fire	FM200	86	FE-1	4.5	3.4	2.6	5.7	0	0	
Fire	FM200	86	FE-1	4.5	4.4	NO	5.5	NA	NA	
Fire	FM200	86	FE-1	4.5	4.7	NO	5.4	~0	~0	
Fire	FM200	86	FE-1	5.3	3.3	2.3	5.5	0	0	
Fire	FM200	86	FE-1	4.5	3.5	3.5	5.4	0	0	
Fire	FM200	99	FE-1	4.5	4.8	4.9	6.1	0	0	
Fire	FM200	86	FE-1	4.5	3.2	4.1	5.1	0	0	
Fire	ZE	125	-	-	5.1	5.1	NA	-	-	ZE flammability check, no FTIR
Conc	ZE	80	-	-	3.3	-	7	-	-	
Fire	ZE	80	-	-	-	-	-	-	-	Agent burned violently
Fire	ZE	80	-	-	4.2	NO	7	6000+	3000+	
Fire	ZE	80	FE-1	4.25	3.5	NO	7	1800	750	SBC addition reduced acid gas production in failed fire test
Conc	ZD	100	-	-	4.1	-	9.2	-	-	
Conc	ZD	85	-	-	3.5	-	8.9	-	-	
Conc	ZD	85	-	-	3	-	8	-	-	
Conc	ZD	85	-	-	2.8	-	7.5	-	-	
Conc	ZD	85	-	-	3	-	8.2	-	-	
Conc	ZD	75	-	-	2.5	-	6.9	-	-	
Fire	ZD	75	-	-	3	3	8.3	0	0	
Fire	ZD	75	-	-	3.9	5	7.6	1000	400	
Fire	ZD	75	-	-	3.6	NO	7.8	2000+	2000	
Fire	ZD	73	FE-1	3.5	2.5	NO	6.2	4000	4000	
Conc	ZD	85	-	-	-	-	6.7	-	-	
Conc	ZD	85	-	-	-	-	6.7	-	-	
Conc	ZD	85	-	-	-	-	6.7	-	-	
Fire	ZD	90	-	-	-	YES	7.1	520	120	
Fire	ZD	85	-	-	3.2	2.6	6.7	260	40	
Fire	ZD	80	-	-	3	10.7	5.8	2000	400	

TABLE F-3 (CONT)

Test Type	Agent	Agent Weight, g	SBC	SBC Concentration, % w/w	Discharge Time, s	Fire Out Time, s	Agent Concentration, %	HF Concentration	COF_2 Concentration	Note
								ppm		
Fire	ZD	76	FE-1	4	2.3	1.5	6	73	<20	
Fire	ZD	72	FE-1	3.75	3.5	7.6	5.5	900	80	
Fire	ZD	77	FE-1	3.2	3.7	3.7	6	620	50	
Conc	BTP	88	-	-	3.6	-	5.3	-	-	
Fire	BTP	88	-	-	4.1	1.7	5.5	0	0	
Fire	BTP	70	-	-	3.5	2.1	4.4	0	0	
Fire	BTP	65	-	-	3.1	1.7	5.6	0	0	Recirculation fan added to all future tests
Fire	BTP	60	-	-	3.3	1.4	3.6	0	0	
Fire	BTP	50	-	-	2.6	1.4	3.1	0	0	
Fire	BTP	40	-	-	2.1	1.4	2.5	0	0	
Fire	BTP	30	-	-	2	1.4	1.9	0	0	
Tests conducted from this point forward use the NEW FIRE SETUP – cup placed in corner of chamber and covered with perforated baffle										
Fire	BTP	43	-	-	2.2	2	2.7	0	0	
Fire	BTP	20	-	-	1.4	NO	1.7	890	130	
Fire	BTP	25	-	-	1.7	NO	1.9	1000	110	
Fire	BTP	31	-	-	1.6	NO	2.3	1140	100	
Fire	BTP	31	-	-	2	16	2.3	890	110	
Fire	BTP	28	FE-1	1.5	4.2	NO	1.4	420	70	No fan - retest
Fire	BTP	28	FE-1	1.5	2.1	NO	1.6	330	70	
Fire	TF-1	100	-	-	2.8	NO	5.1	3690	670	
Fire	TF-1	150	-	-	4.4	7.3	7.4	1500	250	
Fire	TF-1	143	FE-1	7	4.4	10.1	7.1	1500	320	
Fire	TF-1	180	FE-1	7.6	6	6	8.6	840	200	
Conc	SC-1	149	-	-	-	-	9.5	-	-	
Fire	SC-1	150	-	-	3.3	5.7	9.7	219	73	
Fire	SC-1	146	FE-1	5	4.5	6.8	8.5	400	90	
Fire	BTP	70	-	-	1.5	2.7	4.2	13	18	
Fire	BTP	60	-	-	1.1	3.4	3.8	45	59	
Fire	BTP	60	FE-1	3	3	4	3.6	30	14	
Fire	BTP	62	FE-1	3	1.2	4.6	3.8	50	35	
Fire	ZD	76	FE-1	4	1.6	NO	6.2	1612	285	
Fire	ZD	91	-	-	2.5	13.5	7.7	1700	530	
Fire	ZD	90	-	-	2.7	NO	7	2500	650	
Fire	ZD	140	-	-	3	6.1	10.8	1400	500	

TABLE F-3 (CONT)

Test Type	Agent	Agent Weight, g	SBC	SBC Concentration, % w/w	Discharge Time, s	Fire Out Time, s	Agent Concentration, %	HF Concentration	COF_2 Concentration	Note
								ppm		
Fire	FE-1	28	FE-1	28	1	NO	NA	-	-	No nozzle, FE-1 only
Fire	KSA	28	KSA	28	3.3	1.3	NA	-	-	
Fire	FE-1	28	FE-1	28	Clog	NO	NA	-	-	Incomplete discharge - nozzle clog
Fire	KSA	15	KSA	15	1	NO	NA	-	-	KSA, no nozzle
Fire	KSA	15	KSA	15	1	NO	NA	-	-	KSA, with SS 5.6W
Fire	KSA	20	KSA	20	1.6	2.4	NA	-	-	
Fire	ZE	120	-	-	-	*	5.2	7500	11000	Violent reaction of ZE with flame
Fire	BTP	64	KSA	3	2.2	2.2	3.9	0	0	Comparison to Apr 19 Test 3
Fire	BTP	54	KSA	3	1.1	2.1	3.3	0	0	
Fire	BTP	53	KSA	2	1	1.6	3.3	4	0	
Fire	1211	57	-	-	2.3	2.3	*	0	0	FTIR concentration not available
Fire	1211	50	-	-	2.1	2.3	*	0	0	
Fire	1211	45	-	-	1.6	4.6	*	0	99	
Fire	1211	40	-	-	1.5	7.3	*	14	55	
Fire	BTP	30	KSA	1.5	0.7	NA	1.9	116	38	
Fire	BTP	48	KSA	2	1.9	2.1	2.9	0	0	
Fire	BTP	35	KSA	2	0.8	1.7	2.2	0	0	
Fire	BTP	33	KSA	1.5	0.7	NA	1.9	8	18	Questionable results, very little acid gas
Fire	BTP	33	KSA	1.5	0.6	NA	2	0	0	
Fire	BTP	33	-	-	0.6	3.2	2	44	2	Acid gas check
Fire	FM200	89	-	-	4.5	NO	5.8	2000	1000	Under match, acid gas check
Fire	FM200	90	-	-	5.8	NO	5.8	1500	850	
Fire	BTP	33	-	-	0.7	NO	2	217	60	
Fire	BTP	33	-	-	0.5	NO	2.1	186	70	No fan, no stainless baffle
Fire	BTP	33	-	-	1.2	4.7	2	224	14	No baffle, with fan
Fire	-	-	FE-1	28	-	-	-	-	-	Clog - dry powder only, did not flow
Fire	-	-	KSA	20	1	NO	-	-	-	KSA only

TABLE F-3 (CONT)

Test Type	Agent	Agent Weight, g	SBC	SBC Concentration, % w/w	Discharge Time, s	Fire Out Time, s	Agent Concentration, %	HF Concentration	COF_2 Concentration	Note
								ppm		
Fire	-	-	CN-3	28	-	-	-	-	-	Clog - dry powder only, did not flow
Fire	1301	82	-	-	0.6	0.7	4.7	0	0	
Fire	1301	58	-	-	0.2	1.7	3.4	0	5	
Fire	1301	49	-	-	0.1	1.2	2.7	2	4	
Fire	1301	24	-	-	0.1	6.3	1.3	0	52	
Fire	BTP	33	-	-	0.5	28	1.8	7	99	
Fire	BTP	33	-	-	0.6	26.3	1.8	124	67	
Fire	BTP	38	-	-	0.7	10.8	2.1	205	63	
Fire	BTP	43	-	-	0.7	9.8	2.4	185	39	
Fire	BTP	53	-	-	1	7.5	3.1	8	22	
Fire	BTP	60	-	-	1	5.1	3.4	425	44	
Fire	BTP	70	-	-	1.2	5.1	4.1	535	105	
Fire	BTP	80	-	-	1.6	2.2	4.5	76	76	
Fire	BTP	50	-	-	0.7	6.1	2.7	331	37	
Conc	1150	143	-	-	11	-	8.7	-	-	
Conc	1150	196	-	-	12.4	-	12.1	-	-	
Fire	1150	184	-	-	5	7.1	11.5	1066	255	
Fire	1150	177	-	-	6	5.9	11	1630	375	

Conc = concentration verification

Test Report Prepared by the Chemours Fluorochemicals Analytical Laboratory Evaluating the Compatibility of Agents and Sodium Bicarbonate

Stability Testing of SC-1 in the Presence of Sodium Bicarbonate (AA-1)

Work Performed by: Chemours Fluorochemicals Analytical Laboratory Wilmington, DE

Data Collected: June 2016

Report Written by: Hugh Mentz, Chemours Fluorochemicals

Background

The purpose of the testing described below was to investigate any reactivity that may result during storage of SC-1 fire extinguishing candidate agent in the presence of sodium bicarbonate (SBC). To assess the stability, samples of SC-1 were prepared with SBC powder then held for a 14-day exposure at both room temperature and 85°C. Following the exposure, visual inspection, purity, acidity and free fluoride ion results were compared.

Experimental

Thick walled borosilicate glass tubes were cleaned prior to use. The clean and dry glass tubes were moved to a bench top glove bag set-up. Each tube was purged with dry nitrogen before and after 0.3grams of dry sodium bicarbonate powder (AA-1) was added. The tubes were capped and stored in a desiccator. The tubes were evacuated before the SC-1 fire extinguishing candidate agent was loaded. One of the tubes were held at room temperature for 14 days and one was placed within an oven at 85°C for 14 days.

At the end of 14-day period, tube contents were visually examined for change in liquid color and cloudiness. After visual inspection the aged SC-1 was trans-loaded from the sample tubes into clean glass bottles for analysis, leaving the SBC behind. Aged SC-1 were analyzed for purity by GC/MS, acidity by titration, and free fluoride ion by ion chromatography (IC).

Summary of Test Results:

Ion chromatography (IC) was used to measure the level of fluoride ion present in the aged samples. Table 1 shows the levels of F^- in each tube aged in the presence of SC-1 agent and sodium bicarbonates (AA-1). These results shows that with sodium bicarbonate present, the levels of fluoride ion produced in SC-1 samples are below that of the detection limit of the method. Fluoride generation this low is an indication of good product stability.

Acid generation, which may result from deterioration or chemical breakdown of a halogenated material, was also measured. An acid titration method measured the generation of acidity, in terms of concentration (HCl equivalence), in the two types of samples. Table 1 shows that for the (AA-1) sample, the acid generated was minimal and would not be expected to affect the stability of the product.

Experimental Data

TABLE 1. STABILITY OF SC-1 WITH SBC (AA-1)

Sample ID	F, ppm	Acidity, ppm	Purity	Visual
SC-1 in contact with SBC (AA-1) for 14 days at room temperature.	<MDL	<MDL	No change	No visible change
SC-1 in contact with SBC (AA-1) for 14 days at 85 °C	<MDL	<MDL	No change	No visible change
	F^- MDL: 0.3 ppm	acidity MDL: 0.1 ppm		

MDL = method detection limit

Conclusions

A thick walled glass tube was loaded with SC-1 fire extinguishing candidate agent and sodium bicarbonate powder (AA-1). Air and moisture were minimized for these studies. The closed glass tube was aged at room temperature and 85°C for 14 days, respectively. In order to determine if any chemical reaction or degradation had occurred during the aging process, the contents were analyzed by ion chromatography, acid titration methods and GC/MS.

At the end of the 14-day aging the contents of the tubes were visually examined. The aged SC-1 sample was transferred into a clean sample bottles for further analysis leaving the SBC behind. Ion chromatography and acid titration methods were carried out on the aged SC-1 sample. Data collected is show above in Table 1. Fluoride levels were below the level of detection by the standard method for the aged material. Acidity measurements were below the level of detection as well in the aged sample. The GC/MS analysis show no material breakdown.

For a highly critical application, further testing at more aggressive test conditions may be needed. However, from the test conditions prescribed herein, signs of chemical instability or deterioration were not evident.

APPENDIX G. ATC PAN FIRE TESTING DATA FILE

Test	Cylinder	Agent	SBC	Nozzle	Pressure, psi	Weight, g		SBC w/w, %	Pan Size	Discharge Time, s	Fire Out	Agent Remaining, g	Comment
						Agent	SBC						
1	Amx 267	BTP	-	16 hole	80	1,431	-	-	2B	1.8	YES	904	
2	Amx 267	BTP	-	SS H6.5	240	1,434	-	-	2B	4	YES	867	
3	Amx 267	BTP	-	16 hole	80	1,450	-	-	3B	4.3	YES	410	
4	Amx 267	BTP	-	SS H6.5	240	1,420	-	-	3B	6.3	YES	517	
5	Amx 267	BTP	-	SS H6.5	240	1,439	-	-	3B	3.8	YES	891	
6	Amx 267	BTP	-	16 hole	80	1,421	-	-	4B	4.6	YES	271	
7	Amx 267	BTP	-	SS H6.5	240	1,395	-	-	4B	3.2	YES	940	
8	Amx 267	BTP	-	SS H6.5	240	1,425	-	-	5B	12.7	NO	17	
9	Amx 267	BTP	-	SS H6.5	240	1,460	-	-	5B	10	NO	24	
10	Amx 267	BTP	-	16 hole	80	1,190	-	-	4B	2.8	YES	417	
11	Amx 267	Opteon 1150	-	SS H6.5	240	1,660	-	-	4B	17	NO	481	
12	Amx 267	BTP	KSA	16 hole	230	1,420	70	4.9	5B	5.8	NO	0	
13	Amx 267	ZD	KSA	SS H6.5	230	1,320	65	4.9	2B	12.2	NO	0	
14	Amx 267	ZD	KSA	16 hole	230	1,320	65	4.9	2B	6.2	NO	0	
15	Amx 267	ZD	-	16 hole	230	1,297	-	-	4B	7.4	NO	0	
16	Amx 267	ZD	-	SS H6.5	230	1,330	-	-	4B	12	NO	0	
17	Amx 267	ZD	-	16 hole	230	1,328	-	-	2B	7.9	NO	0	
18	Amx 267	ZD	-	16 hole	80	1,076	-	-	2B	8.7	NO	0	
19	Amx 267	ZD	FE-1	16 hole	80	1,031	45	4.4	2B	8.1	NO	0	
20	Amx 267	SC-1	-	16 hole	80	1,223	-	-	2B	8.4	NO	0	
21	Amx 267	ZD	-	BETE P190	230	1,066	-	-	2B	NA	NO	0	
22	Amx 267	ZD	FE-1	BETE P190	230	1,020	42	4.1	2B	4.1	NO	900	
23	Amx 267	Opteon 1150	FE-1	16 hole	230	1,518	70	4.6	2B	6.9	NO	0	
24	PemAll	Opteon 1150	FE-1	16 hole	230	1,216	70	5.8	2B	6.2	NO	0	Swing arm discharge w/ horn
25	Amx 267	Opteon 1150	-	16 hole	230	1,379	-	-	2B	6.9	NO	0	
26	Amx 267	Opteon 1150	-	BETE P190	230	1,417	-	-	2B	7.8	NO	0	
27	Amx 1211	ZD	-	1211 Amx	130	1,550	-	-	2B	7.4	NO	0	
28	Amx 1211	ZD	-	1211 Amx	130	1,525	-	-	2B	6.7	NO	0	
29	Amx 1211	ZD	-	16 Hole	130	1,520	-	-	2B	4.1	YES	328	
30	Amx 1211	ZD	-	16 Hole	130	1,506	-	-	3B	8	NO	0	
31	Amx 1211	ZD	-	16 Hole	130	1,520	-	-	3B	8.1	NO	0	
32	Amx 1211	ZD	-	16 Hole	130	1,510	-	-	3B	6.5	NO	0	
33	Amx 1211	ZD	FE-1	16 Hole	130	1,422	75	5.0	3B	3.6	YES	454	
34	Amx 1211	ZD	FE-1	16 Hole	130	1,456	75	4.9	3B	4.5	YES	222	
35	Amx 1211	ZD	FE-1	16 Hole	130	1,410	75	5.1	4B	6.6	NO	0	
36	Amx 1211	ZD	FE-1	16 Hole	130	1,408	75	5.1	4B	6.2	NO	0	
37	Amx 1211	ZD	FE-1	1211 Amx	130	1,400	75	5.1	4B	6.7	NO	0	
38	Amx 1211	ZD	FE-1	1211 Amx	130	1,405	75	5.1	4B	6.2	NO	0	
39	Amx 1211	ZD	KSA	16 Hole	130	1,454	76	5.0	3B	7.5	NO	0	
40	Amx 1211	ZD	KSA	16 Hole	130	1,416	77	5.2	3B	7.3	NO	0	

APPENDIX G (CONT)

Test	Cylinder	Agent	SBC	Nozzle	Pressure, psi	Weight, g		SBC w/w, %	Pan Size	Discharge Time, s	Fire Out	Agent Remaining, g	Comment
						Agent	SBC						
41	Amx 1211	ZD	KSA	1211 Amx	130	1,420	75	5.0	3B	7	NO	0	
42	Amx 1211	ZD	KSA	1211 Amx	130	1,420	77	5.1	3B	7.9	NO	0	
43	Amx 1211	ZD	KSA	1211 Amx	130	1,420	76	5.1	3B	5.9	NO	0	bottle not shaken, better pushback
44	Amx 1211	ZD	KSA	1211 Amx	130	1,420	77	5.1	3B	6.4	NO	0	bottle not shaken, better pushback
45	Amx 1211	ZD	KSA	1211 Amx	130	1,366	150	9.9	3B	3.8	YES	452	10% SBC concentration
46	Amx 1211	ZD	KSA	1211 Amx	130	1,380	150	9.8	3B	4.7	YES	225	10% SBC concentration
47	Amx 1211	ZD	KSA	1211 Amx	130	1,348	150	10.0	4B	7.2	NO	0	
48	Amx 1211	ZD	KSA	1211 Amx	130	1,344	150	10.0	4B	7.4	NO	0	
49	Amx 1211	ZD	KSA	1211 Amx	130	1,352	150	10.0	4B	8.1	NO	0	
50	Amx 1211	ZD	KSA	1211 Amx	130	1,350	150	10.0	4B	7.5	NO	0	
51	Amx 1211	2-BTP	-	1211 Amx	130	1,944	-	-	4B	3.3	YES	844	
52	Amx 1211	2-BTP	-	1211 Amx	130	1,950	-	-	5B	3.8	YES	669	
53	Amx 1211	2-BTP	-	1211 Amx	130	1,954	-	-	5B	2.7	YES	846	
54	Amx 1211	Opteon 1150	-	1211 Amx	130	1,624	-	-	2B	4.5	YES	756	
55	Amx 1211	Opteon 1150	-	1211 Amx	130	1,620	-	-	2B	2.3	YES	914	
56	Amx 1211	Opteon 1150	-	1211 Amx	130	1,602	-	-	3B	2.9	YES	740	
57	Amx 1211	Opteon 1150	-	1211 Amx	130	1,604	-	-	4B	6.2	NO	0	
58	Amx 1211	Opteon 1150	-	1211 Amx	130	1,620	-	-	4B	6	NO	0	
59	Amx 1211	Opteon 1150	-	1211 Amx	130	1,628	-	-	3B	6.9	NO	0	
60	Amx 1211	Opteon 1150	FE-1	1211 Amx	130	1,538	80	4.9	3B	8.4	NO	0	Poor flow with SBC, discharge rate too slow. Discharge time recorded was only during fire attempt – additional agent remained after extinguishing attempt aborted
61	Amx 1211	Opteon 1150	FE-1	1211 Amx	130	1,490	80	5.1	3B	6.3	NO	0	
62	Amx 1211	Opteon 1150	FE-1	1211 Amx	130	1,520	80	5.0	3B	6.8	NO	0	
63	Amx 1211	Opteon 1150	FE-1	16 Hole	130	1,528	80	5.0	3B	5.6	NO	0	
64	Amx 1211	Opteon 1150	FE-1	1211 Amx	130	1,520	80	5.0	3B	6	NO	0	
65	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,500	75	4.8	2B	10.1	NO	0	
66	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,490	75	4.8	2B	10	NO	0	
67	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,515	75	4.7	2B	9	NO	0	
68	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,505	75	4.7	2B	10.3	NO	0	
69	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,515	75	4.7	2B	5	YES	497	
70	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,515	75	4.7	2B	4.5	YES	511	
71	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,525	75	4.7	3B	2.2	YES	1031	
72	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,515	75	4.7	3B	8.4	NO	0	
73	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,505	75	4.7	3B	11	NO	0	
74	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,500	75	4.8	3B	3.1	YES	701	
75	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,500	75	4.8	3B	10	NO	0	
76	Amx 1211	Opteon 1150	KSA	1211 Amx	130	1,520	75	4.7	3B	NA	-	0	Discharge practice
77	Amx 1211	Opteon 1100	-	1211 Amx	130	1,504	-	-	2B	8.8	NO	0	
78	Amx 1211	Opteon 1100	-	1211 Amx	130	1,490	-	-	2B	5.9	NO	0	
79	Amx 1211	Opteon 1100	-	1211 Amx	130	1,508	-	-	2B	7.5	NO	0	
80	Amx 1211	Opteon 1100	-	1211 Amx	130	1,492	-	-	2B	6.5	NO	0	
81	Amx 1211	Opteon 1100	-	1211 Amx	130	1,510	-	-	2B	7.5	NO	0	
82	Amx 1211	Opteon 1100	-	1211 Amx	130	1,502	-	-	2B	3.3	YES	411	

APPENDIX G (CONT)

Test	Cylinder	Agent	SBC	Nozzle	Pressure, psi	Weight, g		SBC w/w, %	Pan Size	Discharge Time, s	Fire Out	Agent Remaining, g	Comment
						Agent	SBC						
83	Amx 267	Opteon 1100	-	SS H6.5	250	1,006	-	-	2B	10.2	NO	0	Increased pressure, smaller cylinder
84	Amx 267	Opteon 1100	-	SS H6.5	250	1,007	-	-	2B	11	NO	0	Increased pressure, smaller cylinder

Note: The fuel employed in this testing was JP-8.

APPENDIX H. POTENTIAL BLENDED FLUOROCARBON/SBC AGENT AND DRY POWDER DEVELOPMENT APPROACHES FOR FUTURE TESTING

This appendix summarizes recommendations for future work in the following three areas:

- SBC dry powders - improvements in flow, reduction in particle size, improvements in air suspendability.
- Low ambient temperature fire suppression performance - lower boiling candidates.
- Engine nacelle testing of 2-BTP and 2-BTP/SBC.

These areas are covered below.

1. SBC dry powder related recommendations:

Both micron and nanometer SBC particles of two distinct morphologies have been prepared in past work on SBC additives to enhance agent extinguishment performance. These are described below followed by a description of material property issues relevant to the recent testing and potential approaches to future testing and development of more effective SBC powders.

Needle-like particles with dimensions in the range of 20 to 50 nm in width and 50 to 100 nm in length were generated by Nanomaterials Company (now out of business) using a spray based process where droplets were quick frozen leading to fast crystallization in dendritic needle-like clusters in some cases and single needles in others. This experimental product (270 g in total) was free flowing even after nearly a year of storage. Initial pan-fire extinguishment tests at 5-percent loadings in HFC-227ea with this product elicited remarks by the fire fighter of “wow that was like halon” - words that are seldom, if ever, heard. Anecdotal evidence indicated that when discharged into the test area in non-fire tests, the particles could be seen glimmering in the sunlight staying suspended in the room air and slowly dissipating but not settling as the discharge plume dispersed into the warehouse-sized test area. This was predicted based on aerodynamic properties of small nano particles. The possibility that a more total flood volume inertion quality might be realized if this type of SBC powder was employed by itself or as blends was obvious. Unfortunately, as indicated, the sole source of this material is no longer in business, however the technology development was well described in project reports provided quarterly to ATC. This is not the only approach to forming these needle-like SBC powders, as similar results were seen on very small scale with Buchi spray driers in limited testing.

The second particle morphology previously prepared is more regular (like a table salt grain shape) and has cubic or near cube-like particles, some irregular in shape, with dimensions in the range of 2 μm (20 times the largest length and 100 times the typical width of the needle particles described above). These powders were prepared on different occasions by two vendors (Fluid Energy Inc. and Sturtevant, Inc.). The powders were prepared from USP grade SBC by jet milling at room temperature employing either dried air or liquid N_2 boil-off as the process gas, and were free flowing materials that stayed free flowing (all storage and handling in a dry box at <1% relative humidity). These SBC powders were very effective in enhancing the performance of HFC-227ea in pan fire tests and have been adopted for this use. (Note: The use of USP-grade SBC was to ensure the quality and minimal inhalation toxicity of resultant powders and simplify approvals. Other grades might also be equally overall acceptable but were not evaluated.)

Anticaking compounds applied to the SBC powders do result in free-flowing powders but also generally can make adequate clean-up of discharged agent more difficult or even impossible. A search for sufficiently dry anticaking agents with low inhalation toxicity and adequate ability to prevent particle to particle salt bridging, which causes caking and clumping of the SBC, would be a worthwhile effort. An anticaking agent with these properties would likely be completely soluble under clean-up conditions and could be a big step forward in SBC blend performance.

An evaluation of SBC and fluorocarbon compatibility, including accelerated aging tests, will need to be performed on proposed SBC/fluorocarbon agent candidate pairs. New specifications for water content of the SBC and the fluorocarbon will need to be set based on performance in aging studies. In addition, initial fluorocarbon acidity will need evaluation to assure the most stable fielded performance of blended agents. It is likely that fluorocarbon water content limits considerably lower than the current 10 ppm level set for some HFCs would greatly benefit blended agent stability.

The water content of fluorocarbons employed in creating the fire suppressant blend with SBCs is a known factor in the stability of the resulting blended fire extinguishing agent. Efforts to identify optimal water limits and specify those reduced limits depend in part on the identification or development of analytical methods with low water quantification limits. Current limits for quantification of water content are likely too high to be of use in monitoring water content below 1 ppm. The standard Karl Fischer method might be readily modified to achieve lower quantification limits or, alternatively, existing methods perhaps based on gas chromatography or electrical conductivity could be modified to allow sub ppm water quantification limits. SBC water limits of less than 500 ppm are achievable and are expected to improve performance. Solvent extraction and gas chromatography based methods for characterization of SBC water content to levels as low as 100 ppm have been demonstrated.

Potential improvements to the previous method of jet milling SBC to further reduce particle size and moisture content (reduce particle clumping) which would improve the free-flowing characteristics desired for blending stability, discharge, and dispersion of blended agents have been identified. Similarly, approaches to overcoming the caking/clumping seen in the prior cryo-milling process attempts are also covered. These potential approaches are listed in two groups with the first covering the easier less costly and the second covering the more technically challenging.

The easier and less complicated approaches to SBC particle size reduction and powder flowability improvements for jet-milling and cryo-milling SBC products include:

- Jet-milling of mixtures of SBC with 1- to 2-percent of an anticaking compound added to improve followability of the product. At this early stage, the goal is to show that the addition of an anticaking agent produces a powder with improved flow.
- Jet-milling of existing commercial free-flowing SBC powders that incorporate anticaking agents may afford a still free-flowing non-caking SBC powder with particle sizes in the low micron size range. It is possible that this approach may result in the loss of some of the anticaking agent affecting the powders free-flowing non-caking performance, but the cost of such a test is minimal and if successful would afford an easy low cost solution to the flow and caking problem.

- Jet-milling of SBC and other sodium, potassium, or calcium salts in ratios of 95-percent SBC to 5 wt % other salts (carbonates or bicarbonates) to interfere with particle to particle adhesion and improve followability. At this early stage the goal is to show that addition of an anticaking agent produces a powder with improved flow.
- Addition of anti-caking compounds to existing cryo-milled SBC in liquid N_2 processing to keep the apparently small particles generated from clumping together;
- Addition of anti-caking compounds to existing jet-milled SBC in processing to keep the micron-sized particles that are generated from clumping together, and to provide a more free-flowing powder during milling.
- Fluid Energy employs a variety of methods in milling. In past work, they used an 8-inch jet mill to produce product that had a mean diameter of 2.5 μm. At the time, they spoke of attaching a "Classifier" to the jet mill to only allow the smaller particles to exit the attrition milling process. The finer material that did exit would be collected and characterized. This was not tried but would be a relatively easy thing to attempt to evaluate a test batch. The evaluation would include addition of anti-caking agents in some milling tests.
- Use of differently sourced SBC (Solvay process, Soda Ash process, Mined SBC) is worth looking into to see if the materials have different friability characteristics that may result in easier breakup in milling processes and in smaller particle sizes (applied to both jet-milling and cryo-milling processes.
- A search of existing anticaking technologies and vendors to identify existing coatings that afford a free flowing SBC with no caking tendencies at low trace water levels, yet that dissolve under conditions of water based clean-up would be beneficial to the development of optimal blended agent SBC powders.

The less easy, untried approaches to particle size reduction to yield SBCs with nanometer particle dimensions and flow improvements include:

- Cryo-milling (Cal Nano method) of SBC in fluorocarbons instead of liquid N_2. Milling could be performed with and without added anticaking agents. Isolation of the milled SBC may not be required if the fluorocarbon used is a component of the agent blend.
- Spray drying which requires ultrasonic nebulizing spray heads that spray low concentration of SBC in liquid (methanol, water, isopropyl alcohol, ethanol) into cryogenic conditions. Post production requires separation to drain excess liquid and lyophilisation to remove solvent residue. This process can produce needle-like crystals which could reduce or eliminate the need for anticaking agents.
- As a low cost feasibility check, perform initial testing (Q&D) by preparing 1-percent SBC in solvent at room temperature then spray using a nebulizing spray into a stirred cryogenic vat of solvent under a blanket of N_2 to prevent H_2O uptake, filter, recover, and air dry. Do a SEM to see crystal shape if submicron needles go on to phase 2.

2. Low Boiling Agent Candidate Recommendations:

A number of low boiling candidate agents (all fluoroalkenes) were identified but not tested as they were of limited availability, expensive, had unknown toxicities, and therefore posed challenges to the limited resources available for this project. These compounds offer lower boiling points with potential to improve agent space-filling performance in crew areas, hidden fire threatened spaces, low temperature operational conditions, and related applications. These compounds should be tested if conventional options show less than acceptable performance. Though they are research chemicals, commercial interest will develop if tests prove promising.

3. Engine nacelle related recommendations for testing of 2-BTP and SBC powders.

A review of the test report provided in Appendix K shows a need to address several testing related needs in order to better identify agent and agent blend relative performance rankings, to avoid loss of SBC agent component internal to the gNFS, and to better compare the effects of particle size and suspendability of SBCs on undesirable post extinguishment events identified in this testing and the earlier testing done on 2-BTP. Those areas are:

- SBC powder discharge uniformity: a visual evaluation of discharge uniformity may help assure that these tests are not affected by plug flow or plumbing issues.
- SBC powder particle size effects on agent quantities needed for extinguishment and optimal performance. Testing with small particle size SBCs and experimenting with plumbing along with discharge nozzle design/orientation in an effort to maximize suspension of the SBCs within the gNFS and uniformity of the SBCs discharge during the gNFS fire event may aid in lengthening the re-ignition time delay (RTD).

APPENDIX I. CREW COMPARTMENT TESTING DATA SET

TABLE I-1. ATC LOW GWP AGENT LIVE FIRE TEST RESULTS SUMMARY

Test	Date	Agent	No. of F/X	Total mass, lb		Total Agent, lb	Clutter, Y/N	K[a]	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash		Oxygen Min, %	Maximum					5 min TWA, ppm		Comment
				Gas	DC								Start after Fire Out, ms	Peak BOP, psi		Agent, %	CO, ppm	CO_2, %	COF_2, ppm	HF, ppm	Avg COF_2	Avg HF	
21	2-Oct	1100BC	2?	5.6	0.44	6.04	N	2.94	230		2.98	113			5.2	7.5	30,221	6.1	9,984	10,652			Very high by-product
17	1-Oct	1100BC	2	8.1	0.88	8.98	N	2.73	210		1.44	121			16.5	12.1	1,703	1.2	18	< 20			Low by-product, Alden: This is trial 16 by our records.
74	16-Nov	1100KSA	2	8.1	0.88	8.98	Y	2.85	213		3.13	127.82			15.6	11.7	5,657	2.1	198	< 20			42 ms response
75	16-Nov	1100KSA	2	8.1	0.88	8.98	Y	2.59	229		2.54	122.28			15.9	11.8	4,451	1.8	97	< 20			
56	16-Oct	1150BC	2	2.88	0.88	3.76	N	2.35	211		3.46	108.4	1,200	4.32	8	2	3,189	> 6.3	95	3,691	18	1916	4,100 ms approx total fire time, Reflash, 49 ms response
57	16-Oct	1150BC	2	2.88	0.88	3.76	Y	3.06	190		3.01	114.3		3.77	8.9	2.3	10,020	> 6.3	110	7,239	22.5	2232.5	1,539 ms total fire duration? Reflash 46 ms response
25	3-Oct	1150BC	2	3.4	0.88	4.28	N	3.27	2,000		3.91	96	TBD	TBD	9.6	< 1	21,854	> 6.3	110	7,124	14	3728	Very high by-product
26	3-Oct	1150BC	2	5.76	0.88	6.64	N	2.59	205		1.13	103			16.7	7.4	1,895	1.3	45	28	<10	<20	Low by-product
13	26-Sep	1150BC	1	4	0.4	4.4	N	3.13	1,380		2.26	126	TBD	TBD	7.2	< 1	25,190	> 6.3	323	11,824	40	4085.5	Very high byproduct, Alden: This is trial 12 by our records and the dry chem is KSA.
11	25-Sep	1150BC	1	4	0.4	4.4	N	2.34	>1,400		2.6	178	TBD	TBD	7.06	2.4	24,671	> 6.3	212	9,755	17.5	2963.5	Very high by-product
10	25-Sep	1150BC	2	5.76	0.88	6.64	N	1.33	372		3.04	157			16.2	7	3,744	2.2	43	28	<10	<20	low by-product
6	24-Sep	1150BC	2	5.76	0.88	6.64	N	0.42	495		1.13	109	TBD	TBD	17.5	7.5	1,611	0.8	51	< 20	<10	<20	low by-product

TABLE I-1 (CONT)

Test	Date	Agent	No. of F/X	Total mass, lb: Gas	Total mass, lb: DC	Total Agent, lb	Clutter, Y/N	K[a]	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash: Start after Fire Out, ms	Reflash: Peak BOP, psi	Oxygen Min, %	Maximum: Agent, %	Maximum: CO, ppm	Maximum: CO_2, %	Maximum: COF_2, ppm	Maximum: HF, ppm	5 min TWA, ppm: Avg COF_2	5 min TWA, ppm: Avg HF	Comment
69	14-Nov	1150KSA	1	1.44	0.88	2.32	Y	2.52	2,321		2.26	148.69		1.56	10	< 1	19,233	6.5	120	1,953	<10	1481.5	55 ms response, Note: residual flow and significant KSA caking observed, much colder ambient temp during test than previous testing
70	14-Nov	1150KSA	2	5.76	0.88	6.64	Y	2.66	229		2.92	132.69			17.2	6.5	4,224	1.8	145	< 20	20.5	<20	44 ms response, 750 psi, Note: residual flow and significant KSA caking observed, much colder ambient temp during test than previous testing
71	14-Nov	1150KSA	2	5.76	0.88	6.64	Y	2.61	274		2.5	130.56			17.2	6.5	4,003	1.7	109	< 20	12	<20	45 ms response, 750 psi, Note: residual flow and significant KSA caking observed, much colder ambient temp during test than previous testing
72	14-Nov	1150KSA	2	2.88	0.88	3.76	Y	2.05	202		3.08	138.1	486	2.985	NA[b]	1.2	18,322	7.6	268	6573	48.5	1942.5	44 ms response, 750 psi, Note: residual flow and significant KSA caking observed, much colder ambient temp during test than previous testing
51	15-Oct	1150KSA	2	2.88	0.88	3.76	Y	3.04	190		2.68	104			17.4	3.4	1,865	1.4	< 10	< 20	<10	<20	
52	15-Oct	1150KSA	2	2.88	0.88	3.76	Y	2.8	214		3.62	102			17.1	3.4	2,696	1.8	< 10	< 20	<10	<20	Low by-product, 49 ms response

TABLE I-1 (CONT)

Test	Date	Agent	No. of F/X	Total mass, lb: Gas	Total mass, lb: DC	Total Agent, lb	Clutter, Y/N	K^a	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash: Start after Fire Out, ms	Reflash: Peak BOP, psi	Oxygen Min, %	Maximum: Agent, %	Maximum: CO, ppm	Maximum: CO_2, %	Maximum: COF_2, ppm	Maximum: HF, ppm	5 min TWA, ppm: Avg COF_2	5 min TWA, ppm: Avg HF	Comment
53	15-Oct	1150KSA	2	1.44	0.88	2.32	Y	3.01	164		2.96	93.7			17.7	1.6	1,622	1.2	< 10	< 20	<10	<20	Low by-product, 51 ms response
36	9-Oct	1150KSA	2	5.76	0.88	6.64	N	2.6	131	74	2.9	100			16.9	6.9	1,749	1.3	< 10	< 20	<10	<20	
38	9-Oct	1150KSA	2	5.76	0.88	6.64	Y*	1.9	190	74	2.6	86			16.5	8.6	2,050	1.5	< 10	< 20	<10	<20	*Clutter adjusted in subsequent tests: one ammo can was placed thwart in front of FBG.
40	9-Oct	1150KSA	2	5.76	0.88	6.64	Y	2.8	219	72	2.5	99			16.5	7.5	2,747	1.7	11	< 20	<10	<20	
67	19-Oct	1233BC	2	6.73	0.88	7.61	Y	3.08	329		2.12	190.8			16	17.7	3,700	1.7	112	517			49 ms response
63	18-Oct	1233BC	2	6.73	0.88	7.61	Y	3.34	300		2.11				12.2	17.2	3,559	1.7	107	560			46 ms response, HCL: 120ppm
5	21-Sep	1233BC	2	6.73	0.88	7.61	N	2.15	TBD		2.45	121	TBD	TBD	6.5	17.4	35,551	> 6.3	2,012	9,502			Alden: HCl max=14,362
64	18-Oct	227BC	1	1.1	0.88	1.98	Y		2,388		2.47	122	402	0.95	9.1	0.3	15,148	> 6.3	< 10	1,012	<10	505	5 ms 0.373, 10 ms 0.53
59	17-Oct	227BC	2	1.1	0.88	1.98	Y	2.75	172		3.1	91.1			17.8	1.4	1,141	1.1	< 10	< 20	<10	<20	54 ms response
55	16-Oct	227BC	2	1.1	0.88	1.98	Y	3.45	156		3.63	90.2			17.8	1.4	1,288	1.1	< 10	< 20	<10	<20	Low by-product, 38 ms response
1	19-Sep	227BC	2	8.8	0.88	9.68	N	1.17	239		1.45	87			16.6	10.7	1,084	0.7	27	< 20	<10	<20	
2	19-Sep	227BC	2	4.4	0.88	5.28	N	2.78	208		2.12	106			17.3	5.3	1,497	0.9	56	BDL	15	<20	
77	19-Nov	227KSA	1	4.4	0.44	4.84	Y	2.64	406		3.119	132.56			17.1	5.6	3,821	2.2	202	33	16.5	<20	44 ms response
78	19-Nov	227KSA	1	2.2	0.44	2.64	Y	1.7	257		2.699	111.54			18.2	2.6	1,808	1.7	60	24	<10	<20	42 ms response
79	19-Nov	227KSA	1	1.1	0.44	1.54	Y	2.15	262		3.042	115.77			18.3	1.6	1,514	1.7	< 10	28	<10	<20	46 ms response
80	19-Nov	227KSA	1	1.1	0.44	1.54	Y	2.13			2.253	94.12	TBD		6.8	0.4	10,404	6.8	41	286	<10	66	42 ms response
39	19-Nov	227KSA	2	4.4	0.88	5.28	Y	2.5	175	67	2.1	101			17	5.6	1,860	1.2	< 10	< 20	<10	<20	
45	19-Nov	227KSA	2	2.2	0.88	3.08	Y	3.22	109, 161	66	2.65	84											No Chemistry, no reflash

TABLE I-1 (CONT)

Test	Date	Agent	No. of F/X	Total mass, lb Gas	Total mass, lb DC	Total Agent, lb	Clutter, Y/N	K[a]	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash Start after Fire Out, ms	Reflash Peak BOP, psi	Oxygen Min, %	Maximum Agent, %	Maximum CO, ppm	Maximum CO_2, %	Maximum COF_2, ppm	Maximum HF, ppm	5 min TWA, ppm Avg COF_2	5 min TWA, ppm Avg HF	Comment
49	19-Nov	227KSA	2	2.2	0.88	3.08	Y	2.5	125, 200	75	2.54	91			17.8	2.8	1,841	1.2	< 10	< 20	<10	<20	
66	19-Oct	2BTPBC	2	2.65	0.88	3.53	Y	2.5	200		2.15	106.42			17.6	4.6	1,393	0.9	21	< 20			54 ms response
62	18-Oct	2BTPBC	2	5.3	0.88	6.18	Y	2.33	175		2.34				17	8.5	2,300	1.1	63	< 20			45 ms response
14	26-Sep	2BTPBC	2	5.3	0.53	5.83	N	2.45	132		1.71	126			17.3	8.9	1,506	0.9	51	230			Some by-product, Alden: This is trial 13 by our records and 0.56 Kiddex not 0.53.
34	9-Oct	KSA	1	0	1.29	1.29	N	3.6	252	76	2.98	124			18.7	NA	1,365	1.7	< 10	< 20			
42	9-Oct	KSA	1	0	1.29	1.29	Y	2.92	208	81	1.886	127	226	1									No Chemistry, reflash
43	9-Oct	KSA	1	0	1.29	1.29	Y	3.15	190	65	1.82	128	238	1									No Chemistry, reflash
48	9-Oct	KSA	1	0	1.29	1.29	Y	2.3	206, 258	70	1.56	129											No Chemistry
29	4-Oct	KSA	1	0	0.88	0.88	N	2.57	1,097		2.88	120	TBD	TBD									
32	4-Oct	KSA	1	0	1.29	1.29	N	2.73	296		1.79	111											
16	1-Oct	KSA	1	0	0.44	0.44	N	2.36	1,900		2.8	116	TBD	TBD	8.6	NA	10,039	6.3	< 10	< 20			Alden: This is trial 15 by our records.
12	25-Sep	KSA	1	0	0.88	0.88	N	2.71	236		2.53	111											Alden: Cannot find this trial in our records.
8	24-Sep	KSA	1	0	1.76	1.76	N	2.76	188		2.52	109			18.6	NA	824	0.8	< 10	< 20			
35	9-Oct	KX	1	0	1.29	1.29	N	2.6	252	74	2.6	121	352	1.8	10.2	NA	6,585	6.2	< 10	< 20			
44	9-Oct	KX	1	0	1.29	1.29	Y	2.2	197	68	1.66	165	35	0.9									No Chemistry, reflash
47	9-Oct	KX	1	0	1.29	1.29	Y	2.1	255	72	1.85	136	24	0.78									No Chemistry, reflash
28	4-Oct	KX	1	0	0.88	0.88	N	2.38	1,417		2.54	121	TBD	TBD									

TABLE I-1 (CONT)

Test	Date	Agent	No. of F/X	Total mass, lb: Gas	Total mass, lb: DC	Total Agent, lb	Clutter, Y/N	K[a]	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash: Start after Fire Out, ms	Reflash: Peak BOP, psi	Oxygen Min, %	Maximum: Agent, %	Maximum: CO, ppm	Maximum: CO_2, %	Maximum: COF_2, ppm	Maximum: HF, ppm	5 min TWA, ppm: Avg COF_2	5 min TWA, ppm: Avg HF	Comment
30	4-Oct	KX	1	0	0.88	0.88	N	2.52	2,031		2.16	121											
31	4-Oct	KX	1	0	1.29	1.29	N	2.85	1,808		2.82	111											
20	2-Oct	KX	1	0	0.44	0.44	N	2.59	1,100		1.78				12	NA	4,805	5.6	< 10	< 20			
22	2-Oct	KX	1	0	0.88	0.88	N	4.34	338		2.81	125			18.4	NA	1,174	1.5	< 10	53			Alden: High standard error in FBG-position HF, AFES-position HF is less <10.
3	19-Sep	KX	1	0	1.76	1.76	N	2.29	282		1.92	119			18.1	NA	1,098	1	16	< 20			
37	9-Oct	Nano	1	0	0.88	0.88	N	2.7	1869	75	2.6	107	TBD	TBD	7	NA	14,000	6.2	18	< 20			Never fully suppressed
24	3-Oct	Nano	1	0	0.88	0.88	N	3.27	977		3.28	133	TBD	TBD	10.1	NA	4,811	> 6.3	< 10	< 20			High CO
18	1-Oct	Nano	1	0	0.44	0.44	N	2.55	1,127		2.54	133											Reflash? Alden: No chemistry data (FSAB not present).
60	17-Oct	No test									0.14												No test - low peak BOP
19	1-Oct	No test				0	N																
76	19-Nov	Unsupp																					
73	16-Nov	Unsupp				0																	
68	14-Nov	Unsupp																					
65	19-Oct	Unsupp				0																	
58	17-Oct	Unsupp																					
61	17-Oct	Unsupp				0																	
54	16-Oct	Unsupp																					

TABLE I-1 (CONT)

Test	Date	Agent	No. of F/X	Total mass, lb		Total Agent, lb	Clutter, Y/N	K[a]	Fire Out, ms	First Agent, ms	Peak BOP, psi	BOP FWHM	Reflash		Oxygen Min, %	Maximum					5 min TWA, ppm		Comment
				Gas	DC								Start after Fire Out, ms	Peak BOP, psi		Agent, %	CO, ppm	CO_2, %	COF_2, ppm	HF, ppm	Avg COF_2	Avg HF	
50	15-Oct	Unsupp																					
46	11-Oct	Unsupp				0																	
41	10-Oct	Unsupp				0																	
33	9-Oct	Unsupp		0		0	N																
27	4-Oct	Unsupp				0	N																
23	3-Oct	Unsupp				0	N																
15	1-Oct	Unsupp				0	N																
9	25-Sep	Unsupp				0	N																
7	24-Sep	Unsupp				0	N																
4	21-Sep	X1150BC	2	5.76	0.88	6.64	N	2.17	920		1.34	920			12.1	12.4	6,201	3.8	BDL	BDL			

[a]K = maximum rate of pressure rise, typically after valve initiation and prior to turbulent agent/flame interaction, normalized to the volume of the test container, bar-m/s
[b]Continuous emission monitors (CEMs) turned off to avoid damage.

BDL = below detection level
DC = dry chemical
F/X = number of fire extinguishers
FBG = fire ball generator
FWHM = full width half max
NA = not applicable
TBD = to be determined
TWA = time weighted average

Note: Alden -- HF concentrations are estimates until characterization of the calibration gas cylinder is performed.
COF_2 concentrations above 2,030 ppm are estimates.
CO concentrations about 10,000 ppm are estimates.

APPENDIX J. CREW COMPARTMENT TESTING - CHEMISTRY REPORT

Crew Compartment Combustion By-Product Testing Description

The toxic fumes investigation for the Low Global Warming Potential (GWP) Automatic Fire Extinguishing System (AFES) candidate agent's project was conducted by the Field Sampling and Analysis Branch (FSAB) 19 September 2018 through 19 November 2018 at the Aberdeen Test Center, Aberdeen Proving Ground, Maryland. The purpose of the investigation was to document agent concentrations, combustion by-products and degree of oxygen depletion. Combustion by-products include toxic gases. Comparison of these results with available US Army casualty criteria would then assist in the evaluation and selection of agents for further testing.

A comprehensive description of test conditions and a discussion of analyte air concentration results (including the incapacitation doses for toxic gases) measured during this investigation was compiled. Exposure criteria for the AFES candidate agents are not provided because, with the exception of FM200 (HFC-227ea), no official Army guidance is available on the effects of these agents.

The total flooding compartment testing was performed in an approximately 200-ft^3 enclosure (compartment) equipped with AFES hardware, including a controller to detect the fire threat and discharge the extinguishers. The candidate agents were placed in one or two fire extinguishers of appropriate size to achieve the minimum design concentration for the test enclosure. For a subset of tests, metal ammo canisters were added to the enclosure to simulate clutter. A fireball generator (FBG) produced a fireball inside the enclosure for each test (ref 2). Each test used a dry chemical often combined with a gaseous agent to attempt to extinguish the fire.

The concentration of the toxic gases carbonyl fluoride (COF_2), carbon monoxide (CO), acid halides (HF), and candidate gaseous agents were monitored using the two FTIR spectrometers. Toxic gas monitoring was performed in general accordance with accepted and approved methods (refs 3 and 4). Gases were measured at two positions inside the enclosure; one closer to the AFES discharge and one closer to the FBG. For each sample position, a diaphragm pump sampled at a rate of approximately 14 liters per minute; the sample air passed through 1.0 micron Polytetrafluoroethylene (Teflon) particulate filters before entering the analytical instrumentation. The sample streams first passed through separate Fourier transform infrared (FTIR) spectrometers and then through Continuous Emission Monitors (CEM).

Dry powder chemical agent air concentrations were not monitored during or after tests but all powders had previously been characterized for particle size. Four of 21 dry powder only suppression tests included chemistry measurements.

Before testing, FSAB personnel collected reference spectra on each FTIR for each analyte from gas phase standards. Gas standards were certified except for candidate agents which were manufacturer-grade and obtained from the ATC Fire Lab. Reference spectra for 1233zd were collected at 100-percent concentration. Opteon1100 and 2BTP were obtained as liquids, volatilized at 50°C inside polyethylene gas-bags and then diluted with nitrogen in additional bags to 5, 10, and 15 volume percent for Opteon1100, and 4, 6, and 8 volume percent for 2-BTP. Reference spectra for FM200 were collected at 1, 5, 10, 15, and 25 volume percent. Reference spectra of Opteon1150 were collected by diluting Opteon1150 gas with nitrogen in polyethylene bags to concentrations of 5 and 10 volume percent.

The CEM were calibrated daily and the calibration curves for the FTIR analytes were checked before each day of testing using an Environics Model 4040 computerized gas dilution system that diluted concentrated standards with gas from a zero air generator to yield the appropriate concentrations.

Doses that would be received by crew members, had they been present in the enclosure, were calculated for select gases by multiplying the time-weighted average of the gas concentration by the exposure duration.

A comprehensive report FSAB Test Report No.: 2019-FSAB-011 entitled: “Low Global Warming Potential Automatic Fire Extinguishing System Candidate Agents Toxic Fumes Investigation” was prepared.

APPENDIX K. BYPRODUCT EVALUATION PAPER

 28 SEPT 2018

EVOLUTION OF COMBUSTION BYPRODUCTS FROM GASEOUS FIRE SUPPRESSION AGENTS

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EXTENDED ABSTRACT

An interesting observation made during a study of potential fire suppression agents with lower GWP than those currently used, was that the byproducts from FK-5-1-12 evolved quite differently than those from Halon 1301 or HFC227-BC.[1] Continuous sampling gas phase Fourier Transform Infrared (FTIR) spectrometers were used to analyze the combustion byproducts from each trial in near real time. Using this technique allows for the accurate measurement of multiple analytes, including COF_2 and HF. Since the relative toxicity of these compounds are quite different, the ability to quantify each of these compounds is necessary for an adequate determination of injury or incapacitation due to inhalation of these toxic gases.[2]

Specifically, Halon 1301 (Figures 1 and 2) and HFC227-BC (Figures 3 and 4) generally produced lower levels of carbonyl fluoride (COF_2) initially which then decayed into hydrogen fluoride (HF), whereas FK-5-1-12 produced high levels of HF and COF_2 simultaneously (Figures 5 and 6). Adding BC dry chemical to the FK-5-1-12 discharge nozzle improved performance, but did not change the temporal trend, and the levels of byproduct remained above acceptable limits (Figure 7). The result was that the dose of acid and carbonyl byproducts from FK-5-1-12, neat or with dry chemical, were consistently well above the US Army casualty criteria limit of 746 ppm-min (5-minute dose), while byproducts from HFC227-BC and Halon 1301, used with normal design concentrations, were well below the limit. Even when HFC227-BC was applied at less than 1/3 of the HFC-227ea class B minimum design concentration of 8.7% (Figure 3), the byproduct levels were much lower than obtained in any tests using FK-5-1-12 (Figures 5 – 7).

Overall, this result suggests that chemicals, such as FK-5-1-12, that are designed to be more reactive, thus yielding shorter atmospheric lifetimes and therefore lower GWPs, generate much higher byproduct levels during the fire suppression process than more stable, and thus likely higher GWP, compounds.

1. Hodges, S. E. and McCormick, S. J., "Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles," Suppression & Detection Symposium (SUPDET), National Fire Protection Association (NFPA), 2010. http://www.dtic.mil/dtic/tr/fulltext/u2/a517470.pdf

2. ATC Chemistry test report no. 2009-CC-359.

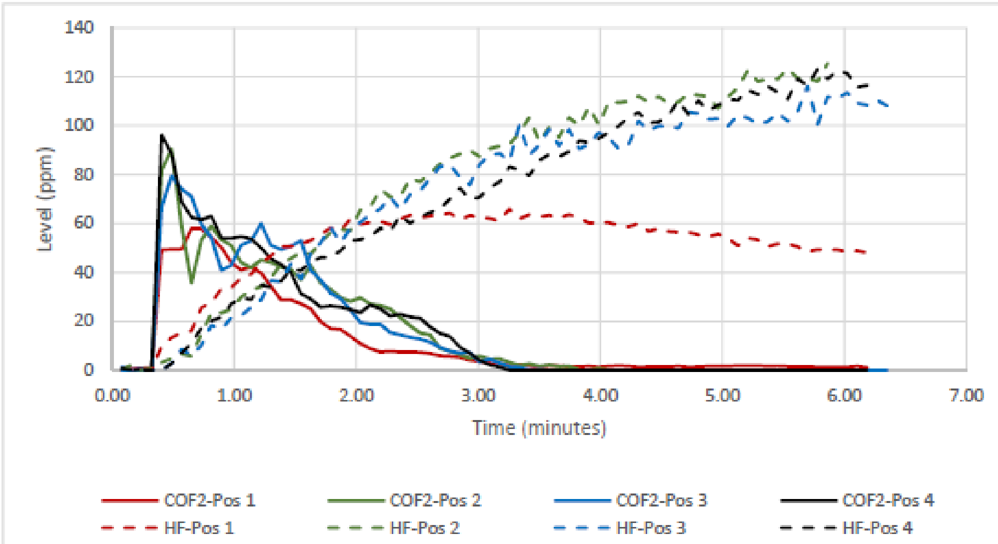

Figure 1. Byproduct levels for Halon 1301: 3.25%, fire out 155 ms, 5-min average dose 439 ppm-min (2009-CC-359_KH5)

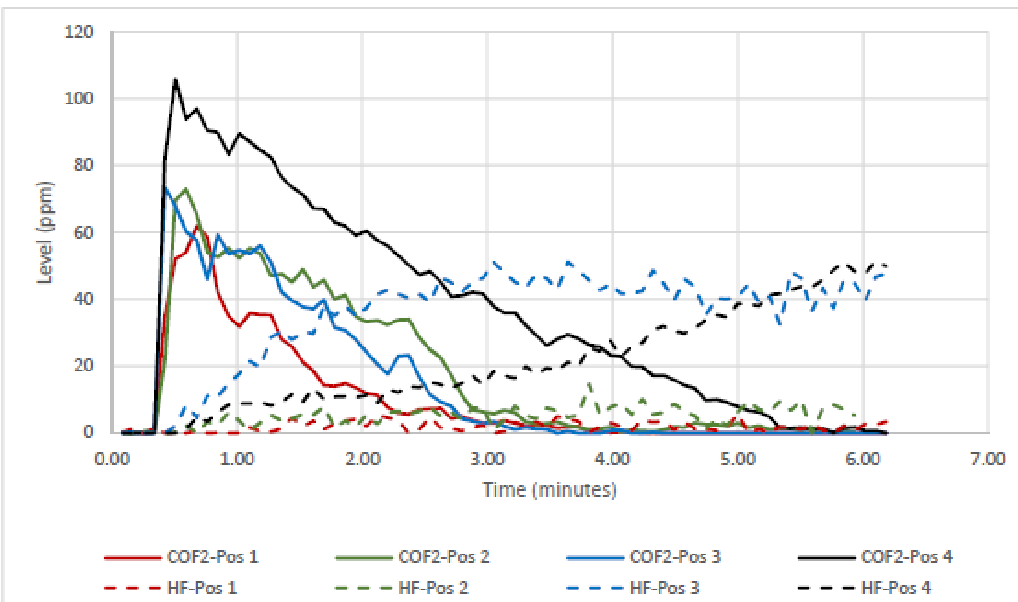

Figure 2. Byproduct levels for Halon 1301: 4.77%, fire out 190 ms, 5-min average dose <233 ppm-min (2009-CC-359_KH3)

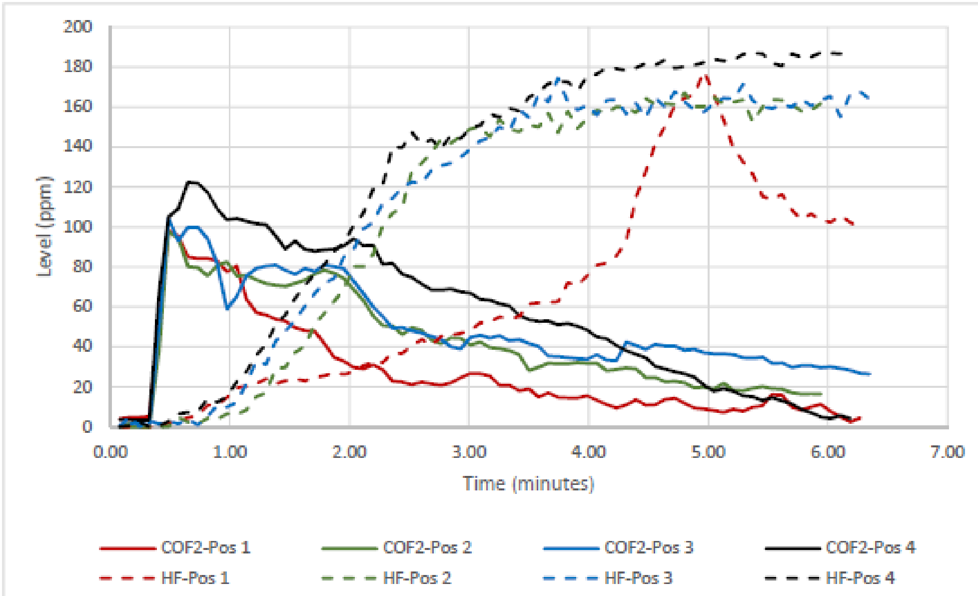

Figure 3. Byproduct levels for HFC227-BC: 2.50% HFC-227ea + 5% w/w BC, fire out 184 ms, 5-min average dose 1,070 ppm-min (2009-CC-359_KFMBC3)

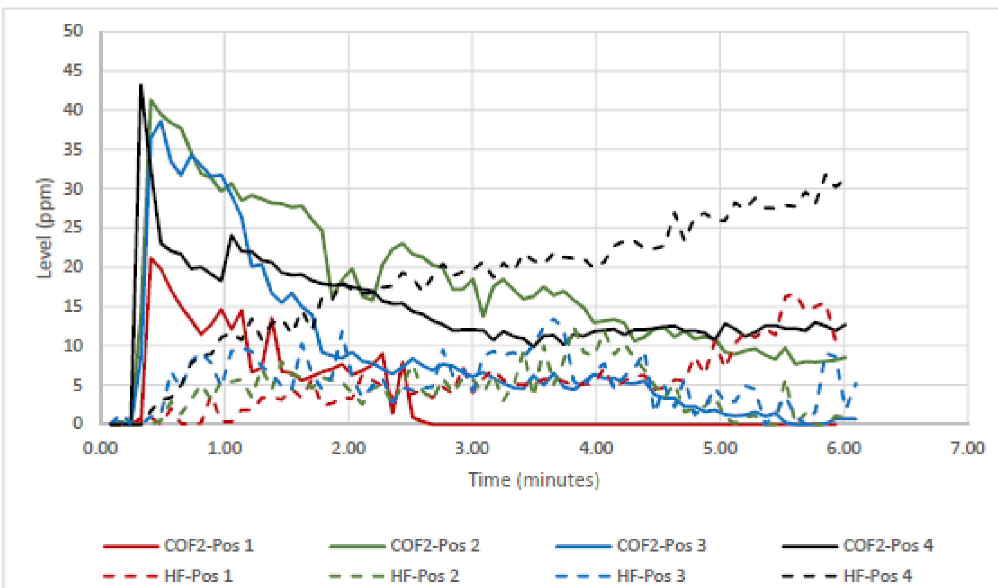

Figure 4. Byproduct levels for HFC227-BC: 4.88% HFC-227ea + 5% w/w BC, fire out 148 ms, 5-min average dose <125 ppm-min (2009-CC-359_KFMBC2)

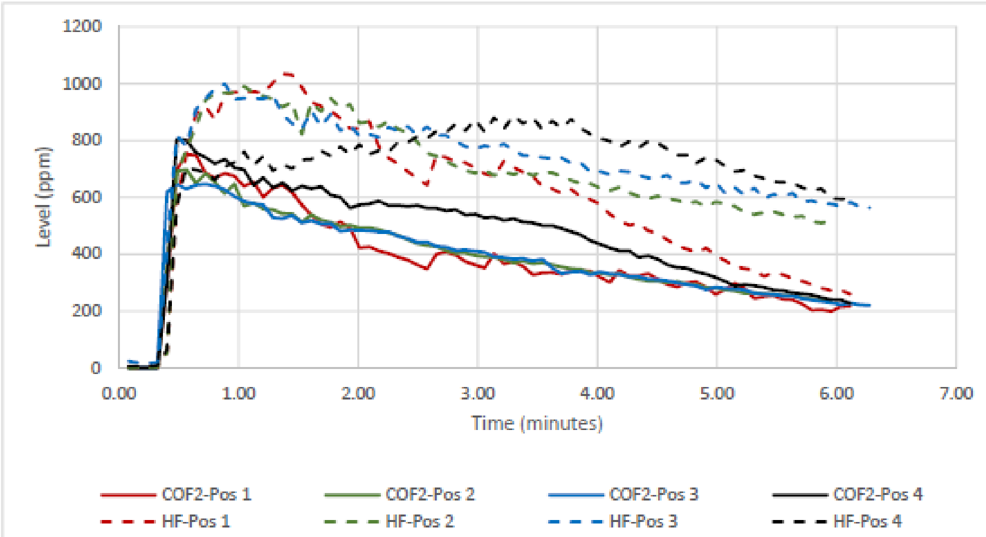

Figure 5. Byproduct levels for FK-1-5-12: 5.90%, fire out 199 ms, 5-min average dose 8,100 ppm-min (2009-CC-359_KNOV1)

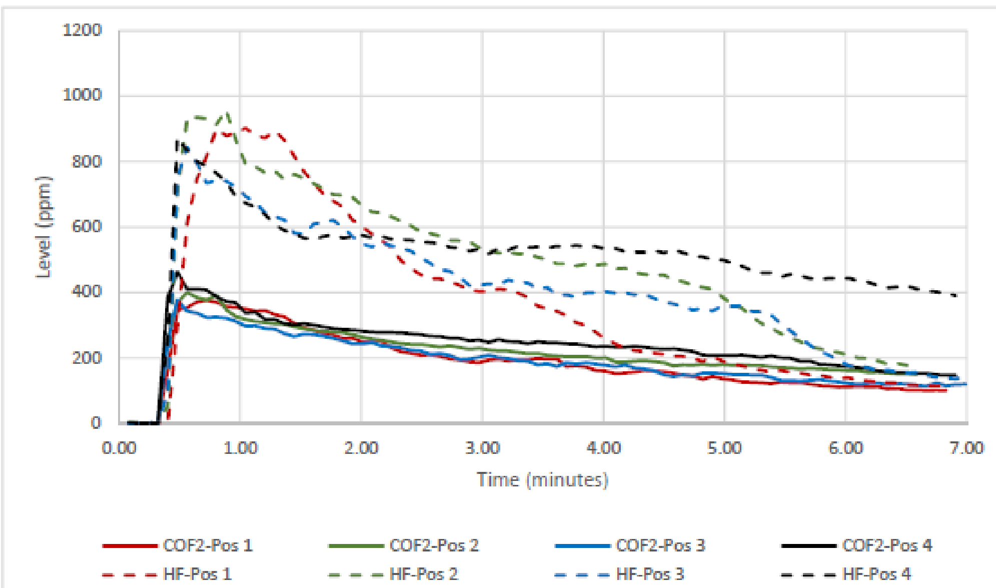

Figure 6. Byproduct levels for FK-1-5-12: 9.31%, fire out 141 ms, 5-min average dose 4,959 ppm-min (2009-CC-359_KNOV2)

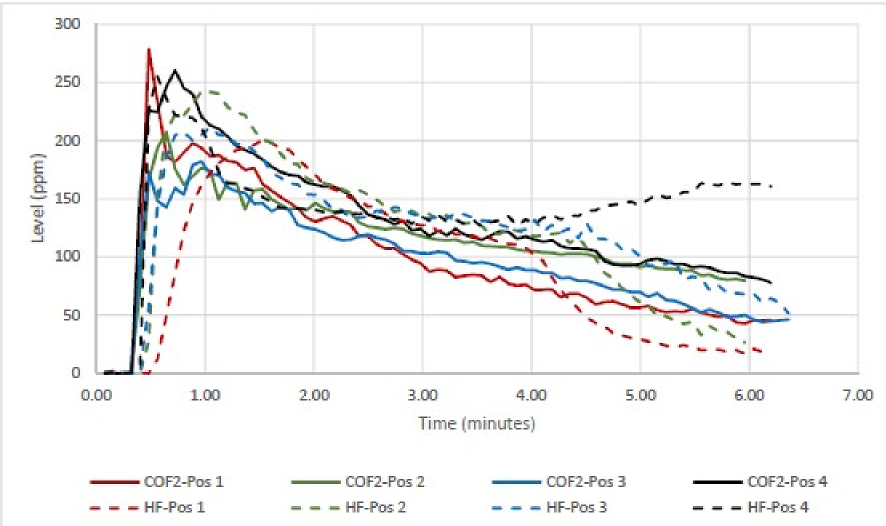

Figure 7. Byproduct levels for FK-1-5-12 with 5%w/w BC: 9.32%, fire out 168 ms, 5-min average dose 1,900 ppm-min (2009-CC-359_KNVBC2)

APPENDIX L. FEDERAL AVIATION ADMINISTRATION - ENGINE NACELLE EVALUATION OF 2-BTP

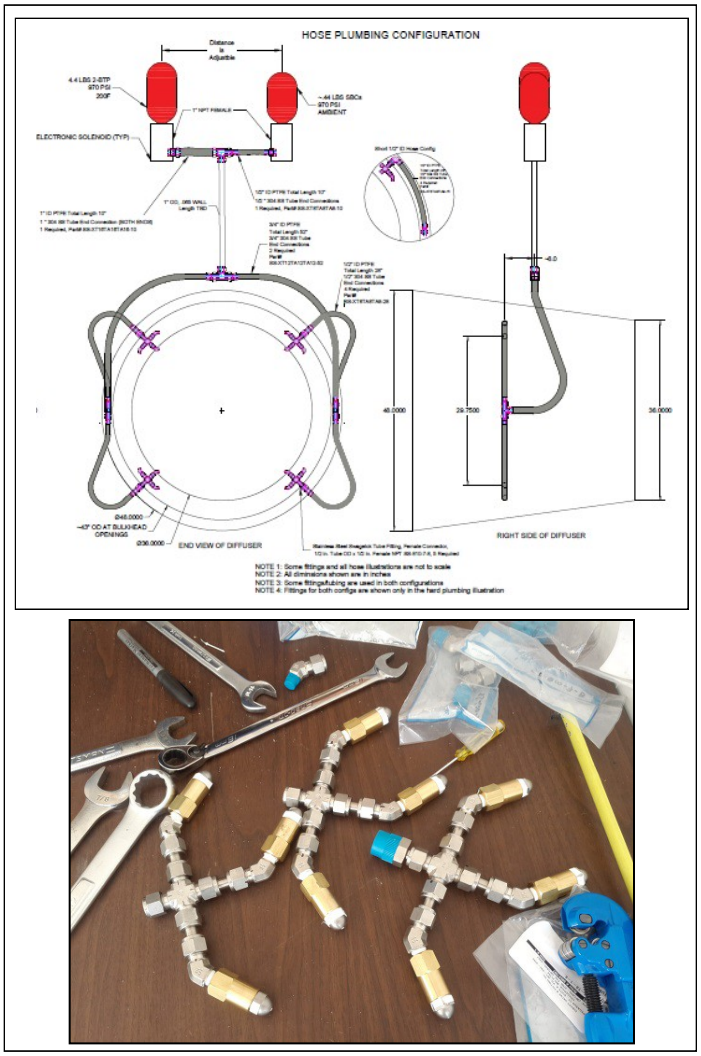

Figure L-1. Discharge plumbing, nozzle array design and Monarch MFG 100.00 X 80PLP 052218 nozzles employed in this testing (2018).

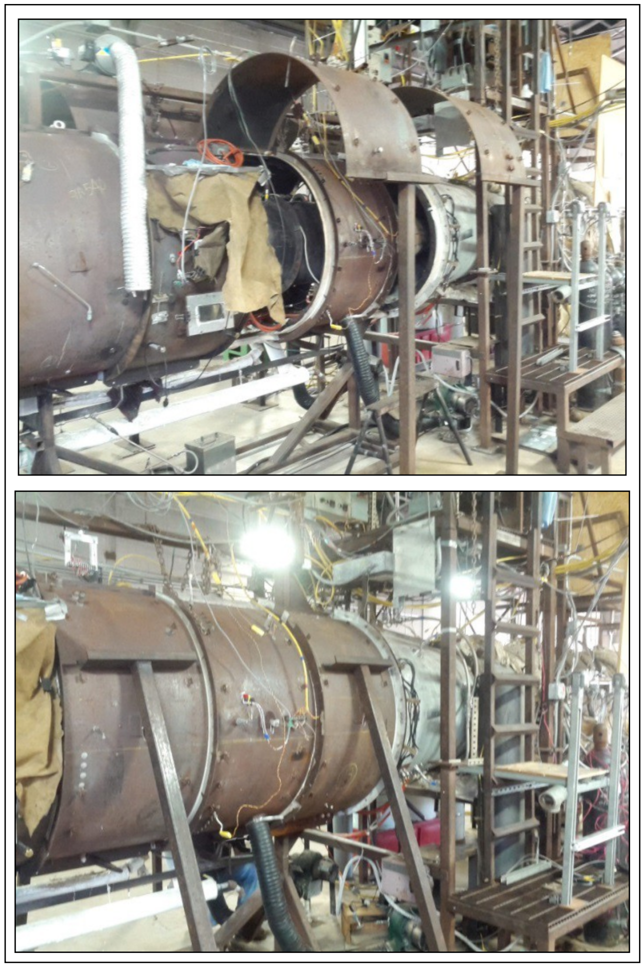

Figure L-2. Nacelle test fixture (top) interior view showing location of spray fire and closed configuration in preparation for testing (bottom).

The following is a detailed description of the engine nacelle testing of 2-BTP with and without SBC. It was prepared by the FAA (Doug Ingerson). (Note: Minor edits have been made to the original document.)

Descriptions of a Test Project Completed in the FAATC Generic Nacelle Fire Simulator with the US Army for the Preliminary Investigation about the Fire Extinguishment Behavior of Blended 2-BTP & Sodium Bicarbonate, 6-17Aug2018.

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[purposely broken internet link; replace AT with ‘@’]

Table of Contents.

Possible Acronyms, Short-hand notations, etc. within this paper.

"H2O	unit of gage pressure, inches of water column
#	number
2-BTP	2-bromotrifluoropropene
ACY	airport designator, Atlantic City International Airport (KACY)
ASOS	Automated Surface Observing System
btl	bottle
cfg	configuration
CF3I	halon 13001, iodotrifluoromethane
chk	check
ckt	circuit, as in electrical circuit
COBS	core oil burner system; used during low ventilation as 2ND heat addition to ventilation stream
cor	core
ctl	control
cyl	cylinder
DAQ	data acquisition system
di	duct interface [atmospheric gap] of the FAATC gNFS; gap between the outlet of the gNFS test section & the inlet of the red exhaust duct
dist	distribution
DVR	digital video recorder; produces digitized visual records
elec	electrical
exh	exhaust
ext	exterior, extinction, extinguisher or extinguishment
FAATC	Federal Aviation Administration's W.J. Hughes Technical Center, Pomona, NJ, 08405; physically located at the Atlantic City International Airport.
firex	fire extinguisher, fire extinguishing
FK-5-1-12	3M Novec 1230
f-line	fuel line
frx	fire extinguisher, fire extinguishing [context sensitive]
fwd	forward
globl	global, broad-spectrum, typical
gNFS	FAATC generic nacelle fire simulator [same as the FAATC NFS]
h125	HFC-125, pentafluoroethane, DuPont FE-25
h1301	halon 1301, bromotrifluoromethane
Hal02 RBLT	FAA-owned/modified Pacific Scientific Halonyzer 2
Hal03	Pacific Scientific Halonyzer 3
HWA	hot-wire anemometer
HWA°C	hot-wire anemometer, manufactured by Degree Controls Incorporated
KAD	Kidde Aerospace & Defense, Wilson, NC.
KSA	Kidde firex agent, sbc solid aerosol
ID	identification
ILDH	inline duct heaters; used to heat NFS internal ventilation flow
inH2O	unit of gage pressure, inches of water column
inHg	unit of gage pressure, inches of mercury column
inj	injection
int	interior
in H2O	unit of gage pressure, inches of water column
ksig	unit of gage pressure, 1000 pound-force per square inch

lt	light
lwr	lower (i.e. lower sta551 TCs, pool fire, 6 TCs)
mfr	manufacturer
mmH2O	unit of gage pressure, millimeters of water column
mod	modified
MPSe	Minimum Performance Standard for Halon 1301 Replacement in Civil Aircraft Engine Nacelle and Auxiliary Power Unit Compartments
MPSHRe	Minimum Performance Standard for Halon 1301 Replacement in Civil Aircraft Engine Nacelle and Auxiliary Power Unit Compartments
MSSI	Meggitt Safety Systems Incorporated, Simi Valley, CA.
mV	millivolt
NFS	nacelle fire simulator
not.rec	not recorded
nzl	nozzle
orn	orange
p/n	part number
PacSci	Pacific Scientific HTL/KinTech [see MSSI]
pdl	puddle or pool
PID	proportional, integral/reset, differential/rate; reference to operating mode of an electronic process controller
prem	preliminary
pres	pressure
psia	unit of absolute pressure, pound-force per square inch
psid	unit of differential pressure, pound-force per square inch
PST	Pitot-static tube
p-t	pressure transducer
qty	quantity
rak	rack
rev	revision
rls	release, discharge
RTD	reignition time delay; time fire is suppressed, per MPSe rev04 guidance
rttnl	rotational
s/n	serial number
sampl	sample
sbc	sodium bicarbonate
sec	section or seconds
sfc	surface
sig	signal
spr	spray
sta	station number in inches, longitudinal reference of the NFS
std dev	standard deviation
Tb	2-BTP & SBC mix in a single tee-fitting; the 2-BTP & SBC enter the tee in opposed flow [bullhead flow]
TBD	to be determined
TC	thermocouple, type-K
temp	temperature
trggr	trigger
tst	test
Tt	2-BTP & SBC mix in a single tee-fitting; the 2-BTP passed through this tee through-run

upr	upper (i.e. upper sta551 TCs, spray fire, 6 TCs)
valv, valvs	valves
VCR	video cassette recorder; produces magnetic visual records
VDC	voltage, direct current
vlv	valve
xdcr	transducer
xmssn	transmission
y-int	"y"-axis intercept

The identification of a manufacturer in this paper does NOT constitute any form of recommendation or endorsement. Manufacturers are identified to provide complete detail in this report.

Background.

US Army Novel Concept.

Quite some time prior to this specific activity, the US Army completed a project to replace the hand-held halon 1301 fire extinguisher found in the crew compartments of Army “light” helicopters. Much detail exists for this program but is omitted here for brevity [if seeking information on this activity, contact Mr. Tim Helton. The notable & applicable outcome from this project was a hand-held fire extinguisher [firex] containing HFC-227ea & sodium bicarbonate [SBC] that can replace its halon predecessor. The parity justifying this equivalence was established by acceptably extinguishing pool fires with the replacement hand-held firex, analogously to the UL test/listing process for commercially-available, hand-held fire extinguishers sold in the open market place, in addition to adequately performing against other challenges not detailed herein.

The observation of mixing SBC with another firex agent, which is not as capable as halon 1301, offers consideration as a halon replacement pathway, by simple inspection, although notable complexity exists and must eventually be considered.

More recently, US Army personnel conceived another novel concept, attempting to extend the HFC-227ea/SBC concept. This more-recent novel concept incorporates an inert solid-propellant-gas-generator [SPGG] component that injects its thermodynamic energy into a vessel so its contents of SBC & 2-BTP [2-bromotrifluoropropene] can expel into a compartment as a total-flooding agent to extinguish a fire within.

Although the previous/rigorous developmental details are not familiar to the author, the US Army personnel elected to consider 2-BTP in place of HFC-227ea. This species’ selection relates to its favorable environmental characteristics [ALT & GWP]. As for expulsion by SPGG, this addresses the detrimental thermodynamic properties of 2-BTP, characterized by an atmospheric boiling point for 2-BTP of 34°C/93°F when compared to halon 1301 at -58°C/-72°F, which is a notable consideration for end-use in fielded applications. And lastly, blending SBC with 2-BTP to produce a hybrid firex agent is thought to mitigate the detrimental ability of 2-BTP to contribute to combustion [discussed later in this paper] & enhance 2-BTP fire extinction performance.

As described, this novel concept was considered a reasonable candidate for preliminary, full-scale, investigational testing by the US Army. The US Army then requested test support from the FAA Fire Safety Branch to investigate if preliminary testing of this novel concept emulated & favorably compared to a 2004 2-BTP test project involving the FAA Fire Safety Branch, Kidde, & Boeing Commercial Aircraft. The FAA Fire Safety Branch agreed to provide 2 weeks of support & scheduled it for 6-17 Aug. 2018.

The initial firex concept provided by the US Army for testing intended to simulate the SPGG-energized firex bottle concept, as the SPGG component did not yet exist and FAATC personnel wanted to avoid using energetic materials during this testing. This initial concept relied on 2 separate firex bottles, 1 containing “hot” 2-BTP & the other “room-temperature” SBC, which would individually mount & connect to a mixing manifold [a tee fitting]. During the simultaneous discharge of the firex bottles, the 2-BTP & SBC each would enter the mixing manifold and exit as a 2-BTP/SBC mixture for injection into the gNFS and subsequent dispersion in its ventilation to challenge the fire threat. The “hot” 2-BTP would result from heating its firex bottle in an oven well before a test so it could partially emulate the advantage of an elevated thermodynamic state resulting from an SPGG-energized firex bottle. The “room” temperature for the SBC was selected to avoid negatively affecting its state. Additionally, separating the 2-BTP & SBC, given this was a preliminary investigation, avoided potential negative behaviors from the blended firex agent at elevated temperature.

Point-of-Contact & Individuals On-site During Testing.

The individuals involved in this testing were :

- US Army :
  - Engineering research/test : Mr. Tim Helton [Redstone Arsenal, Huntsville, AL], Mr. Dan Kogut [Aberdeen Test Center, Aberdeen, MD], & Mr. Josh Fritsch [TARDEC, Warren, MI].
  - Engineering research/test, contract support : Dr. Doug Mather [Seattle, WA].
  - Technician, contract support : Mr. Mike Harvey [Aberdeen, MD].
- FAA Fire Safety Branch [FAATC, Atlantic City Intl Airport, NJ] :
  - Technician, contract support : Mr. Jason Fleming.
  - Engineering test support : Mr. Doug Ingerson.

Mr. Helton & Dr. Mather were onsite @ the FAATC during test build-up & initial testing 6-9 Aug. 2018. Mr. Fritsch was on-site during testing on 9 Aug. Mr. Kogut, Mr. Harvey, Mr. Fleming, & Mr. Ingerson were resident during 6-10 & 13-17Aug. 2018 for test build-up, testing, & tear-down.

Additional Pertinent Background.

The FAATC generic nacelle fire simulator [gNFS] is maintained & operated by personnel located at the FAATC belonging to or associated with the FAA Fire Safety Branch. This test fixture & its associated environments have been & are used sporadically to assess the behavior of potential halon-replacement candidates being considered for use in the fire zones of powerplant & auxiliary power unit compartments found in civilian/commercial aircraft. This fixture has a demonstrated performance history for halon 1301 that relates dispersion & fire suppression behaviors in its environments. An accompanying document [“USArmyNSBC2BTP-DataPkg-OVRVUnIMAGESnNFSnTELEMETRY-revFinl.pdf”] details many aspects of the FAATC gNFS that are not explained in this document.

Parity between halon 1301 & other firex agents in this test fixture & its environments is principally assessed with the reignition time delay [RTD]. The RTD is a duration that begins when a firex agent becomes effective and extinguishes a fire threat while fuel & ignition sources persist, and ends when a firex agent becomes ineffective, as indicated by the fire’s reignition [the fire is suppressed for the RTD]. Other test-related observations are considered also.

This investigational testing singularly utilized a spray-based fire threat. Before achieving an RTD in such an individual test, the basic sequence starts with the ignition of the spray-based fire threat that is subject to prevalent forced internal ventilation. The fire burns for a 45-second pre-burn duration to allow local boundary heating to occur. When the pre-burn duration elapses, the firex bottle is discharged [the spray fire continues burning 15 more seconds after the firex bottle discharge], injecting the firex agent into the gNFS internal ventilation, which forces interaction among these 2 things. While mixing with the ventilation stream, the injected firex agent migrates downstream and then interacts with the spray fire. If extinguishing the fire, a RTD begins. During a RTD the firex agent quantity eventually erodes to an ineffective quantity, due to the persistent forced ventilation washing out & reducing the firex agent’s resident quantity, thus it no longer maintains flame extinction and allows the fire to reignite, which ends the RTD. If the fire did not initially extinguish, then no RTD existed [RTD = 0].

In addition to the catalog of halon 1301 behavior in the FAATC gNFS, a database exists for another project accomplished in 2004 that investigated 2-BTP as a potential replacement candidate, which concluded unsuccessfully. The unsuccessful outcome related to an idea, based on these & other test observations, that 2-BTP can degrade, when exposed to certain conditions, and liberate fuel-like decompositional species that participate in & enhance associated combustion, which is certainly not a desired behavior of a potential firex agent.

These local test observations indicate this detrimental phenomenon relates to fire ignition when 2-BTP exists in concentrations within the pre-combustion environment [before combustion initiates or resumes] at less than its fire-extinction design concentration. Although this participation relates to 2-BTP's inadequate presence before fire ignition, & appears inconsequential regarding its post-fire presence to extinguish a pre-existing fire [i.e. when injected into a powerplant fire zone to extinguish an accidental fire], one must consider the convoluted statistical character of systemic failure, which may present a reignition hazard [i.e. a fire extinguished by 2-BTP may reignite when it still may locally reside].

For the case of the local 2004 2-BTP testing in the FAATC gNFS, 2-BTP was repeatedly observed to push smoke and/or flame out of the gNFS duct interface into the test bay after fire reignition. The effluent exited from this atmospheric gap, a purposeful physical separation in the gNFS duct pathway, into the larger test bay where the smaller gNFS is housed. This observation always occurred at the end of the RTD [fire reignition purposely occurring upstream in the test section]. Halon 1301 is not observed to do this. Additionally, audible reports were occasionally heard to occur.

The release of smoke & flame, in addition to audible report, were frequently occurring phenomena, although not 100% certain. The extreme example occurred 22sep2004 @ 1051 EDT when a fireball no less than an 8-foot diameter issued from the atmospheric gap & an easily-heard audible report were observed by test personnel in the control room adjacent to the test bay [test 20040922-12]. In contrast, 2-BTP fire extinction tests in this same project also occurred without escaping effluent from the duct interface and without audible report.

The telemetry capability of the gNFS at this time was limited. No sufficiently-sensitive pressure transducers were in service, let alone properly located in/on the gNFS. The visual record consisted solely of visible-spectrum recordings on magnetic video tape, without any audio-track recording. During this 2004 testing, a 2ND camera was temporarily placed on a vertical support to observe the duct interface, allowing those behaviors to be recorded.

The audible reports mentioned here lack physical measurement, but are qualitatively described as a "thud", "thump" or minor "kaboom" that was sufficiently loud to be heard in the control room, over the noise of the operating gNFS in the test bay, where a corrugated-steel wall separates these 2 spaces. No structural damage was noted to occur to the gNFS during this testing.

During testing with other firex agents, effluent was observed to escape from the duct interface into the test bay at the end of the RTD. HFC-125, FK-5-1-12, & MSSI Blend A pushed out occasional "minor" quantities of smoke or smoke & flame. Kidde's KSA pushed out white aerosol & CF3I quantities of purple aerosol, without attending flame. None of these firex agents imparted an ominous combustion impression; only 2-BTP has. Additional testing illustrated Blend A did not pop foil seals that were in place when the duct interface was structurally closed off, where additional subsequent testing demonstrated these same foil seals failed around 2 psig. Recall, we have not observed halon 1301 to push anything of consequence from the duct interface for the known configurations used locally, whether “high”- or “low” ventilation.

One must acknowledge the circumstances in the duct interface are complicated. The ventilation flow field is notably varying geometrically & thermally with longitudinal translation [the associated duct’s cross-sectional geometry, structural, & ventilation flow/pressure interrelationships are changing notably]. Further, when in a RTD the firex agent prevents flaming combustion, thus unburnt fuel continues to spray and migrate downstream collecting in the duct interface [inside the red exhaust duct’s inlet], where the complicated ventilation flow field mixes fuel, oxidizer, & neat firex agent. As such, the longer the RTD, the more fuel collects in the red exhaust duct’s inlet. Eventually, some 8 feet forward, the spray fire reignites when the firex agent becomes ineffective at either the intentional “hot” surface or the electrical arc gap ignition source. The fire then propagates downstream, along the non-reacting fuel/oxidizer/firex agent mixture, and finally presents itself to that in the duct interface to react, where nothing or something escapes to the test bay.

<u>Work allocation.</u>

The US Army tended to all aspects relating to their firex system, its components, & its operation/servicing, including the firex agent bottle mounting structure & firex agent injection plumbing network’s installation onto/into the FAATC gNFS, test-to-test check and/or alteration, and eventual removal from the FAATC gNFS. These personnel possess the detailed notes about how these configurations changed with test progression.

FAATC personnel maintained & sustained a functional FAATC gNFS, achieved/provided necessary capability for coordinated interoperability during the testing, provided pertinent feedback/interpretation of test results as testing progressed, & created then transferred a test data package to the US Army.

<u>Actual Schedule.</u>

US Army test personnel arrived 6 Aug. 2018. Unpacking & test build-up occurred 6-8Aug. Testing occurred 8-10 & 13-17Aug. Tear-down & repacking occurred 17Aug2018. The remaining US Army test personnel & their belongings departed 17 Aug. 2018.

Unpack/test build-up included :

1. positioning US Army material in the test bay of FAATC building 205 needed for repetitive testing [scales, 2-BTP, oven, 2-BTP firex bottles, SBC, SBC glove box, SBC firex bottles, firex discharge valves, discharge valve electrical control circuit, N2, all tools/materials needed for servicing/handling firex bottles]
2. designing, fabricating, & installing the firex bottle mounting frame on the gNFS firex rack’s deck.
3. designing, fabricating, & installing the firex agent injection plumbing network onto/into the FAATC gNFS.
4. linking the FAATC house DAQ/CTL computer system to permit computer-controlled firex bottle discharge by opening the associated valve[s]; the FAATC house DAQ/CTL computer system did so by operating a relay having a 120 VAC coil & contacts capable of paralleling the control switch in the US Army discharge valve’s control circuit.
5. developing an ability to capture/monitor the pressure gages of the test’s firex bottle[s] with the local DVR [no pressure transducers available at the time of this testing].

Testing occurred 8-10 & 13-17 Aug2018. The here-included table summarizes the daily test counts. More test details are found in this document in tables 1 & 3, and in far greater detail in the other accompanying computer files in this data package.

Date :	8aug [wed]	9aug	10aug [fri]	13aug [mon]	14aug	15aug	16aug	17aug [fri]
Number of tests completed : [18 total]	2	1	3	2	3	2	3	2
See the accompanying file "USArmyNSBC2BTP-ArmyTestDataBase.xls" for substantial test detail & comparison.								

Test tear-down/repack included :
1. uninstalling/removing all US Army equipment & material from the gNFS & test bay
2. packing the same in their trailer.

Data-Package Description.

A data package was created for the US Army to consider as a result of this effort. This package includes several files which are here named & described.
1. This file, a semi-formal working report describing activities, observations, & providing discussion for consideration named :
   "USArmyNSBC2BTP-WkgRportPapr-6-17aug2018-revFinlForArmyPublication.pdf"
2. An informal working report describing activities, observations, & providing discussion for consideration.
   a. Name : "USArmyNSBC2BTP-WkgRportPapr-6-17aug2018-revFinl.pdf".
3. FAATC gNFS orientation document
   a. Name : "USArmyNSBC2BTP-DataPkg-OVRVUnIMAGESnNFSnTELEMETRY-revFinl.pdf".
4. Spreadsheet database;
   a. Name : "USArmyNSBC2BTP-ArmyTestDataBase.xls"
   b. Many sheets within the single file/workbook.
   c. Includes its own table-of-contents that explains its contents.
   d. Includes all numerical telemetry.
      i. A numerical data worksheet exists for each of the 18 tests.
         1. Thermal [°F] behaviors
         2. Pressure transducer behaviors [not converted; mV signals].
      ii. Single worksheet for pressure transducers & select thermal behaviors.
         1. Pressure histories are appropriately converted [inches $H2O$].
         2. Thermal behaviors [°F] at sta551 in the upper hemisphere to indicate the fire's behavior.
5. DVR video-clip database.
   a. Multiple individual DVR video-clips were created for each of the 18 tests performed during 8-17 Aug 2018; each named after the particular test & the camera view it observed during the given test. See table 3 in this document for a "high" level listing.
   b. A master DVR video-clip file information database is included as a single worksheet in the spreadsheet database computer file.

c. Several additional tests completed in 2004 & 2006 are also included so they may be reviewed & compared to the aug2018 tests to substantiate subsequent discussion. Clips are provided for representative 2-BTP tests from 2004 & representative halon 1301 tests from 2006.

Test Configurations & Procedures.

FAATC Generic Nacelle Fire Simulator [gNFS].

Review the accompanying database computer file "USArmyNSBC2BTP-DataPkg-OVRVUnIMAGESnNFSnTELEMETRY-revFinl.pdf", as descriptions here will not be as thorough.

The gNFS test section is a steel, concentric-tubular structure having conical entrance & exit structures. Forced ventilation is passed through the annular cross-section [10.3 ft long x 2 ft ID x 4 ft OD]. The 2-foot diameter core of the test section has an upstream nose cone ending at approximately sta428 and abruptly terminates at sta551 without any tapering structure. The annular volume contains a spray fire threat in its upper hemisphere originating at sta502 & extending downstream when burning. During this testing, the fire threat was fueled by Jet-A/JP8 turbine fuel passing through 2 atomizing spray nozzles at roughly 150°F while flowing around 0.25 US gal/min.

The gNFS was operated for all the aug2018 tests at "low" ventilation. Doing so required appropriately baffling the gNFS inlet & operating the in-line, electrical-resistance, duct heaters [ILDHs] to near-maximum capability of roughly an indicated air temperature of 295°F at their location & operating the core-oil burner system [COBS] that creates elevated temperature gradients along the core surface inside the test section ranging from 700°F in 1 location to other unknown temperatures elsewhere on the core surface, which are hotter or cooler.

After each test, 4 doors of the gNFS test section were opened to permit post-test observation of its interior to study how the SBC deposited internally. Following the study & photo-cataloging, the test section was cleaned by the FAATC contract support technician with minor assistance from FAATC engineering staff. The main method to clean the gNFS interior was a pneumatic blowdown fed by the building's shop-air compressor & passing to atmosphere through a metallic-tube wand. The pneumatic source was used to blow out & remove loose remnant piles of solid aerosol, solid aerosol loosely adhered to the gNFS doors' interior faces, & some plated residues. The technician progressed from the sheet metal inlet diffuser downstream to the spray fire region, opening 1 door for a given segment at a time, while the ventilation supply blower & wall-mounted test bay fans were operating to extract any liberated aerosol. Occasionally, FAATC personnel water-wetted some towels and wiped down interior faces of test section doors to remove persistent aerosol. Do note that the test section underwent a creeping accumulation of the SBC during this test project. However, the accumulating remnant aerosol is considered to have negligible impact on the test results, as the remnant SBC was principally non-aerodynamic.

Fire Extinguisher [Firex] Configuration & Its Progression through Testing.

The firex storage & injection plumbing network configurations are described conceptually, as no actual dimensions were discerned or retained by the author. Additional test variables included the number, type, & quantities of firex agent discharged, & the temperature of the 2-BTP discharged.

The firex injection plumbing penetrated the inlet diffuser approximately sta398 @ 01:30, 04:30, 07:30, & 10:30. There were typically 12 internal injection nozzles used, and occasionally 10. Actual atomizing nozzles, and NOT butt-cut tube, were used for 17 of 18 tests. For the last test of this series, 12 "small" pipe caps replaced the atomizing nozzles, where a pattern of 6 holes were drilled in each cap with a #56 [0.0465"] drill bit.

The firex agent was stored in US Army firex bottles which were vertically mounted to a vertical frame installed on the gNFS firex rack decking. The firex bottle configuration had 3 different configurations during this testing.

1. Bullhead-tee [Tb] mixing manifold. The original assembly had a larger-volume, 2-BTP firex bottle & a smaller-volume, SBC firex bottle where the outlets from each discharge valve were facing one another & connected to a mixing manifold made with a bullhead tee. The length of each connecting tube was similar, but each had a different diameter, as dictated by the connection to the respective discharge outlet.
2. No mixing. When discharging 2-BTP solitarily, the bullhead tee manifold was replaced with an appropriately oriented 90° elbow [el] fitting.
3. Through-tee [Tt] mixing manifold. In later testing [14 Aug], the mixing manifold connecting the 2 firex bottles was modified. The bullhead tee manifold was relocated further downstream from the 2-BTP firex bottle, reoriented for 2-BTP through-tee flow & SBC side-tee flow, & a 90° el replaced the bullhead tee manifold at its original position.

Continuing along the pipe flow path from the outlet of the mixing manifold, the flow dropped below the rack deck in rigid-walled metallic tube, passing through the deck's foot-ring hole, and then encountered a horizontal/lateral, bullhead-tee, flow-split [the opposing flows exiting the tee were horizontal] that continued on through 2 flex-hose branch lines [a left one & right one]. One flex-hose branch line passed to one side of the gNFS along the outside of the sheet metal inlet diffuser & the other to the opposite side. Will next describe 1 branch, omit describing the other, & state the 2 branches were mirror images.

The left branch departed the 1st flow-split then hit another [2nd] flow-split further downstream. The 2nd flow-split was a vertical, bullhead-tee flow-split. The outlets from the left-side's 2nd flow-split each had a flex-hose passing & remaining outside the left hemisphere of the sheet metal inlet diffuser. At the downstream end of each of the 2 sub-branch flex hoses, they attached to a fitting that penetrated through the inlet diffuser's sheet metal wall. Each sub-branch line [1 upper left, 1 lower left] ended in a cross-fitting [this fitting was inside the gNFS sheet metal inlet diffuser] where the 3 remaining outlets of the cross each had 1 injection nozzle attached.

The 2 upper hemisphere nozzle assemblies [6 total nozzles, a nozzle assembly = 3 nozzles per 1 cross fitting; 1 assembly on the left & 1 on the right] were oriented so 2 pairs of injection nozzles aimed horizontally/laterally & at each other [1 nozzle pair per assembly], and the remaining pair were pointing gravitationally down [1 nozzle per assembly]. The lower hemisphere also had 2 nozzle assemblies, where 2 nozzle pairs pointed gravitationally up [1 nozzle pair per assembly] & the remaining pair pointed horizontally/laterally at each other [1 nozzle per assembly]. This configuration was subsequently altered by orientation [where the nozzles pointed], the number of nozzles used [10 instead of 12], & nozzle orifice ["small", "large" or "drilled pipe cap"].

2-BTP was discharged as part of the 2-BTP/SBC blend or solitarily. 2-BTP was discharged either at "hot" or "room" temperature. SBC was always discharged at "room" temperature. When mixed in a single firex bottle [16-17 Aug], 2-BTP & SBC were discharged at "room" temperature.

When 2-BTP was injected "hot", its temperature is inferred from temperature measurements made of the 2-BTP firex bottle's shell [a thermocouple was externally clamped to the firex bottle shell for each test] since a direct temperature measurement of the firex bottle's contents was not possible. The 2-BTP was heated for several hours before a "hot" 2-BTP test, thus the firex bottle and agent were cooling down leading into a test. The conservative case assumes the 2-BTP is the shell temperature, when in actuality it may be somewhat warmer, since this is a cooling process and the firex bottle contents likely lag behind & exceed the firex bottle shell temperature.

For all instances, N2 was added to the firex bottles to attain a given storage pressure. The total pressure in firex bottles filled with 2-BTP alone changed with its storage temperature [assumed the goal to be a larger pressure at the higher temperature]. The total pressure in the SBC bottle is assumed a constant. [The author knows nothing about the total servicing pressures for any of the firex bottles. Recollection is that the initial test conditions had 2-BTP & SBC at the same total pressures.]

The firex bottles used during this testing had no easily-accessible plumbing to permit using pressure transducers to capture internal pressures during firex agent discharge/injection [a negative result of schedule pressure]. To provide a crude understanding of the transient pressure behaviors during discharge/injection, the local DVR visually recorded the applicable pressure gage face[s] during each test. This information is useful to determine if the bottles discharged simultaneously and in the same durations [the author did not review this].

Telemetry.

The numerical telemetry sensor package for this body of tests included type-K thermocouples [not corrected for radiation] sensing either fluid [air, flame-affected regions or turbine fuel] and various surface temperatures [all are in °F], pressure histories from “small”-value pressure transducers [0-5 inches H2O; 1 psi $\approx$ 27.7 inches H2O], & the single hot-wire anemometer at the inlet of the FAATC gNFS which was left as unconverted raw signal [mV] & not so relevant here.

The visual telemetry package included the use of 4 visual-spectrum cameras for most tests. The 2 main camera views [spray fire inside the gNFS test section & the gNFS duct interface’s exterior area] were recorded on magnetic tape & by DVR, and the balance solely by the DVR. This information is identified & detailed in table 3. Additionally, a red LED was used in the camera view field of the spray fire to indicate when the firex bottle discharge valve[s] was[were] commanded to operate.

Each visual record includes a superimposed date/time stamp & a stopwatch to measure elapsing time to the hundredths of a second. Do not confuse this with a second date/time stamp that is created by the DVR and also included in visual record. Simply look for a stopwatch in the visual record, note its characteristics, and find the other imposed textual information that matches. The date/time stamp & stopwatch, all having the same visual characteristics, is the actual date/time & elapsing time for the given test captured in the visual record. Also, note that ALL stopwatches in the various views for a single test’s visual records are synchronized [they are all indicating the same time in the test across all its different visual records]. They are within 0.01 second of each other. The date/time stamp associated with the stopwatch is synchronized 1 time per test day in the morning. Neither of the date/time stamps should be used to measure time in the video records.

The red LED’s state [on or off] and other observed visual behaviors can be timed according to a superimposed stopwatch in the visual record, which in turn can then be linked to the numerical data, by some common event, to provide deeper understanding of what occurred in a test, if so curious.

Control during Test.

Each test was conceptually a result of the same sequence, although explicit times & elapsing durations vary. The test itself is 150 seconds long & is a computer-controlled sequence of electromechanical events that create real-world test conditions. A list follows that provides an indication of the task sequencing performed to accomplish a single test.

- Prepare fuel system to satisfy pending test demand.
- Begin & finish preparing firex system details needed for pending test.
- Begin moving & heating the gNFS internal ventilation stream.
    - turn on ILDHs
    - when local air temperature = 200°F, turn on the COBS
- Army personnel mount serviced “room”-temperature firex bottle[s]; typically the SBC.
- If testing with a “hot” 2-BTP firex bottle, advise Army personnel to mount it when the COBS temperature = 500°F.
- Wait for all ventilation heating equipment to cycle for at least a 5-minute duration.
- Configure fuel system for test.
- Configure firex discharge control circuit for test.
- Make local warning of impending test.
- Collect necessary pre-test information.
- Move all personnel into the control room.
- Appropriately select & set control switches needed for test on master control console.
- Start the numerical DAQ/CTL computer system, the visual-recording equipment [VCRs, DVR], & perform the test; @ t = :
    - 0 seconds : start capturing baseline data without any fire
    - 30 sec : ignite the spray fire with a 10-second duration pilot flame
    - 75 sec : elapse the 45-second pre-burn duration; discharge firex bottle[s]
    - 90 sec : stop spray fire
    - 150 sec : end test
- Secure utilized control switches from test on master control console.
- Stop all recording equipment remaining active.
- Shutdown ventilation heating equipment & cool the gNFS.
- Secure firex discharge valve control circuit from test.
- Prepare fuel system to satisfy pending test demand.
- When the gNFS adequately cools, shutdown ventilation flows, open the test section doors, & access interior for post-test observations.
- Perform post-test recovery & cleaning of the firex bottle[s].
- Perform the post-test gNFS cleaning & return it to service.
- Review numerical & visual data records, discuss outcome, plan & make alterations for the next test as needed.
- If needing repeated test, start process from the beginning.

Test Observations/Discussion.

<u>Characterizing the Individual Tests.</u>

Since this is an investigational test project, test results must be ranked to assist with decision-making. This is a two-fold focus since the included SBC of the 2-BTP/SBC blend might mitigate the combustion-enhancing phenomenon relating to 2-BTP & perhaps also enhance the 2-BTP fire extinction performance. Therefore, these tests are characterized here with 2 pertinent measures to allow directly comparing the results from the bodies of testing 2004 & 2018, which are subsequently further detailed. Will use the parameters of :

- the RTD to asses fire extinction performance
- a qualitative score characterizing the observed behaviors at the gNFS duct interface to compare these behaviors

Additionally, “small”-value pressure transducers were installed in the gNFS to sense & allow capturing static pressure histories in the various flow fields monitored for these 18 tests. The converted pressure histories are all included on 1 worksheet in the larger spreadsheet file for US Army consideration. These pressure histories should correlate to events that occurred during these tests. The author has not substantially reviewed these pressures histories, nor has plans to do so at this time due to other “higher” priority project assignments. Note that “small” pressure differences, measured in only inches of water column, are needed to move notable quantities of smoke or foretell of impending energetic reaction, so be diligent if dismissing these “small”-value pressure measurements as negligible.

Reignition Time Delay [RTD]

The RTD demonstrates a numerical correlation to measured quantities in the gNFS test environment. The simplest illustration is that the RTD will increase if increasing the quantity of injected firex agent while keeping its discharge duration & injection configurations similar, as HFC-125 demonstrated in the 2002-2003 time frame, which surprisingly fit a linear prediction in a useful range of test conditions.

For the spray fire, the RTD is the prime value for comparison among various firex agents & is a reasonably simple endeavor to determine. It is the arithmetic difference in time between the fire’s extinction & reignition, measured in seconds to the hundredths place, as indicated by a superimposed stopwatch in the visual record of each test. It is typically and easily determined from post-test review of the spray fire’s visual record, although judgement sometimes enters into its consideration [is the fire out now? or 3 video frames later?].

As for RTD indications to the hundredths place, this precision may be a false assertion because the visual record is only resolved to 33 frames per second [roughly 33 ms, 0.033 sec, between frames, thus affecting the hundredths place in only 2 video frames] & far more so, the behavior of the test environment itself includes notable variation, i.e. “noise” [occasionally seen that RTDs double or half in value for “repeated” testing]. In contrast, the RTDs are historically retained to the hundredths place to assure a unique value results from each test performed, allowing observers to see the gradients from the test results as they repeat or are affected by intentionally changed test parameters [i.e. altering injected firex agent quantity…].

For the 6-17aug2018 test project, 2 items occurred that deviate from historical formal halon-replacement testing that potentially could impact the RTD, but do not for this work. They relate to the visual-spectrum camera viewing the spray fire region & the bundle of stainless-steel tubes that function as a “hot” surface ignition source in the spray fire threat.

The camera viewing the spray fire behavior was different from that used in all past testing. As such, the electronic response to notably changing light intensities [dark, initial fire ignition, fire extinction, dark, fire reignition] & the view field of the camera used during this test project differed from those historically used. Since this is investigational testing & the current camera’s performance was similar to those of the past, no detrimental impact is thought to exist which would negatively affect the interpretation of these test results now or in the future.

Additionally, if formally halon-replacement testing per MPSe rev04, the protocol indicates the need to change the bundle of 4 circumferential stainless steel tubes serving as a “hot” surface ignition threat/source in the spray fire threat after it experiences 10 spray fire extinction tests. This guidance is provided so potentially interfering behaviors resulting from nuances related to “hot” surface ignition [material degradation, geometric alteration, etc.] may be avoided during such testing, to minimize time lost needed to consider these potentially distracting phenomena. During the 6-17aug2018 test project the tube bundle was not new nor was it replaced during the accomplished 18 tests. FAATC personnel verified the tube bundle was properly positioned before each test & monitored its behavior through the course of this testing. Nothing peculiar is thought to result from this deviation, thus no negative impact on the interpretation of these test results is expected now or in the future.

Qualitatively Scoring Observations at the gNFS Duct Interface.

The next significant behavior to observe for this testing is what occurred at the gNFS duct interface, as this behavior can be compared directly with that of the 2004 2-BTP testing previously accomplished at the FAATC, to see if improvements result from this novel concept.

To rank these observations, a linear, qualitative, scoring system was created; no weighting was placed on any given observed parameter. A “low” score is favorable, 0 being the most desirable, meaning that nothing escaped from the duct interface nor was an audible report heard. A “high” score is not favorable, 7 being the worst, meaning much smoke escaped, much fire escaped, and an audible report was heard. Smoke & flame effluent from the duct interface were scored after reviewing the visual records of the tests. Audible report was indicated as an occurrence in a test, or not. The scoring system carries these definitions and has the following values :

1. Escaping smoke & flame each ranked on a 4-point scale :
    a. Nothing [no] escaped duct interface = 0
    b. “minor” [mnr] smoke or flame escaped = 1; minor; challenging to see, but is observed to escape when the visual record is closely reviewed
    c. “obvious” [obv] smoke or flame escaped = 2; obvious; plainly seen to escape; most of the gNFS exit flange & red exhaust duct circumferential entrance remain visible
    d. “notable” [ntb] smoke or flame escaped = 3; notable; the gNFS exit flange & red exhaust duct circumferential entrance are obscured by exiting flame or smoke quantity released is atypically large
2. Audible report ranked as :
    a. No audible report heard = 0
    b. Heard an audible report = 1

Each test’s duct interface score is the sum of the individual scores characterizing the smoke, flame, and audible behaviors observed for that test. Do note ambiguity exists in the scoring from this scheme [i.e.2+3+0 = 3+2+0 = 2+2+1] & its impact is not considered here.

<u>Comparing the Individual Test Characterizations.</u>

To permit comparing the results from all the tests in this project, 3 graphs were created that are included in this file. They are identified as figures 1-3 and follow on later pages. Each graph has the same general configuration. The x-axis is the RTD, measured in seconds. The y-axis indicates the qualitative value of the duct interface scoring.

Each figure/graph includes the same data point that represents the current average behavior of halon 1301 for this test fixture in this test condition. The average RTD for halon 1301 is now considered a value of 3.80 sec having a duct interface score of 0 [nothing escapes the duct interface and nothing is heard when fire reignition occurs], resulting in a data point on each of the 3 figures as [3.80, 0]. This is one comparison that the novel concept must address.

These same figures/graphs will be referenced in subsequent discussion, so a comparison between the recently-investigated novel concept can be compared to the previously-completed 2004 2-BTP testing, to assess if improvements resulted.

<u>Observations/Discussion.</u>

Test Fixture Performance & Test Environment Behavior

The test fixture & its environment were monitored during the course of this testing by the continual observation of, the preparation for, & completion of each test, along with the review of in-house numerical test data files created during the ramp-up to accomplishing each test by FAATC personnel [these data files are not part of the data package]. In general, the test fixture & its environment appeared to behave consistently during this test project's duration & with its historical behavior. Do not interpret this to mean there is no environmental or behavioral variation, because there absolutely is. However, no overt flaws were observed or detected, aside from a few items, which have no impact on the provided test results.

1. Neglected to connect electrical connectors necessary to discharge the firex bottle valves on 1 test. Simply recycled & performed the test after making the necessary connections.
2. The video signal of the spray fire region dropped from its recording equipment & display monitor at test start on 2 sequential occasions. Found/adjusted coaxial cable connections to resume reliable signal delivery, recycled test equipment, & then performed the test.
3. Experienced incremental loss of some thermocouples during the progression through this test support, which principally resulted from the pneumatic blow-down wand inadvertently contacting a thermocouple here or there while cleaning the gNFS test section's interior following the tests. This is a typical expectation when testing with a solid aerosol. The thermocouples will eventually be repaired/replaced & returned to service.

Comparing/Discussing Figures 1-3.

Many different firex configurations were used during this short-duration test project to broaden the realm of that investigated, producing a limited number of repeated tests as a consequence. However, with such a spread, global observation remains feasible, in an attempt to uncover suggestions offered by this data pool.

<u>Considering Figure 1.</u>

Figure 1 is a collection of data points permitting a global review of the test behavior if solely discriminated by whether the firex agent was solitary 2-BTP or the 2-BTP/SBC blend.

Although solitary 2-BTP tests compose roughly 28% of the test data pool, the scatter suggests the addition of the SBC is an improvement since 4 of the 5 [80%] solitary 2-BTP tests equate to or more negatively perform at the duct interface when compared to 10 of 13 [77%] 2-BTP/SBC tests. Further affirmation is that the sole audible report during these 18 tests occurred during a solitary 2-BTP test.

When comparing the respective RTDs, the 2 data groups demonstrate notable overlap. However, including SBC produced 4 RTDs that were smaller than any for solitary 2-BTP. But, with such breadth seen in this data overlap, whether these 4 underperforming test data points are significant is not known, given the imbalance in test counts between the solitary 2-BTP [5 tests] & 2-BTP/SBC tests [13 tests] & the notable variation in the firex configurations used during this testing.

The behaviors shown in figure 1 do not appear similar to that of halon 1301. Globally, these tests & their associated conditions do not indicate adding SBC to 2-BTP will improve the behavior of this blended firex agent to that of halon 1301. However;

1. additional considerations relating to & observations made during this work suggest, in contrast to this comment, that comparable behavior may be possible.
2. a more thorough review of this data is advised, as this was a simple “by-inspection” review.

Considering Figure 2.

Figure 2 is the same collection of data points permitting a different global review of the test behavior if discriminating by whether the firex agent was solitary 2-BTP or the 2-BTP/SBC blend & if 2-BTP was “hot” or “room”-temperature at the time of firex agent discharge/injection.

The only casual observation made is that including SBC apparently has no effect. Otherwise, nothing appears obvious in terms of duct interface behavior or RTD from figure 2.

Again indicating a more thorough review of this data is advised, as this was a simple “by-inspection” review.

Considering Figure 3.

Figure 3 reduces the collection of data points reviewed to those that are part of a repeated series of tests, where each firex configuration is briefly described below figure 3; 4 groups of repeated test for a total of 13 tests. Again, this is a casual, “by-inspection” review, and a more thorough review is suggested.

Casually reviewing figure 2 suggests adding SBC is an improvement, since :

1. 3 of 4 [75%] solitary 2-BTP tests equate to or more negatively perform at the duct interface than 8 of 9 [89%] 2-BTP/SBC tests.
2. 6 of 9 [67%] 2-BTP/SBC tests have a similar or larger RTD than 3 of 4 [75%] solitary 2-BTP tests.

Figure 3 illustrates 2 firex configurations move in the direction of the halon 1301 performance, although they do not compare with halon 1301 performance equally. The initial firex configuration [frx cfg “A”], used 8-9 Aug. 2018, having 2 separate firex bottles with 1 holding 4.4 lbf “hot” 2-BTP & the other 0.44 lbf SBC, a bullhead tee mixing manifold, and the original injection nozzle configuration. The second firex configuration [frx cfg “H”], used 16-17 Aug. 2018, having a single firex bottle containing 4.4 lbf “room”-temperature 2-BTP & 0.66 lbf SBC, which had a single pipe run [no mixing manifold] into the 1st flow-split and subsequently into an injection nozzle configuration oriented like the original configuration, but with the larger-orifice nozzles installed.

Additional Test Observations/Discussion.

Fire extinction.

The test results plainly indicate the 2-BTP/SBC blend is capable of extinguishing fire, as the RTD was always non-zero. In some instances, fire extinction approaches that of halon 1301, although behaviors at the duct interface do not align favorably.

Considering Duct Interface Behavior in Aug2018 & the Past with 2-BTP & Halon 1301.

The 2004 test project, previously identified in this document, involved MPSe rev03 testing with solitary 2-BTP. In contrast, the 2018 test project included a few solitary 2-BTP tests & the remainder with a 2-BTP/SBC blend. Even with this variation, the author firmly believes the tests from each project are qualitatively similar regarding the behavior observed at the gNFS duct interface.

To assist the involved US Army personnel in understanding this, visual records from a few 2-BTP tests performed in 2004 for this gNFS test configuration were retrieved, digitized for electronic use/review, and characterized per the duct interface scoring scheme described earlier in this document. By reviewing tables 1 & 2, it is seen that the characterizations of the 2-BTP behaviors from 2004 at the gNFS duct interface fit within that seen in 2018, thus 2018 tests behaved analogous to those in 2004.

Those reading this should understand that the selected 2-BTP tests from 2004 were not chosen to impart a bias. Instead, the tests are representative, where some others may have behaved similarly, others more favorably, and others had nothing escape from the duct interface [such as the 3 mentioned in the next section].

Extending this consideration further, a few more visual records were retrieved & digitized for tests from 2004 & 2006 to illustrate the behavior of halon 1301 in this same gNFS test configuration. Generally speaking, halon 1301 does not create effluent that escapes from the duct interface. Again, these tests are representative to illustrate the behavioral differences at the duct interface between halon 1301 & 2-BTP.

After the consideration of these observations, a reasonable person should arrive at a conclusion that there is something peculiar about the behavior of 2-BTP that differs from halon 1301, which may require deeper study to address potential concerns for the end-use of 2-BTP.

Although the author did not study all the indications from the “small”-value pressure transducers in the gNFS from every test in the aug2018 project, some histories were reviewed by inspection. From the cursory review of these 2-3 tests, the recorded behaviors indicated reignition at the RTD’s end was the most prevalent pressure excursion captured [fractions of inches of water column]. The excursion associated with reignition is typically an obvious & “larger” excursion than for the initial ignition of the fire or the injection of the fire agent into the ventilation stream. Although applying caution here, because it is known that unburnt fuel will accumulate in the duct interface during the RTD [creating another combustion/energy source that is not present when the fire initially ignites at the onset of a test, thus a separate consideration from the presence of 2-BTP], the author assumes a “small” contribution of the excursion relates to any effluent escaping the duct interface during the fire reignition at the end of the RTD. The data awaits deeper review for future consideration.

Audible cue.

During the completion of the 18 tests in the 2018 test project, 5 solitary 2-BTP tests were accomplished & the balance done with the 2-BTP/SBC blend. A single audible report was heard during a solitary 2-BTP test.

After checking the local database for the last 2-BTP tests accomplished in 2004, 6 are listed that put 4.4 lbf 2-BTP repeatedly up against the "low" ventilation/JP8 spray fire, which occurred on 22-23Sep2004. The sequential RTDs were 3.87, 3.00, 2.05, 2.39, 1.87, & 1.72 sec; note the variation that suggests something was changing. Of these 6 tests, 1 had an audible report along with the notable smoke & flame escaping from the duct interface [3.87 sec RTD; this was the most energetic test, 20040922-12], 2 tests only experienced a release from the duct interface, & 3 had nothing escape. Events occurred at the duct interface for the tests listed here with the longer RTDs. Although this information suggests a clear association, caution is advised as other tests exist which are not referenced here & need consideration to fully understand the complexity of this phenomenon [there were other audible reports also].

As such, the observed infrequency of audible report during the 18 tests performed in 2018 implies an improvement in 2-BTP performance. The apparently obvious idea is that the included SBC changed this condition. Another possible consideration may also relate to the manufacturing of 2-BTP over the years between 2004 & 2018, which may have changed somewhat. The author anecdotally recalls discussions in 2004 among the industry team members about 2-BTP stabilization with some type & quantity of buffer additive; the author has no personal notes on this topic. Perhaps improvements in 2-BTP manufacturing explain this shift in behavior. Nothing can be proven here, nor is attempted, but concepts are identified for the larger realm of unbiased consideration.

Observing the post-test SBC residue in the gNFS test section.

After conducting each test in the aug2018 test project, the gNFS test section was opened so testing personnel could observe its interior to collect additional data to further understanding. US Army personnel photographed the left side of the gNFS test section's interior to capture the post-test SBC deposition patterns after exposing the interior. Some interesting observations relate to the simple act of watching how the SBC fell from the collection points in the test section's lower hemisphere as the gNFS doors were opened for post-test inspection, documentation, & study.

As the doors were opened on the left side of the gNFS, from front to back, the amount of SBC observed to fall to the test bay floor was greatest nearest to the injection cross-section [the sta428-453 door] & decreased in quantity moving aft until no appreciable SBC was noted to fall to the floor when the fire zone door was opened [sta502-527 door]. Qualitatively, there was an obviously decreasing amount of dropped SBC when the gNFS doors were opened in this downstream sequence.

Another SBC characteristic was readily observed as the gNFS doors were opened. There is a simple correlation, although again a qualitative one. For all tests that had 2 firex bottles simultaneously discharging their contents [i.e. separated 2-BTP & SBC subsequently mixing in a tee during discharge], a non-aerodynamic residue fell directly to the test bay floor as each door was opened; would characterize it as a collection of "quite small chunks" of SBC-like material. In contrast, when opening the doors following the tests when the 2-BTP & SBC were mixed in & discharged from the same firex bottle, a different behavior was seen. Of all the SBC that fell from the test section as a door opened, an observable/smaller portion remained aerodynamic & drifted somewhat with the local test bay ventilation [i.e. a "light" breeze] passing beneath the gNFS test across the test bay floor as it eventually fell to the floor; would characterize this as looking like a talc-like material.

Regretfully, the author has no feel for what a deposition pattern looks like for a given SBC quantity [what does 200 g of SBC look like when thrown/scattered on a floor?]. There was always an obvious post-test residue in the gNFS test section. The author is unable to approximate how much SBC was lost to the boundary. Regardless, qualitatively, it appears to have been an appreciable portion of that stored in the firex bottle before discharge. This implies that which passed through the gNFS duct interface was mostly 2-BTP, which may still not have experienced the rationalized benefits of including SBC with 2-BTP.

<u>Additional Applicable Ancillary Discussion.</u>

Pressure Transducers.

During the aug2018 test project, pressure transducers were not used to monitor firex bottle internal pressures. Schedule pressure prevented the installation of these useful sensors.

For tests utilizing 2 simultaneously discharging firex bottles, each having its own transducer may have helped to better understand the discharge/injection event. With this information, an assessment regarding the interplay between the 2 pressure vessels & the repeatability of the pressure decay histories for repeated test may have determined whether consistent behaviors existed or not. This would lend to a better general phenomenological understanding of the system behavior, and perhaps allow acquiring additional insight to address challenge.

The author reviewed 2 random data files from previous local testing. One represented 2-BTP discharges in 2004 analogous to the work in the aug2018 project [included atomizing injection nozzles]. The pressure decay was observed to progress in 2 different near-linear manners, where the decay in the higher pressure region had a near-vertical, negative slope & then smoothly transitioned into a second line having a less-vertical, negative slope, which then transitioned smoothly into an exponential-like curve that flared to horizontal; time between storage to empty pressures was approximately 2-3 seconds, with 80-90% of the pressure decayed inside the 1st second. The second pressure decay reviewed was from a test involving the discharge of a solid aerosol in the 2010 timeframe. Again, 2 predominant behaviors are observed. The initial loss again occurs in near-linear fashion with a near-vertical, negative slope. Approximately half way through the pressure loss there is a transition to something looking like an exponential curve that then tapers to the horizontal indicating an empty pressure vessel. This discharge is almost near complete in 1 second.

In both cases, no pressure recovery was observed during the pressure decays, like that found in a high-rate firex agent injection, typical of a halon 1301 firex system, indicating dissolved N2 flashes out from the firex agent's transiting liquid fraction of the included 2-phase flow.

Although these randomly-grabbed test behaviors appear loosely similar, how a system of 2 coupled firex bottles would behave is unknown. By casual inspection for that known about the initial coupled, 2-firex-bottle arrangement in the aug2018 testing, a transitional flow imbalance is suspected to complicate the discharge at the bullhead tee mixing manifold, and possibly interfering with the balanced mixing of 2-BTP & SBC during discharge. Since each tube connecting a firex bottle to the mixing tee was a different diameter and the firex bottle pressures started as the same, 2-BTP is suspected the dominant flow initially, as a force imbalance would initially occur between the ganged firex bottles when the discharge valves opened. Given force is a product of pressure & the area it's applied to, the force from the 2-BTP will be greater than that from the SBC bottle, since the tube cross section associated with the 2-BTP firex bottle is larger and the pressures in the 2 firex bottles were the same. However, as time elapses, the larger tube may exhaust its firex bottle's contents faster resulting in a reduced pressure relative to the SBC bottle, so the SBC flow may then dominate.

In short, all this crude illustration shows is the pressure decay for the ganged firex bottles will likely produce a discharge event that may be complicated. Having pressure transducers in play might help to unravel this complexity to better understand it, or not.

Improving the Aerodynamicity of the SBC.

Perhaps the ultimate problem experienced during the aug2018 test project was the loss of SBC to the test environment's boundary, instead of remaining aerodynamic, as observed by the continual post-test SBC residue found upstream of the fire threat. Although the author can't judge how much SBC departed the flow, 200 g [0.44 lbm] is a "small" amount to begin with and a measurable SBC quantity was observed left behind in the post-test deposition pattern for each test of the aug2018 project.

Tapping experience from earlier local work with a solid aerosol, mainly operating as an observer, the injection plumbing network was significant. Injection plumes were oriented so the largest possible distance could be included between nozzles aimed at each other, to avoid close-quarter impingement. Nozzles were also positioned to prevent injection plumes from impacting boundaries squarely. Instead, they were oriented to impact the plumes obliquely across a surface; i.e. plumes ran along the inner face of the outer gNFS shell in a circumferential manner. When considering the orientation of the injection nozzles used during the aug2018 test project, a portion of the injection nozzles contradict these principles, although the author recognizes the initial and important intent to emulate the 2004 testing with solitary 2-BTP during the aug2018 activity.

Reconsidering the observation of the SBC falling from the gNFS doors to the test bay floor as the doors were opened provides another suggestion. The ganged firex bottles apparently negatively affected the aerodynamic character of the SBC when discharge occurred. This contrasts with the observed, more aerodynamic, post-test residue when the 2-BTP & SBC were mixed and discharged from a single firex bottle.

Total-flood Versus Streaming Applications.

Recent passing thought has realized this concept. Inherently, the SBC is a particle, which will behave different than a gas in many ways. The initial premise of the HFC-227ea/SBC blend in a hand-held firex vessel is well tuned to its design challenge. HFC-227ea and the SBC particles are very agreeable to a fire extinction challenge requiring a streaming delivery, which relies on a much localized delivery. The stream impacts & disturbs the pool fire dynamics & chemical equilibriums, where the pool fire is used to assess the hand-held firex vessel.

By inspection, the characteristics of 2-BTP & SBC individually or when blended, when compared to that of halon 1301, appear to align more favorably to a streaming delivery concept, in contrast to openly & freely expanding to fill a compartment, something required from a "total flooding" firex agent.

However, with a sufficient injection configuration, the 2-BTP/SBC blend could be adequately dispersed within a volume to extinguish fire, which was demonstrated repeatedly in the FAATC gNFS during 8-17aug2018.

Summarizing Comments.

1. The 18 tests performed during the 6-17aug2018 fire extinguishment test project with solitary 2-BTP & the 2-BTP/SBC blend persistently extinguished the gNFS "low"-ventilation/spray fire for all firex configurations used.

2. Some of the fire extinction behaviors during the 8-17aug2018 fire extinguishment testing approached that of halon1301, although unfavorable disparity exists regarding the behavior observed at the gNFS duct interface.

3. The behaviors of escaping effluent from the gNFS duct interface during the 8-17aug2018 fire extinguishment testing were similar to those observed during the local 2004 2-BTP test project.

4. When collectively reviewing the bases of figures 1 & 3, the 2-BTP/SBC blend is subtly suggested to perform better than solitary 2-BTP, in terms of fire extinction performance & the behavior at the gNFS duct interface. This assessment relies upon reviewing & comparing the aug2018 dataset in 2 manners; one for the full collection of 2018 individual test data points [figure 1] & a smaller set of 2018 data points are appropriately collected & collated to represent the 4 groups of repeated tests [figure 3]. This subtly suggested "minor" improvement is not readily explained by this test data, although it may be related to adding SBC and/or changes in the 2-BTP manufacturing process that occurred, if any did, between 2004 & 2018.

5. The repeated post-test SBC residue indicates it did not remain fully suspended in the gNFS internal ventilation flow. The quantity lost from that initially injected is unknown and may be significant, based on the observed magnitude of the post-test deposition patterns. Therefore, uncertainty remains about the impact of SBC on improving 2-BTP's performance. Improving the 2-BTP/SBC injection may assist to better understand this premise.

Working Report Figures.

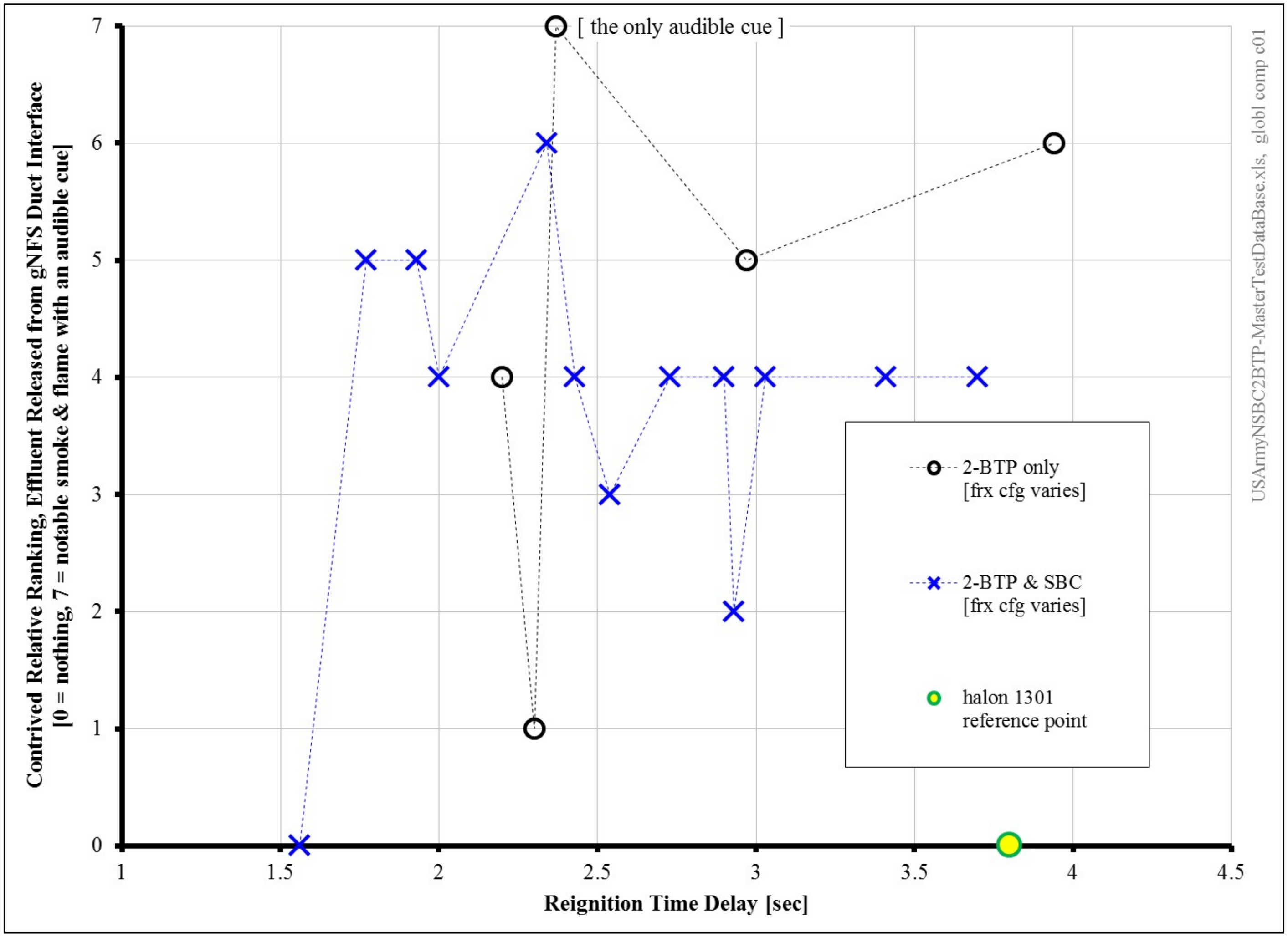

Figure 1. Comparing RTDs of 2-BTP to Those of 2-BTP & SBC.

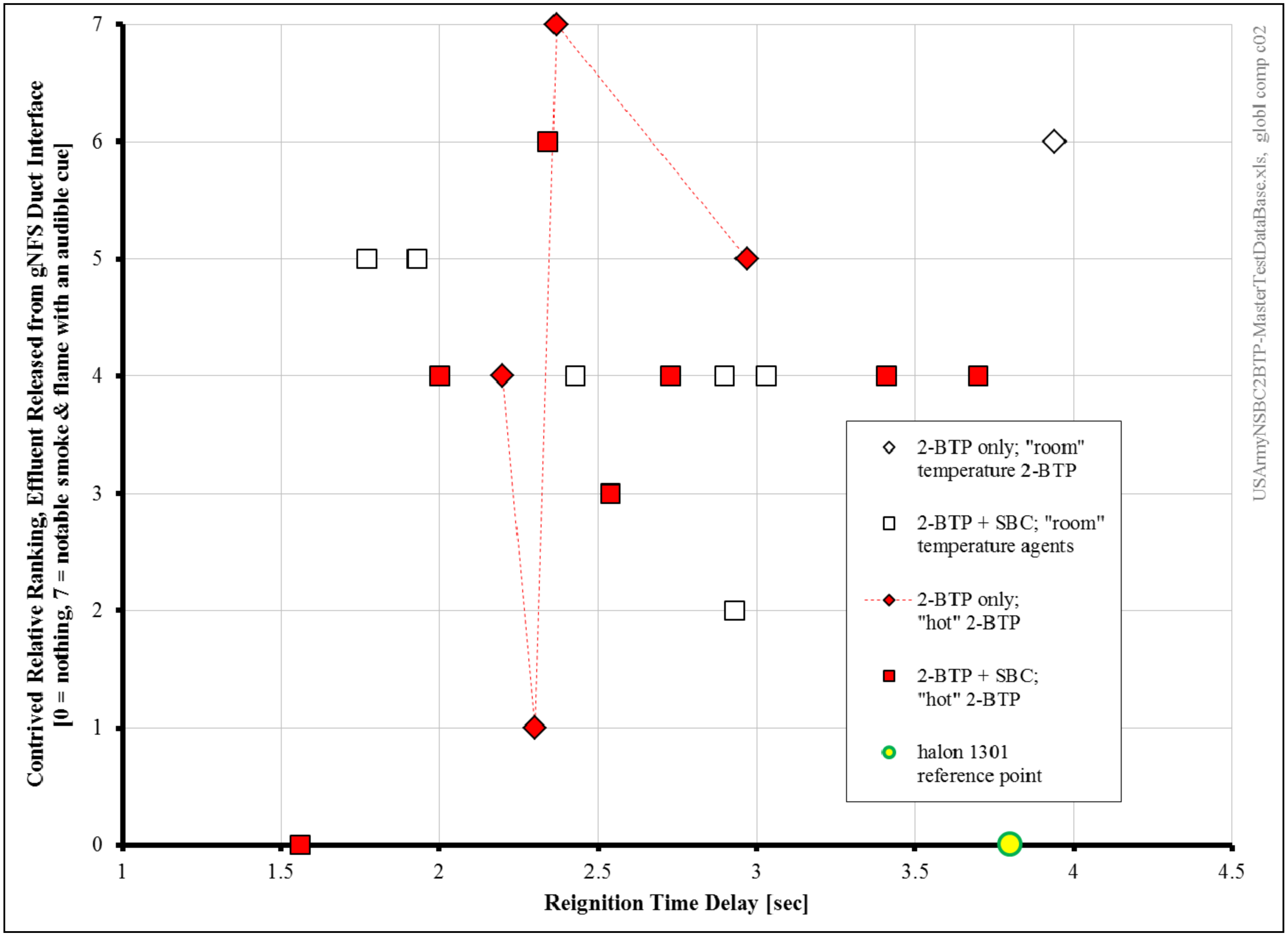

Figure 2. Comparing RTDs, “hot” & “room”-temperature 2-BTP for Solitary 2-BTP & the 2-BTP/SBC Blend.

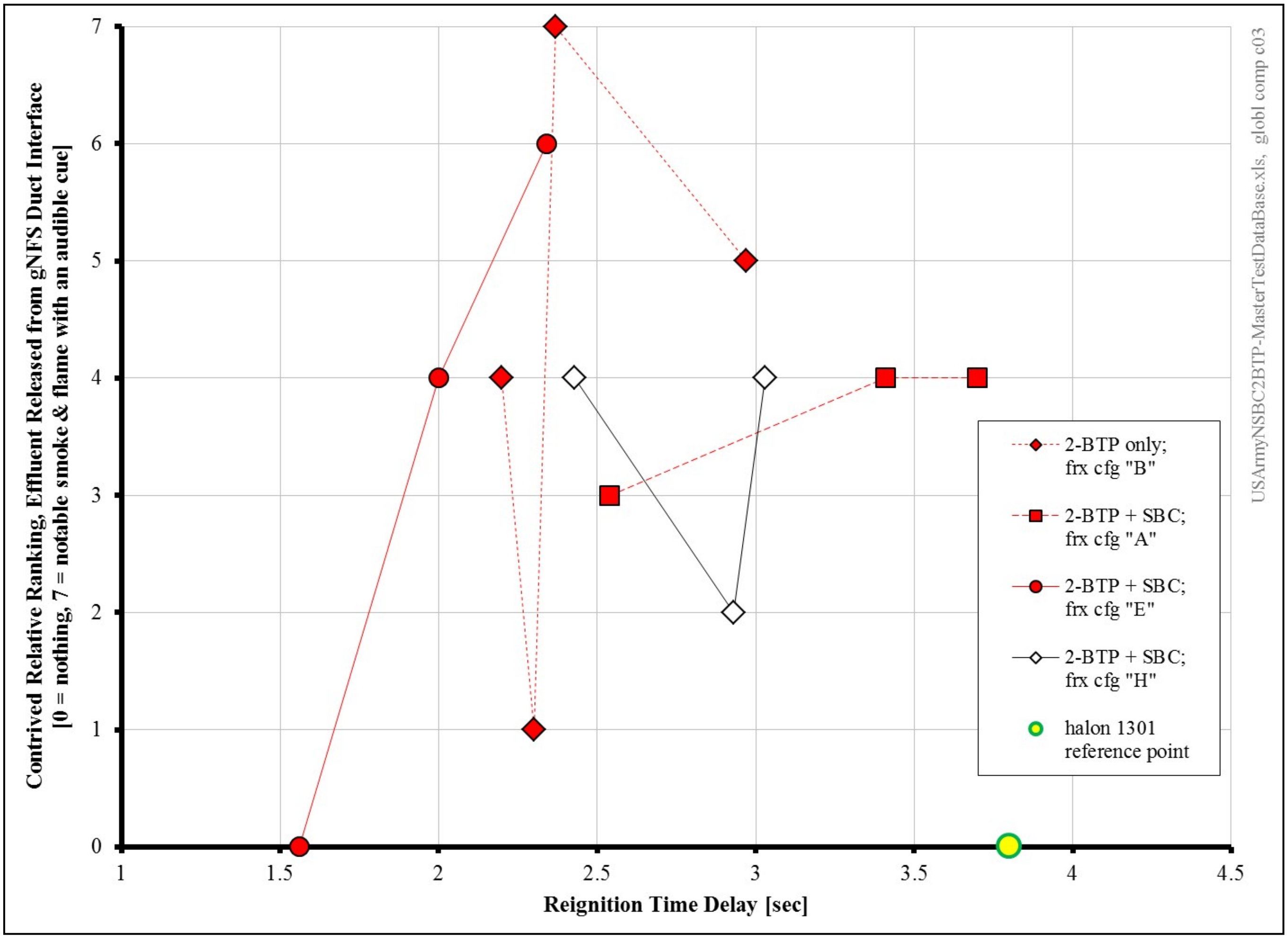

Figure 3. RTD Behaviors for Various Groups of Repeated Tests.

Frx cfg “A”, 8-9aug2018, Tb mix manifold, 4.4 lbf “hot” 2-BTP, 0.44 lbf SBC.
Frx cfg “B”, 10 & 13aug, no mix manifold, 4.4 lbf “hot” 2-BTP.
Frx cfg “E”, 14-15aug, Tt mix manifold, 4.4 lbf “hot” 2-BTP, 0.44 lbf SBC, inj nzls different.
Frx cfg “H”, 16-17aug, no mix manifold, 4.4 lbf “room” 2-BTP, 0.66 lbf SBC, inj nzls different.

Working Report Tables.

Table 1. Basic Test Information, 6-17Aug2018 Testing with 2-BTP & SBC or 2-BTP.

Test ID	Fuel burned	Globl Frx cfg	Frx agent	Frx Agent Weight [lbf]	Temperature, shell of 2-phase frx btl [°F]	Number of frx btls	Exterior Plumbing Cfg	Reignition time delay [sec]	Smoke Escape Duct Interface ?	Flames Escape Duct Interface ?	Audible cue?	Duct Interface Score
20180808-03-102530	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	146	2	2-feed, Tb	2.54	yes/obv	yes/mnr	no	3
20180808-05-144830	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	151	2	2-feed, Tb	3.41	yes/obv	yes/obv	no	4
20180809-03-133530	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	148	2	2-feed, Tb	3.7	yes/obv	yes/obv	no	4
20180810-03-093220	Jet-A/JP8	B	2-BTP	4.4	145	1	1-feed	2.2	yes/obv	yes/obv	no	4
20180810-06-114530	Jet-A/JP8	C	2-BTP/SBC	4.4/0.44	91	2	2-feed, Tb	2.9	yes/obv	yes/obv	no	4
20180810-08-140030	Jet-A/JP8	B	2-BTP	4.4	156	1	1-feed	2.97	yes/obv	yes/ntb	no	5
20180813-03-112940	Jet-A/JP8	B	2-BTP	4.4	152	1	1-feed	2.3	yes/mnr	no	no	1
20180813-05-141620	Jet-A/JP8	B	2-BTP	4.4	155	1	1-feed	2.37	yes/ntb	yes/ntb	yes [c]	7 [c]
20180814-03-093920	Jet-A/JP8	D	2-BTP	4.4	84	1	1-feed	3.94	yes/ntb	yes/ntb	no	6
20180814-07-120035	Jet-A/JP8	E	2-BTP/SBC	4.4/0.44	146	2	2-feed, Tt	1.56	no	no	no	0
20180814-09-142010	Jet-A/JP8	E	2-BTP/SBC	4.4/0.44	155	2	2-feed, Tt	2	yes/obv	yes/obv	no	4
20180815-03-100740	Jet-A/JP8	E	2-BTP/SBC	4.4/0.44	157	2	2-feed, Tt	2.34	yes/ntb	yes/ntb	no	6
20180815-05-134350	Jet-A/JP8	F	2-BTP/SBC	4.4/0.44	159	2	2-feed, Tt	2.73	yes/obv	yes/obv	no	4
20180816-03-083940	Jet-A/JP8	G	2-BTP/SBC	4.4/0.44	84	1	1-feed	1.93	yes/obv	yes/ntb	no	5
20180816-05-105240	Jet-A/JP8	H	2-BTP/SBC	4.4/0.66	87	1	1-feed	2.43	yes/obv	yes/obv	no	4
20180816-07-140930	Jet-A/JP8	H	2-BTP/SBC	4.4/0.66	91	1	1-feed	2.93	yes/mnr	yes/mnr [d]	no	2
20180817-03-085920	Jet-A/JP8	H	2-BTP/SBC	4.4/0.66	86	1	1-feed	3.03	yes/obv	yes/obv	no	4
20180817-05-105430	Jet-A/JP8	I	2-BTP/SBC	4.4/0.66	90	1	1-feed	1.77	yes/ntb	yes/obv	no	5

Table 2. Basic Test Information About Additional Tests Provided for Consideration.

Test ID	Fuel burned	Globl Frx cfg	Frx agent	Frx Agent Weight [lbf]	Temperature, shell of 2-phase frx btl [°F]	Number of frx btls	Exterior Plumbing Cfg	Reignition time delay [sec]	Smoke Escape Duct Interface ?	Flames Escaped Duct Interface ?	Audible cue?	Duct Interface Score
20040915-12-1508	oil	n/a	halon 1301	2.5	~100	1	1-feed	2.45	no	no	No	0
20040916-10-0843	oil	n/a	halon 1301	2.5	~100	1	1-feed	2.52	no	no	No	0
20040920-10-1046	oil	n/a	2-BTP	4	~100	1	1-feed	2.44	yes/obv	yes/mnr	No	3
20040920-12-1511	oil	n/a	2-BTP	4.4	~100	1	1-feed	2.82	yes/ntb	yes/ntb	Yes	7
20040922-12-1051	Jet-A/JP8	n/a	2-BTP	4.4	~100	1	1-feed	3.87	yes/ntb	yes/ntb	Yes	7
20060320-14-1454	Jet-A/JP8	n/a	halon 1301	2.5	~100	1	1-feed	2.81	yes/mnr	no	No	1
20060321-11-0913	Jet-A/JP8	n/a	halon 1301	2.5	~100	1	1-feed	2.74	no	no	No	0
20060512-14-1422	Jet-A/JP8	n/a	halon 1301	2.5	~100	1	1-feed	3.56	no	no	No	0
20060512-15-1529	Jet-A/JP8	n/a	halon 1301	2.5	~100	1	1-feed	3.38	no	no	No	0

Acronyms, definitions, & short-hand notation used in tables 1 & 2, “BASIC TEST INFORMATION TABLE, 6-17AUG2018, 2-BTP & SBC OR 2-BTP” & “BASIC TEST INFORMATION TABLE, ADDITIONAL TESTS PROVIDED FOR CONSIDERATION.”.
Notes contained in these tables.
[c] : audible cue heard by the 4 people located in the control room during the test in real time; analogous to a "low"- intensity, "long"- duration, "far-distant" rumble of thunder; reviewed audio track of the associated recording & could not hear the audible cue [experienced difficulty with the sound-tracking of the recording equipment for all tests this day]
[d] : flames exit red exhaust duct at its assembly seam downstream from the atmospheric gap almost opposite of the viewing camera, not through the atmospheric gap itself
Notes about the grading of the observations occurring at the gNFS duct interface as a result of fire reignition.
no = nothing seen to atypically escape; nothing heard
mnr = minor; challenging to see, but is observed to escape when the visual record is closely reviewed
obv = obvious; plainly seen to escape; most of the gNFS exit flange & red exhaust duct circumferential entrance remain visible
ntb = notable; the gNFS exit flange & red exhaust duct circumferential entrance are obscured by exiting flame; smoke quantity released is atypically large
The observations of atypical behavior at the duct interface are scored in the following qualitative manner :
0 = observation classified as “no”; nothing atypical seen or heard
1 = observation classified as “mnr”; heard an audible cue
2 = observation classified as “obv”
3 = observation classified as “ntb”
A duct interface score is the sum of these 3 categories; i.e. summing all the grades of “smoke escape”, “flame escape”, & “audible cue”.

Table 3. DVR Video-Clip Information Table							
Test ID	**Camera count**	**Camera views**	**fuel burned**	**globl frx inj cfg**	**frx agent**	**frx agent wt [lbf]**	**duct interface score**
20040915-12-508	1	di.	oil	"cert-lo"	halon 1301	2.5	0
20040916-10-0843	1	di.	oil	"cert-lo"	halon 1301	2.5	0
20040920-10-1046	1	di.	oil	[a]	2-BTP	4	3
20040920-12-1511	1	di.	oil	[a]	2-BTP	4.4	7
20040922-12-1051	1	di.	Jet-A/JP8	[a]	2-BTP	4.4	7
20060320-14-1454	1	di.	Jet-A/JP8	"cert-lo"	halon 1301	2.5	1
20060321-11-0913	1	di.	Jet-A/JP8	"cert-lo"	halon 1301	2.5	0
20060512-14-1422	1	di.	Jet-A/JP8	"cert-lo"	halon 1301	2.5	0
20060512-15-1529	1	di.	Jet-A/JP8	"cert-lo"	halon 1301	2.5	0
20180808-03-102530	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	3
20180808-05-144830	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	4
20180809-03-133530	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	4
20180810-03-093220	4	fz/spray, di, PGF2btp, FrxRakBounce.	Jet-A/JP8	B	2-BTP	4.4	4
20180810-06-114530	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	A	2-BTP/SBC	4.4/0.44	4
20180810-08-140030	3	fz/spray, di, none, diR.	Jet-A/JP8	B	2-BTP	4.4	5
20180813-03-112940	4	fz/spray, di, PGF2btp/useless, PGFsbc.	Jet-A/JP8	B	2-BTP	4.4	1
20180813-05-141620	4	fz/spray, di, PGF2btp, gNFSleft.	Jet-A/JP8	B	2-BTP	4.4	7 [c]
20180814-03-093920	4	fz/spray, di, PGF2btp, gNFSleft.	Jet-A/JP8	B	2-BTP	4.4	6
20180814-07-120035	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	C	2-BTP/SBC	4.4/0.44	0
20180814-09-142010	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	C	2-BTP/SBC	4.4/0.44	4
20180815-03-100740	2	fz/spray, di.	Jet-A/JP8	C	2-BTP/SBC	4.4/0.44	6
20180815-05-134350	4	fz/spray, di, PGF2btp, PGFsbc.	Jet-A/JP8	D	2-BTP/SBC	4.4/0.44	4
20180816-03-083940	4	fz/spray, di, PGF2btp, diR.	Jet-A/JP8	E	2-BTP/SBC	4.4/0.44	5
20180816-05-105240	4	fz/spray, di, PGF2btp+sbc, diF.	Jet-A/JP8	E	2-BTP/SBC	4.4/0.66	4
20180816-07-140930	4	fz/spray, di, PGF2btp+sbc, diF.	Jet-A/JP8	E	2-BTP/SBC	4.4/0.66	2
20180817-03-085920	4	fz/spray, di, PGF2btp+sbc, diF.	Jet-A/JP8	E	2-BTP/SBC	4.4/0.66	4
20180817-05-105430	4	fz/spray, di, PGF2btp+sbc, diF.	Jet-A/JP8	F	2-BTP/SBC	4.4/0.66	5

Acronyms, definitions, & short-hand notation used in Table 3, “DVR Video-Clip Information Table”.
Notes contained in this table.
[a] : look up in the KAD database about its 2-BTP work in 2004.
[c] : audible cue heard by the 4 people located in the control room during the test in real time; analogous to a "low"-intensity, "long"- duration, "far-distant" rumble of thunder; reviewed audio track of the associated recording & could not hear the audible cue [experienced difficulty with the sound-tracking of the recording equipment for all tests this day]
Notes about weights of SBC in this table.
0.44 lbf = 0.44 lbm = 200 g [testing near sea level]
0.66 lbf = 0.66 lbm = 300 g [testing near sea level]
Notes, explaining the abbreviations describing the various camera views.
fz/spray = spray fire zone inside the FAATC gNFS
di = "normal" view, duct interface between the FAATC gNFS & the red exhaust duct
PGF2btp = frx btl pres gage face, 2-BTP frx btl
PGFsbc = frx btl pres gage face, sodium bicarbonate
PGF2btp+sbc = frx btl pres gage face, 2-BTP & sodium bicarbonate
FrxRakBounce = useless view of frx rack deck area; does capture structural motion resulting from frx bottle discharge
diR = view of the duct interface from the frx rack near the frx btls
diF = reverse view of the duct interface from the floor
Explaining “total DI ranking sum”…
This value is a sum of 3 values that characterize the visual quantity of smoke &/or flame that escaped from the gNFS duct interface [atmospheric gap] & whether or not an audible cue was heard.
See each “Basic Test Information Table”, a total of 2, for individual grading breakdown for each test.

TABLE L-1. ATC TEST DATA SUMMARY FOR THE ENGINE NACELLE TESTING

Test No.	Date, 2018	Time	Configuration	SBC		BTP, g	N2, psi	SBC		BTP		Shell Temp, °F	Discharge Time, s	RTD, s	SBCs Remaining, g
				Type	Weight, g			Bottle	VHA	Bottle	VHA				
Standard plumbing configuration - 12 monarch 100 nozzles oriented as close to recreating previous BTP testing as possible															
1	08-Aug	1025	Heated BTP + SBCs	FE-1	199.6	2,032	970	4207897	ABQ0061	4570072	ABS0704	141	2.5	2.4	35
2	08-Aug	1450	Heated BTP + SBCs	FE-1	199.6	1,996	970	4207094	ABS0651	4452783	AAV9349	148	2.5	3.41	34
3	09-Aug	1335	Heated BTP + SBCs	FE-1	199.6	2,018	970	4207904	ABS0651	4570072	ABS0704	148	2.7	3.7	32
Single bottle discharge setup - BTP discharged through 90° elbow															
4	10-Aug	0935	Heated BTP NO SBCs	-	-	1,982	970	-	-	4452783	AAV9349	145	2.9	2.2	NA
Standard plumbing configuration															
5	10-Aug	1145	Ambient BTP + SBCs	FE-1	199.7	2,009	970	4207897	ABQ0061	4570149	AAV9335	91	-	2.9	30
Return to single bottle setup															
6	10-Aug	1400	Heated BTP NO SBCs	-	-	1,991	970	-	-	4570072	ABS0704	156	2.6	3	-
7	13-Aug	1130	Heated BTP NO SBCs	-	-	1,987	970	-	-	4452783	AAV9349	152	2.5	2.3	-
8	13-Aug	1415	Heated BTP NO SBCs	-	-	1,991	970	-	-	4570149	AAV9335	155	2.4	2.37	-
9	14-Aug	0940	Ambient BTP NO SBCs	-	-	2,005	970	-	-	4570149	AAV9335	84	2.6	3.94	-
Begin new plumbing configuration - 12 nozzles reduced to 10 drilled out nozzles (lower 2 plugged), upper nozzles turned slightly upstream. Monarch 70 main orifice was drilled out to 9/64-in. and Monarch 100 spinner and nut were used, SBCs injected to T-fitting below BTP elbow.															
10	14-Aug	1155	Heated BTP + SBCs	FE-1	199.6	1,991	970	4207904	ABQ0061	4452783	AAV9349	146	2.5	1.56	20
11	14-Aug	1420	Heated BTP + SBCs	FE-3	199.6	1,991	970	4207897	ABS0651	4570072	ABS0704	155	2.7	2	39
12	15-Aug	1010	Heated BTP + SBCs	FE-3	199.6	2,009	970	4207904	ABQ0061	4452783	AAV9349	157	2.7	2.34	47
Plumbing configuration change - return to 12 nozzle orientation with drilled out monarch 70s, other aspects of plumbing unchanged.															
13	15-Aug	1345	Heated BTP + SBCs	FE-3	199.6	1,991	970	4207897	ABS0651	4570149	AAV9335	159	2.2	2.73	43
Return to single bottle setup - BTP slurry injected through 90° elbow. BTP slurry was ultra-sonicated for 5 min in the Branson unit and lightly agitated halfway through to ensure mixing.															
14	16-Aug	0840	Ambient BTP Slurry	FE-3	199.6	1,996	970	-	-	4452783	ABQ0061	84	2.5	1.93	0
15	16-Aug	1055	Ambient BTP Slurry - Increased SBCs %	FE-3	300	2,005	970	-	-	4452783	ABQ0061	87	2.4	2.43	0
16	16-Aug	1400	Ambient BTP Slurry - Increased SBCs %	FE-3	300	2,009	970	-	-	4452783	ABQ0061	91	2.4	2.93	0
17	17-Aug	0900	Ambient BTP Slurry - Increased SBCs %	FE-3	300	1,996	970	-	-	4570149	ABQ0061	86	2.4	2.03	0
Nozzles changed to pipe caps with 6x 0.0465-in. holes in each cap. Caps oriented the same direction as nozzles.															
18	17-Aug	1055	Ambient BTP Slurry - Increased SBCs %	FE-2	300	1,996	970	-	-	4452783	AAV9335	90	1.7	1.77	0

TABLE L-2. ATC TEST NOTES FOR THE ENGINE NACELLE TESTING

Test No.	Note
1	Slow propagation during re-ignition. Seemingly smaller pressure pulse.
2	Longer RTD, more violent re-ignition. Smoke. Slightly more pressure.
3	No black smoke, more white instead. Flame outside the interface but not as violent as test No. 2.
4	More smoke (gray/dark). Flame escaped but not violent.
5	Flame escaped. Moderate dark smoke. Flame up into exhaust tube.
6	Most violent re-ignition so far. Large fireball escaped all sides. Large amount of black smoke.
7	"Something seemed audible" - FAA Witness. Puff of white smoke out backside of fixture. No flame escape on re-ignition.
8	Large fireball. Larger puff of black smoke. Possible audible noise/pressure thud. One of the worst trials. O-ring completely off poppet, recovered machine shop side upper cross.
9	Large bright fireball with very fast re-ignition. Moderate white/gray smoke. No audible cue.
10	Very positive test (FAA). Slower extinction (lingering swirling flames). "Nothing" on re-ignition/exhaust interface. Very mild.
11	Violent re-ignition but contained in exhaust interface. Large fireball but not as bad as test No. 9. Black smoke. Weak extinguishment.
12	Slow extinction. Swirling fire out. Violent re-ignition. *No pressure gage videos - DVR was not set to record*. Black/dark smoke. Brief fireball escaped interface. *FE-3 seems to be slightly cakier than FE-1 for post shot residue.
13	Quicker extinguishment. Fast re-ignition, but not violent/instantaneous. Moderate fireball with gray smoke. Some flame escape from interface but minimal. O-ring lost completely and recovered.
14	Quicker extinguishment. Rapid re-ignition. More dark/gray smoke. Moderate fireball, but more smoke than fire escaped the interface. O-ring lost and recovered.
15	Faster extinguishment (even with ~0.5 s of lingering flame). Quick re-ignition but not violent. Moderate flame/smoke escaped but dissipated quickly. O-ring lost and recovered.
16	"That was encouraging" - FAA Witness. Minimal flame/smoke escape. Good trial. Less powder fell from fixture upon opening. *No O-ring losses - just rolled on poppet.*
17	Quick extinction. Larger fireball and slightly more smoke than trial No. 2 of this configuration. More powder fell from fixture when opened. O-ring rolled but not lost.
18	Quicker discharge. Faster re-ignition but seemed like a smaller fireball. Less smoke. Small amount of flame escaped the interface.

Note: Many of the observations regarding smoke output, degree of violence in the re-ignition, fireball production, audible cue, etc. are subjective and are not quantified by a measurement.

APPENDIX M. REFERENCES

1. ADSS Test Directive Approved, ATEC, 2 March 2016, subject: Fire Extinguishing Performance Test of Low GWP Agents, ATEC Project No. 2017-DT-ATC-RDECO-G5550.

2. 2019-FSAB-011, Low Global Warming Potential Automatic Fire Extinguishing System Candidate Agents Toxic Fumes Investigation, 22 January 2019.

3. TOP-2-2-614, Toxic Hazards Tests for Vehicles And Other Equipment, 28 February 1995.

4. IOP-FSAB-014, Measuring Concentrations of Toxic Fumes during Live Fire and AFES Performance Testing, 30 May 2012.

APPENDIX N. ABBREVIATIONS

2-BTP = 2-bromo-3,3,3-trifluoropropene
A5 = article 5
AERTA = Army Environmental Requirements and Technology Assessments
AFC = U.S. Army Futures Command
AFES = automatic fire extinguishing system
AMCOM = Aviation and Missile Command
APU = auxiliary power unit
ATC = U.S. Army Aberdeen Test Center
BDL = below detection level
BOP = blast overpressure
CAS = Chemical Abstract Services
CCDC = Combat Capabilities Development Command
CF_3Br = bromotrifluoromethane
CF_3CHF_2 = pentafluoroethane
CF_3CHFCF_3 = 1,1,1,2,3,3,3-heptafluoropropane
CFT = cross-functional team
CO_2 = carbon dioxide
COF_2 = carbonyl fluoride
DC = dry chemical
DoD = Department of Defense
ESOH = Environment, Safety and Occupational Health
F/X = number of fire extinguishers
FAA = Federal Aviation Administration
FBG = fireball generator
FSAB = Field Sampling and Analysis Branch
FWHM = full width half max
GCC = Gulf Cooperation Council
gNFS = generic nacelle fire simulator
GVSC = U.S. Army Ground Vehicle Systems Center
GWP = global warming potential
HF = hydrofluoric acid
HFC = hydrofluorocarbon
HFE = heavy fuel engine
HPFE = hand-held portable fire extinguisher
IR = infrared
ITH = integration time horizon
IUPAC = International Union of Pure and Applied Chemistry
LOAEL = lowest-observed-adverse-effect level
MDC = minimum design concentration
MDL = method detection limit
NA = not applicable
NOAEL = no-observed-adverse-effect level
ODP = ozone depletion potential
ODS = ozone depleting substance
REFROP = reference fluid properties
RTD = re-ignition time delay
PROFISSY = properties of fire suppression systems
PRV = pressure reaction vessel

SBC	= sodium bicarbonate
SME	= subject matter expert
SPGG	= solid propellant gas generator
TARDEC	= U.S. Army Tank Automotive Research, Development and Engineering Center
TBD	= to be determined
TWA	= time weighted average
USP	= United States Pharmacopeia

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