NGP PROJECT 6E: "VERIFICATION OF PRINCIPLES" – REAL SCALE TEST APPROACH

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INTRODUCTION

The purpose of the test program comprising Project 6-E of the Next Generation Fire Suppression Technology Program (NGP) is to (1) verify the new extinguishing agent distribution guidance developed during the course of research comprising the NGP[*] program, (2) verify the relative performance of chemicals as a function of their thermophysical properties and test fixture conditions, and (3) identify any currently unexplained phenomena of the entire extinguishing process. These elements will be considered in the configuration and environmental conditions of a full-scale, or "real scale" engine nacelle, using a realistically sized test simulator designed to recreate the conditions of operating aircraft engine nacelles, as well as generating realistic fire events with which to perform extinguishing experiments. As such, this testing provides a bridge to the laboratory and intermediate-scale agent screening devices devised and used in the duration of the NGP research program, to assess their ability to intelligently estimate the influence of real nacelle operating parameters on the relative merits of different extinguishing agent candidates, as useful, controllable and economical screening tools.

It is understood that these bench-scale test apparati, such as cup, opposed flow and turbulent spray burners, as well as flow and agent condensation simulation devices, have the ability to control multiple parameters, exclude or isolate others, and create uniform flow, discharge and mixing conditions when desired, often in a one or two dimensional fashion, to permit the development of phenomena characterizations, general design criteria and repeatable experimental protocols. However, the "real-scale" environment does not afford such controllable or simplified, standardized operating conditions, with complex three dimensional flows and transient mixing processes, and inherent statistical variances in flame and distribution characteristics, due to substantial and varying turbulence, and other process instabilities, most of which cannot be controlled even in a test environment. Similarly, physics-based computer models of the extinguishing process have been developed or enhanced during the course of NGP research, incorporating its findings as they have been made available, and validated to date based upon results observed in a laboratory environment. The models are constructed so as to also permit the simulation of more complex geometries and flows associated with real-scale engine nacelle fires, by incorporating the knowledge derived to date. Therefore, both these models and the small and intermediate-scale screening apparati will be assessed as to their merits in predicting the behavior and performance of extinguishing agents and systems in real scale aircraft engine nacelle fires, under various operating conditions, as judged by their correlation to, and predictive abilities of the results observed from the real-scale tests.

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[*] The mission of the NGP program is to identify, analyze and demonstrate fire extinguishing chemicals ("extinguishants"), technologies or design techniques that can match the efficiencies of Halon 1301 as nearly as possible. The program is now focused on engine nacelle fire extinguishing applications.

In concert with the general purposes of this task in support of the NGP program, the results from the preceding research projects of the NGP have also resulted in the observation and identification of several general principles of the extinguishing process that dictate the performance of a fire extinguishing agent and system under various conditions. Representatives of the many investigators and contributors to the NGP program during its execution have reviewed these noted principles, and have condensed them into a streamlined set of the most significant and profound examples. The interest in verifying these principles as well will also influence the structure and content of the test series, with the data also evaluated in light of its abeyance with these principles.

GENERAL PRINCIPLES OF INTEREST TO EVALUATE IN "REAL-SCALE"

The following is a condensed set of some of the most pertinent general principles of the extinguishing process that have been observed and noted as result of NGP research, to be verified or modified as a result of planned real-scale engine nacelle experiments:

Principle 1: Extinguishants with boiling points higher than the local engine nacelle airflow and surface temperatures do not disperse sufficiently in time for engine nacelle fire mitigation, whereas those with boiling points below the prevailing temperature can disperse sufficiently if properly applied.

Rationale: Extinguishants with boiling points above the prevailing ambient temperature in the nacelle after discharge will not immediately flash vaporize, relying on the lengthy process of evaporation to produce sufficient quantities of vapor to extinguish fires before they are entrained by the ventilation air out of the nacelle outlets. The resulting liquid jet discharged will then break up into an array of droplets, the size distribution based upon the liquid physical properties and flow characteristics. The potential for these droplets to reach the remote fire location, having been successfully entrained into the air flow streamlines versus making contact with the nacelle structure and component surfaces (hence condensing on such surfaces and preventing their fire mitigation contribution) is dependent upon the resultant droplet sizes and their momentum in the particular flow field. Additional droplet evaporation of the liquid reaching the fire source may occur by entrainment into the flame region, with the degree of evaporation then dictated by its residence time in the flame reaction zone. These complexities are largely avoided by the flash vaporization of all or a large portion of liquid of low boiling-point extinguishants that quickly assume gaseous flow properties, and are generally more "forgiving" of nacelle structure and component (commonly known as "clutter") variations upstream from the fire, providing a more uniform flow due to expansion and diffusion, and assuring a greater degree of extinguishant vapor present for entrainment near the flame. However, many candidate "next generation" replacements for Halons exhibit boiling points higher than the lowest nacelle temperatures observed in actual operation. Therefore, the study of the effects of liquid droplet evaporation, transport and condensation through realistic nacelle flow geometries, as a function of air velocity and other factors, is warranted to determine if special discharge accommodations or the application of excess extinguishant mass is sufficient to overcome transport and entrainment inefficiencies in some cases, or if certain candidates and conditions preclude their effective use for nacelle applications.

Principle 2: The measured "cup burner" extinguishing concentration of a candidate extinguishant is an effective predictor of the critical flame suppression concentrations required within the flame recirculation zone of an engine nacelle fire.

Rationale: Bench-top "cup burner" devices meter precise flow rates of vaporized extinguishants at set volumetric concentrations in air into a vertical glass chamber, in which a small cup of liquid fuel is placed and lit. The volumetric concentration is then gradually increased until extinguishment is observed. This test has become an international standard in determining the critical concentration required to achieve the extinguishment of flames with various extinguishants. Due to the steady state nature of extinguishant introduction into the region surrounding the flame, it is understood to provide an in essence infinite residence time of extinguishant in contact with a flame to extract heat or inhibit flame-sustaining chemical reactions. The results from this apparatus are highly repeatable by various researchers, due in part to eliminating the key transport issues associated with extinguishment.

In a realistic engine nacelle fire, for example, the air flow over obstacles creates air shearing effects behind obstructions and recirculation vortices. These recirculation zones are locally stable flow regions that can support and sustain flames that are created due to the contact of released fuels and ignition sources. Air is entrained from flow over the obstacle to mix with and feed the flame in a sustained manner. It is difficult to apply extinguishants to such hidden, stable flames for several reasons. First, only a portion of the extinguishant applied over the obstacle is effectively entrained into the recirculation zone, particularly if it comprises some high-momentum droplets to some extent, due to the momentum of the flow and its tendency to follow its original direction of flow due to inertia. Secondly, the extinguishant will only reside within the recirculation zone for a limited period of time, before it is ejected and released downstream of the fire. It is theorized that a critical volumetric concentration of extinguishant, equivalent to the cup burner concentration, must be entrained into the flame zone and reside for some minimum period of time, mixing with the reacting flow until extinguishment is completed, to correlate to the infinite residence times associated with cup burner data. Typical engine nacelle fire extinguishing systems exploit a high rate of discharge to minimize dilution by the incoming ventilation airflow, and to minimize the overall mass of extinguishant discharged to optimize the required system weight. This approach generates a transient concentration profile that approximates a more nearly Gaussian profile in time (with a peak concentration at some point in the middle of the discharge period), with significant variations of the profile under various system and operational conditions, and at various locations in the nacelle. The theory proposes that the time period that the critical cup burner concentration (for the extinguishant in question) is held <u>directly within the recirculation zone of the flame</u> at a minimum as observed in the local transient concentration profile will dictate the success or failure in extinguishment.

Principle 3: The "quality" or degree of uniformity and effective transport of various extinguishants can be sufficiently predicted using CFD codes upgraded during the research of the NGP program.

Rationale: Numerous investigators and contributors to the NGP research program have devised methodologies and algorithms, or fundamental data to support their development, that have been used by specialists in upgrading existing computer fluid dynamics/heat transfer codes to incorporate such knowledge for the process of extinguishant flow and dispersion after release. New data and models of droplet development and flow through clutter, for example, have been incorporated into these models. A nacelle structural model using the codes will be made of the test fixture, with selected operational scenarios planned for tests will be recreated using the code, with the results both used as a predictive tool to assist in testing, and with the test results also providing a means of validating the capabilities of the codes to date, or suggesting further improvements based upon observed test results.

Principle 4: Increasing the number of local extinguishant discharge sites increases the dispersion "quality" in terms of balanced concentration profiles, up to some practical limits.

Rationale: By providing multiple, presumably dispersed remote sites for which to independently discharge extinguishant into the nacelle, the discharged extinguishant at each site has a shorter distance and volume to spread and mix with air before it encounters expanding extinguishant mixtures from adjacent discharge regions. Therefore, there is less distance to establish gradients in concentration, and multiple points of origin assure minimum variance in concentration within smaller regions. Additionally, this time period to reach relative homogeneity as the expanding extinguishant vapor/air mixtures meet at the boundaries of adjacent discharge regions occurs much faster due to the shorter discharge paths required, further reducing the relative effects of ventilation airflow dilution as it sweeps through the nacelle and carries extinguishant from the nacelle through its outlets. Therefore, relative concentration uniformity is reached on a time scale that can be relatively fast compared to the air exchange rate due to incoming ventilation airflow, which can potentially result in extinguishment anywhere a fire is present before airflow dilution degrades these conditions. However, as the number of remote discharge sites is further increased, diminishing returns are observed, as the relative mixing efficiency improvements become more modest as the discharge periods required for mixing uniformity become progressively shorter. Since an increased number of discharge sites results in more discharge tubing, brackets and possibly nozzles, the additional increase in aircraft weight suggests the existence of an optimal number of release sites for a given nacelle configuration with respect to weight optimization.

Principle 5: The extinguishant concentration established in the recirculation zone is a function of the injection time and mixing time behind the obstacle ("clutter") that stabilizes the flame.

Rationale: Prior research by Takahashi, Hamins, Hewson and others in the NGP program, as well as other researchers, have proposed and demonstrated that the relative quantity of extinguishant entrained from the free stream over a bluff body that anchors a flame into the flame's recirculation zone is a function of the ratio of the free stream velocity over the clutter to the height of the clutter itself, also with influences of the injection time on the total time the entrained extinguishant resides in the recirculation zone. These conditions and structures will determine if the extinguishant mixed in the free air stream is sufficiently entrained into the recirculation zone, and held for a sufficient time with at least cup burner concentrations sufficient to extinguish the flame.

Principle 6: The observed behavior by several NGP researchers of extinguishant passage through clutter of various configurations will be verified under full scale, three dimensional conditions.

Rationale: Prior NGP research efforts have characterized the degree of flow interruption, pressure drop and re-direction through clutter of various idealized configurations, including any condensation of liquid portions of mixed-phase extinguishant flows on the clutter arrays. Most of these studies were performed on idealized, two dimensional clutter representations, and computer models of this behavior were also derived. The complex three-dimensional flows and clutter arrangements in realistic nacelles may challenge these simplified representations.

Principle 7: Assuming that a mix of extinguishant vapor and liquid aerosol reach the flame reaction zone, the sufficient vaporization of liquid particles to enhance extinguishment will be dependent upon the aerosol particle sizes, the liquid's heat transfer characteristics, residence time in the recirculation zone, and other related parameters.

Rationale: If some mixture of liquid aerosol particles is interspersed with the extinguishant vapor as it enters the recirculation zone of the flame, the ability of the particles to evaporate and increase the extinguishant vapor loading in the flame to facilitate extinguishment is dependent upon its vaporization characteristics and residence time in the flame. The evaporation rate is based upon the common heat transfer properties known for these extinguishants, and the droplet diameters (or characterization of their distribution).

Principle 8: The effectiveness of bromine in extinguishing flames, at least on a per unit mass basis, is independent of the type of molecule in which it is bound.

Rationale: It is thought that the dominant effects observed by liberated bromine atoms in inhibiting self-sustaining flame reactions far supercede secondary effects of other species and radicals formed by the breakup of the extinguishant molecule itself. As such, for brominated, chemically active extinguishants, they serve in essence as a bromine delivery mechanism. Their efficiency would then be dictated by the relative mass of bromine present to the overall mass of the molecule (this presumes that the molecule will be sufficiently disassociated to fully release all its bromine content in the flame). This general analogy greatly simplifies the search for some chemically-active extinguishant alternatives, if this observation and hypothesis can be shown to be verified by full-scale tests.

Principle 9: Hybrid gas generator fire extinguishers (HFEs) are a more effective way of suppressing fires when using extinguishants with high boiling points.

Rationale: Many of the most promising candidate extinguishants identified by NGP research, in terms of very low required cup burner concentration values, feature very high boiling points, in comparison to the Halon 1301 currently used, as well as many of the first-generation Halon replacements. It is anticipated that much of this high efficiency will be lost due to condensation on nacelle clutter elements prior to reaching the flame zone, or to difficulty in entraining into the recirculation zone. This difficulty may be alleviated by applying the heating and propulsive power of gas generator extinguishers. These devices, which pyrotechnically convert solid materials into gaseous reaction products with the generation of much heat within fractions of a second, function similarly to automobile airbag inflators and similar devices. They have been shown in recent years to be highly effective in their own right in generating copious quantities of inert gas in a weight and space efficient manner. One derivative of this approach is to use a small gas generator cartridge to heat, vaporize and propel highly efficient extinguishant fluids. Such a device can rapidly heat a high boiling point liquid to discharge it as a superheated gas, with the inherent flow effectiveness associated with lower boiling point extinguishants. However, since the boiling point of these extinguishants will still be higher than the nacelle and air flows of interest, the potential exists for rapid cooling and condensation before the expanding, pre-heated gas reaches the fire zone. The attempt to quantify these competing effects under realistic nacelle geometries and operating conditions has not been performed in a controlled manner to date, and is of interest to assess this means as a way of exploiting these promising candidates. Any efficiencies observed (and resultant system size reductions as well) will be compared to increases in system complexity and size when incorporating a gas generator unit with a separate extinguishant chamber. The ability to virtually eliminate the large vapor space above the liquid in the bottle, since the extinguishant's vapor pressure will be small and a large space for compressed nitrogen gas will be unnecessary (the pressurization being alternatively supplied by the small solid propellent gas generator), can result in further system size reduction.

Principle 10: The suppression effectiveness of a non-catalytic extinguishant in a full-scale engine nacelle is determined by its ability to absorb heat as it enters the flame zone.

Rationale: Studies conducted by NGP researchers Sheinson and Pitts on the importance of thermal effects in simple flame systems indicate that the key property of a non-catalytic extinguishant is its ability to absorb heat starting upstream of the flame zone. The heat absorbed may be sensible, or it may involve a phase change or decomposition. The degree to which the latent heat can be used to decrease the amount of extinguishant necessary to suppress a fire in a full-scale engine nacelle needs to be verified in real-scale conditions, as seen in intermediate-scale experimental apparati.

AIRCRAFT ENGINE NACELLE TEST FACILITY (AENTF) FEATURES AND CAPABILITIES

FACILITY SPECIFICATIONS

The Aircraft Engine Nacelle Test Facility (AENTF) at Wright-Patterson Air Force Base was constructed expressly to realistically recreate the environment experienced within a wide range of aircraft engine nacelles, with the capability to conduct repeated, full-scale nacelle fire tests under those conditions. An overall diagram of the key mechanisms of the facility is shown in Figure 1.

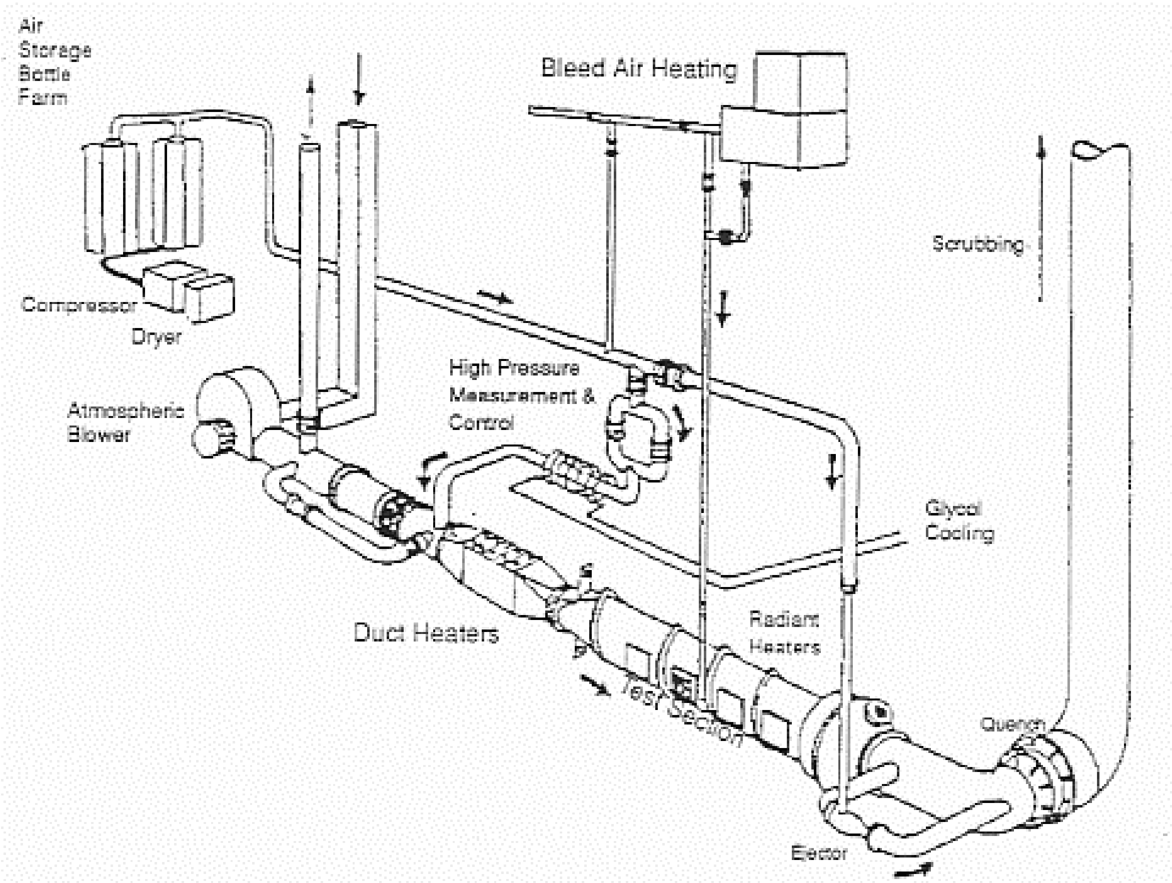

Figure 1. AENTF Primary Mechanical Components.

A primary feature of the facility is the capability to recreate the airflow conditions within the nacelle volume, with respect to both airflow rates and temperatures. An atmospheric blower and associated high-pressure bottle farm is used to provide up to 11.0 lbs. per second of airflow, which is more than adequate for the types of aviation platforms currently in operation. An industrial chiller is used to chill the rapidly flowing air, which subsequent reheats due to insulation limitations between the chiller and the nacelle section, resulting in a nacelle internal temperature of -30 F (-34.4 C) or less. A remote fuel supply cart is used supply heated flammable fluids, such as JP-8 jet fuel or various aviation hydraulic fluids, preheated and pressurized to their appropriate operating values before being introduced into the nacelle section. A separate extinguisher unit is used that permits heating or cooling of the extinguisher contents, with cooling provided by an immersion bath of dry ice, regulated by a heat tape wrap, to a container temperature of down to -65 F (-53.9 C) for cold temperature tests. A remote control room is used to monitor internal nacelle conditions of airflow rate, temperature and pressure, as well as fuel and extinguishant conditions, before and during each test. The operation of the fuel release, airflow control, fire and extinguisher initiation, and shutdown procedures are all controlled by automated, computerized controls at this site, and video monitoring.

“Generic” Real-Scale Nacelle Test Fixture

The test fixture recommended and planned for use in this test series is a “generic”, reconfigurable engine fixture nacelle previously used in the National Halon Replacement for Aviation, back in the mid-90s, as well as more recent Halon replacement testing for the U.S. Army. It features the capability for extensive reconfiguration to replicate a variety of engine nacelle configurations and operating conditions. The outer nacelle case of the test fixture is a cylinder 4 feet in diameter, and fifteen feet in length, as an effective test section. For this program, the three foot diameter internal cylindrical simulated engine core section is planned for use. Rather than changing core diameters and the “clearance” area between the nacelle and engine core, the airflow patterns (including local recirculation) will be changed by changes in the clutter (rib) height. The outer nacelle has ports in two locations to mount fuel nozzles and spark ignitors to produce two downstream fire locations. The entire nacelle assembly can be rotated to represent “top”, “side” or “bottom” fire locations. Similarly, multiple ports for the fire extinguisher assembly are present downstream to effectively shorten or lengthen the effective test section, as well as “top”, “side” and “bottom” discharge ports, where the extinguishant can be discharged in-line, 90 degrees off center, or 180 degrees off center from the site of the fire, to evaluate the ability of the extinguishant to wrap around the nacelle volume to remote sites before it is exhausted from the nacelle. Annular ribs can also be mounted on the inside of the outer nacelle and on the inner core of heights varying from one inch to three inches, to simulate structural ribs, supports and nacelle components (they alternate in frequency, from the nacelle surface extending down, to the engine core extending up, every 12 inches downstream). They also serve to realistically block the flow of extinguishant and to serve as “bluff bodies” that shield the base of the fire and create recirculation zones that make fires stable and resistant to blowout. In the flame region, ribs parallel to the flow are also present to simulate clutter with surfaces that extend parallel to the flow, and to realistically inhibit the lateral “wrapping” of the extinguishant flow around the engine core surface, requiring entrainment over these lengthwise obstructions to enter the flame’s recirculation zone. A photograph of this test fixture (installed) is shown in Figure 2.

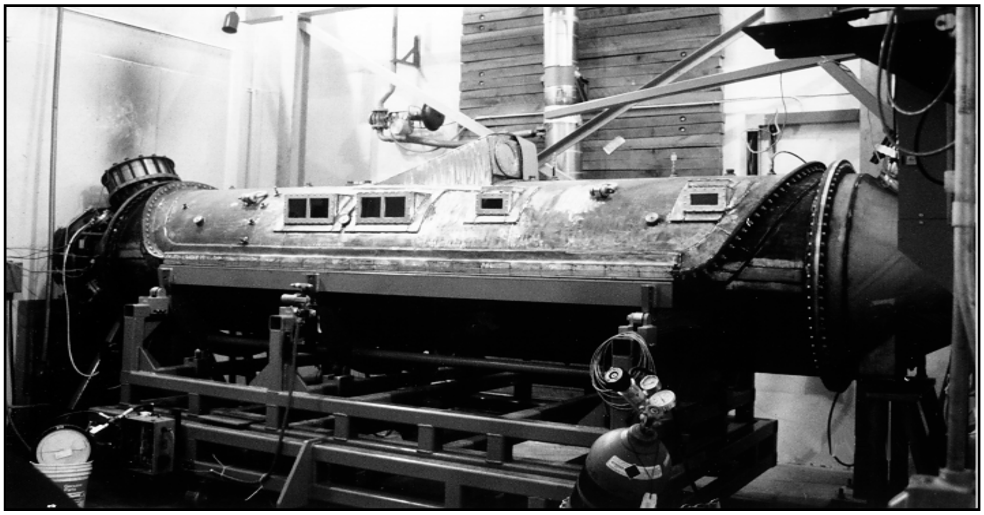

Figure 2. Universal Test Fixture Installed in Facility.

Figure 3 is a close up illustration of the region of the fixture near the origin of the fire site, and the configuration of components in proximity (dimensions are in inches).

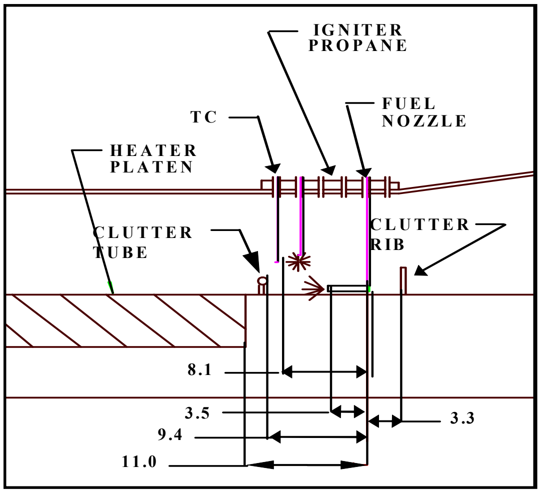

Figure 3. Drawing of Close Up of Fire Site, Nearby Components in Nacelle.

DESIGN OF EXPERIMENTS METHODOLOGY

To collect sufficient data while considering all the potential physical parameters (or “factors”) of interest, within the cost and schedule constraints of the program, requires employing the use of orthogonal matrices in a Design of Experiments (DOX) approach, as was used in the aforementioned National Halon Replacement for Aviation. This process can sometimes be used most efficiently by separating all the parameters of interest into one or more independent groups of dependent factors, each with their own customized experimental matrices, to evaluate the most factors and interactions of interest within these limits. Splitting a large matrix into sub-matrices is best accomplished when a global process can be conceptualized as two or more separate and independent sub-processes, where unique factors are of interest to each (although there can be some similarities between the two). This acknowledges that due to the separate issues and factors of each sub-process, interactions that extend between factors in different sub-processes are often irrelevant. This permits the scaling of the number of factors for each sub-process to a minimum, with smaller, more efficient matrices with the missing cross-matrix interactions not of interest. Since the matrices are independent, it permits the selection of a different critical response variable for each matrix of a sub-process. If simultaneous measurements are made of multiple response variables of interest for the individual runs in a given matrix (such as observation of mass required to extinguish, required peak concentration or duration of residence time), which is possible with each response variable having its own independent analysis from the same set of data, then it is often useful to couple the two or more matrices with at least one common response variable to sustain a global analysis, particularly if the data should suggest a design and settings of factors in both to optimize both sub-processes into an optimal global process.

This special circumstance appears to be advantageous for the topic of interest in this test program. It can be visualized that the extinguishment process comprises two relatively independent sub-processes – the sub-process of discharging the extinguishant in an appropriate quantity and manner uniformly throughout the nacelle in an efficient manner, and the sub-process of determining what quantity and configuration of extinguishant concentration is needed to extinguish fires locally at the site of the fire zone, to determine the critical conditions required for uniform replication in the nacelle in the first sub-process mentioned. Not only do these two sub-processes have different factors that control each process (with some in common), but they have different required instrumentation needs, and even differ in their need for the presence of fire or not! These unique test setup differences suggest further test operation optimization by segregating their setup into independent sub-matrices. This optimization is particularly required to accommodate the additional number of tests required for each "run" (test configuration and set of conditions) for replications and the number of tests using varying quantities of extinguishant, to determine the threshold quantity required for extinguishment as determined using a pre-established "bracketing" procedure. This procedure, refined in earlier engine nacelle fire test programs, typically requires approximately twenty tests for each run to confirm five successful extinguishments with an approximate 90% degree of confidence, and within a 10% weight tolerance band, of a final extinguishment mass threshold value for each run.

TEST APPROACH, CONFIGURATION AND PROCEDURE

Phase I – Local Conditions in Fire Zone Required for Extinguishment

Purpose: The purpose of this test phase is to determine how factors of the local fire zone configuration, operating conditions and extinguishant discharge conditions and composition influence the conditions required within the recirculation zone of the fire to result in extinguishment.

Response Variable(s): The response variable to be measured is the minimum duration that the cup burner concentration is held in the recirculation zone where the flame is present at the threshold of extinguishment, in accordance with the initial hypothesis. The area under the concentration-time curve will also be tabulated, if it is observed that changes in the discharge rate and concentration-time profile change the required residence time of the extinguishant at cup burner concentration, under otherwise identical conditions.

Factors of Interest and Settings:

(1) Airflow Rate: 1.0 lbm/sec and 3.0 lbm/sec. (local velocity measurements can be made near the flame region, if needed)

(2) Clutter (rib) Height: 1.0 inch high and 3.0 inches high

(3) Fire Type: Spray fire or pool fire

(4) Relative Air Temperature to Extinguishant Boiling Point, or Revised Temperature Difference (note: The aspect of whether the ventilation air temperature (and extinguishant storage bottle temperature) is some minimal value either above or below the extinguishant's boiling point should control the extent of flash vaporization and additional evaporation during transport; therefore, rather than keep the air flow temperature and extinguishant boiling points as independent factors (which would have differing relative effects on extinguishants with differing boiling points if the air temperature settings are kept as uniform), a combined relative air temperature ("temperature delta") of the air temperature to the extinguishant boiling point will be considered as a factor. A setting both above and below the boiling point of some set amount will

be used, with the absolute value dependent upon the boiling point of the extinguishant tested.): -10 C below the extinguishant boiling point, and +60 C above the extinguishant boiling point.

(5) Presence of Chemical Reactivity and Inhibition (note: chemical reactivity and inhibition in a flame, presumably by scavenging hydroxyl radicals and other key catalysts that sustain combustion reactions, is influenced by different mechanisms and conditions than simple reaction zone cooling until reaction rates drop below sustainability, as with simple thermal extinguishants; hence an interest in studying the affects of the various factors on chemically-active extinguishant efficiencies versus non-chemically active candidates): a chemically-active and non-chemically active extinguishant candidate - CF3I and HFC-227 respectively.

(6) Extinguishant Flow Rate: 3.0 lbm/sec (-1) and 10.0 lbm/sec

An L-16 (16 run configuration) test matrix is proposed for these six factors at two levels.

Instrumentation:

Since the focus of this test phase is to study the detailed mechanisms and processes within the flame region itself, it is proposed to install an array of Halonyzer concentration measurement probes within the region of the flame, to characterize the local concentration gradients within this region, and to identify any local inhomogeneities that might exist. Figure 4 is an illustration of an anticipated layout of these Halonyzer probes. They function by siphoning a local sample of the atmosphere in the proximity of the probe opening, heating and vaporizing the mixture, and measuring densities of the mixture and comparing to calibrated mixtures of the extinguishant in question and air. This device is typically used in sets of twelve probes, and when such probes are placed in a dispersed pattern throughout the nacelle, they serve as an FAA-certified method of verifying a uniform concentration of discharged extinguishant in nacelle systems to confirm the design of a sufficiently balanced discharge system. In this series three probes will be placed just above the rib shielding the flame, half the distance between the top of the rib and the top of the nacelle, to measure the free stream concentration of extinguishant as it enters the flame region. One probe will be mounted in-line with the fuel nozzle and the presumed base of the flame, and one probe on either side, approximately one rib height apart, to measure inhomogeneities in the mixture as it flows past the rib. Three similarly spaced probes will be placed to sample near the nacelle core, behind but as close to the rib as possible and yet be just downstream of the fuel nozzle, to be in a region that is normally immersed in the flame and in the recirculation zone. The adjacent probes are also intended to measure lateral inhomogeneities in the concentration within the recirculation zone. A similar trio of probes will be mounted further aft of this set but still within the expected recirculation zone, to measure any lengthwise inhomogeneities. Next to the center probe behind the rib will be two additional probes on both sides, facing laterally (to the left and right). Since it is uncertain how sensitive these probes and their measurements are to the direction in which they are oriented (it should depend upon the relative momentum of the flow and local pressure in comparison to the negative pressure suction of the probe), these probes will be better able to directly measure lateral flows resulting from helical flows that sweep tangentially into the flame region, versus over the upstream rib. Any measurement difference between these probes and the upstream-facing central probe will suggest an orientation sensitivity that must be accounted for. A twelfth probe will measure just outside the discharge port of the extinguisher unit, to compare its timing and concentration patterns to that measured over the downstream rib. A fiber optic probe may also measure sprays behind the rib.

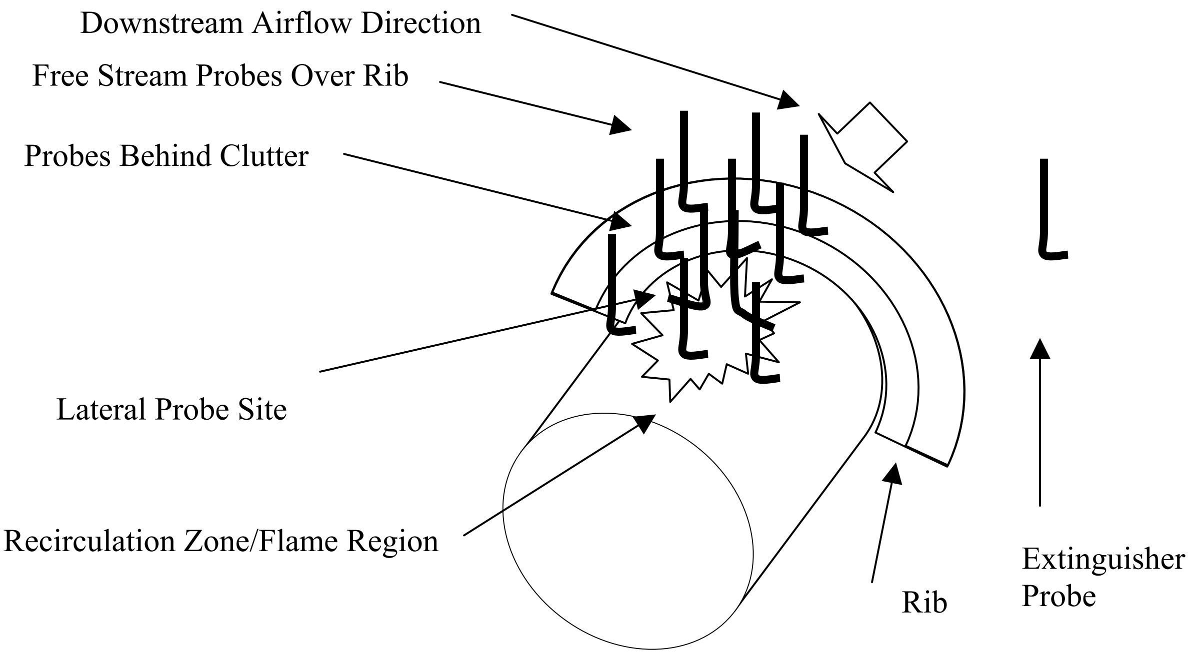

Figure 4. Halonyzer Probe Mounting in Flame Region.

A pitot tube can be used above the downstream rib to measure a local velocity value. Thermocouples will be used to measure the temperature profile in the recirculation zone as well during the extinguishment process. Pressure readings inside the extinguisher will not only measure the steady state conditions to assure proper conditions for the test, but also transient pressure drops during discharge that indicate the extent of evacuation and mass flow rate.

<u>Approach</u>:

1. A pan will be used to hold the fuel for the pool fires, residing in the bottom of the nacelle. The pan elevation is lower than the height of the ribs, which serve as a bluff body to stabilize a flame on the fuel pan pool. An illustration of the pan, seated in the nacelle, is shown in Figure 5.

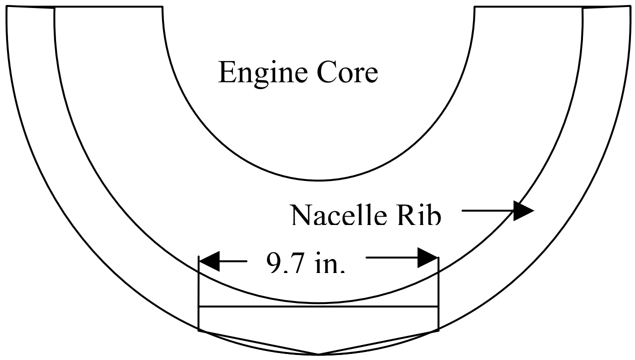

Figure 5. Pool Fire Pan in Nacelle.

2. Following the active fire tests, the extinguisher mass charges at the threshold of extinguishment for each run will be repeated in a no-fire condition, to collect Halonyzer trace

data for those conditions, using the previously described probe matrix. If possible, one Halonyzer probe may be configured to collect liquid entrained in the probe, at the point just exterior to the nacelle, before it enters a heated section. Three repeats will be done for each run, and the data averaged to minimize test instabilities.

Analysis:

DOX Approach – The test data will be analyzed using ANOVA (analysis of variance) and other established protocols for orthogonal arrays. The data will first be analyzed with response to the duration in the fire zone that the cup burner concentration is retained, as a minimum. If this is found to be sensitive to the mass flow rate (and hence the profile of the concentration-time curve), then the data will also be analyzed with respect to the area under the concentration-time curve to see if this criteria eliminates the variance with the mass flow rate, or some other similar criteria. Note that other factors may also influence this required residence time, and will be noted in the analysis, as well as factors that do not offer appreciable or statistically significant sources of variance.

Modeling – The test nacelle will be modeled in VULCAN, and the same conditions run to determine if agent concentration profiles, and the gross mass capacities that produce local cup burner residence times which result in extinguishment, are matched by the code, for selected runs of the test matrix. Specific probe readings that suggest local inhomogeneities, or significant lateral entrainment, will also be useful in understanding the realism of the model.

Analysis - Other computational analysis will be performed on the fundamental conditions observed for extinguishment, based upon the key dimensionless parameters and other criterion established earlier in the NGP program. The predicted amount entrained into the recirculation zone, for example, for a given rib height and air flow rate can be compared to differences in the concentration traces of the probes above the rib in the free stream versus that immersed in the recirculation zone (providing data to assess the mixing time for the clutter, which may correlate to the Strouhal number). If the recirculation zone is shown to be inhomogeneous, then some averaging technique or representative equivalent may need to be derived and compared to the physical models that presume homogeneous conditions. The effects of several key cited dimensionless numbers will be able to be estimated using calculations with the actual test data. These could include the ratios of the rate of extinguishant mass injection to the air mass flow rate, and the ratio of the product of the rate of extinguishant mass injection and the injection period, divided by the total mass of air and extinguishant in the nacelle at any one time.

Phase II – Assessment of Extinguishant Dispersion Optimization

Purpose: The purpose of this test phase is to determine how factors pertaining to an engine nacelle's operating conditions and extinguishant system overall design parameters control the uniformity of the extinguishant discharge characteristics, as evidenced by the transient extinguishant concentration profiles measured simultaneously throughout the nacelle. Another purpose is to determine the system capacity and design requirements necessary to provide a sufficient supply of extinguishant to any location where a fire might be present, and of a duration deemed sufficient for fires experienced under those operating conditions.

Response Variable(s): The first response variable to be measured is the average and standard deviation of the extinguishant concentration duration at cup burner values for all twelve measured remote locations in the engine nacelle (or a substituted parameter such as area under the concentration-time curve if so determined from Phase I), for a given mass of extinguishant. Four different extinguishant mass charges will be tested for each run, sufficiently high such that the lowest concentration measured of any of the probes is sufficient to extinguish all the fires presented by the conditions in all of the runs. A curve fit procedure will be performed for the four points in each run to determine a relationship between the mass and the average and standard deviation for the probes, and the mass at which all probes meet the minimum concentration for each run. Another response variable will be the change in concentration from one location to the different adjacent probe locations under cold conditions in comparison to the hot air flow conditions and otherwise identical configurations, to indirectly estimate the amount of extinguishant lost due to condensation in the transport from one site to the next.

<u>Factors of Interest</u>:

(1) Airflow Rate: 1.0 lbm/sec and 3.0 lbm/sec.

(2) Clutter (rib) Height: 1.0 inch high and 3.0 inches high

(3) Number of Injection Sites of Extinguishant: One setting will involve the use of a single extinguisher and discharge port, in the side of the nacelle as in the Phase I testing. The other setting will entail the use of two independent extinguishers (although fired simultaneously), each directed through a low-flow restriction T-section and tubing conduit to two opposite ports in the nacelle (if two opposing ports do not currently exist in the test fixture, the T-section may be mounted inside the nacelle). The layout for this variant is shown in Figure 6.

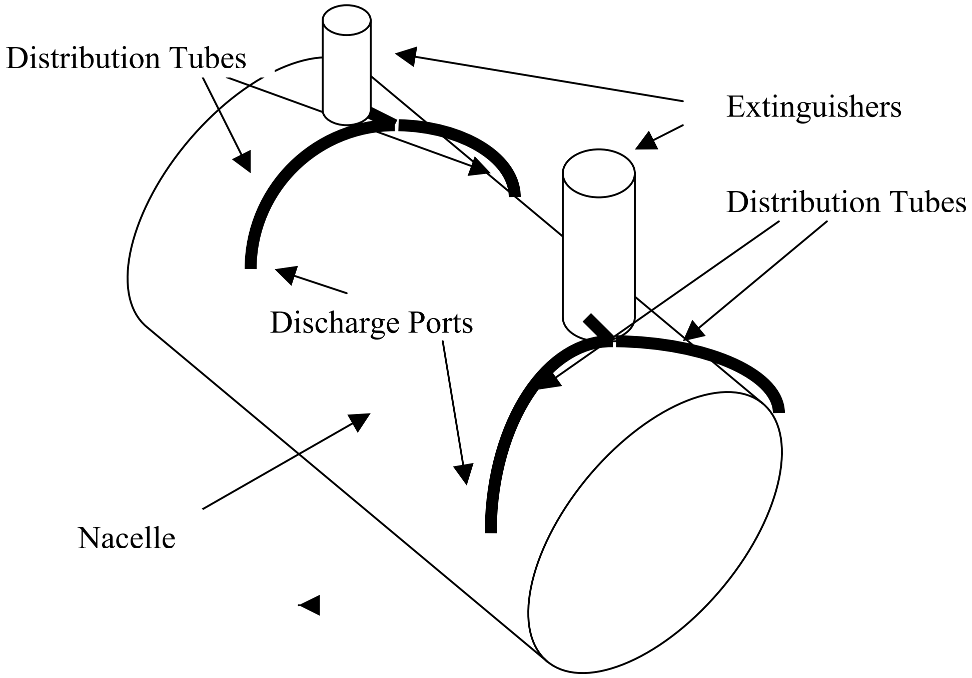

Figure 6. Layout for Multi-Port Discharge.

(4) Relative Air Temperature to Extinguishant Boiling Point, or Revised Temperature Difference: -10 C below the extinguishant boiling point, and +60 C above the extinguishant boiling point.

(5) Nozzle Exploitation (Note: Nozzles can be used to break up the liquid flow into much smaller droplets, of a controlled diameter distribution. A smaller droplet configuration promotes faster

evaporation by means of an increased surface area interface with the ambient area through which evaporation can take place at a faster rate. A smaller droplet will also completely evaporate to pure gas state much quicker. These traits are thought to be significant enhancements at cold operating temperatures, when flash vaporization is not possible, and the faster evaporation can continue until the surrounding air reaches the vapor pressure associated with that extinguishant at that temperature (if it ever does), with a much better chance of achieving this state before it is transported out of the nacelle.): The settings will be either the presence or lack of nozzles.

(6) Extinguishant Flow Rate: Currently flow rates are planned of 3.0 lbm/sec and 10.0 lbm/sec.

A 16 run, L-16 test matrix is also proposed for this phase, for the six factors at two levels.

Instrumentation:

For this series of tests the Halonyzer probes will be spread out into twelve separate "zones" to measure the uniformity of concentration in the nacelle during and after discharge. Each of three downstream positions will be split up into four quadrants, thus comprising twelve separate zones of the nacelle. The layout of the zones is illustrated in Figure 7.

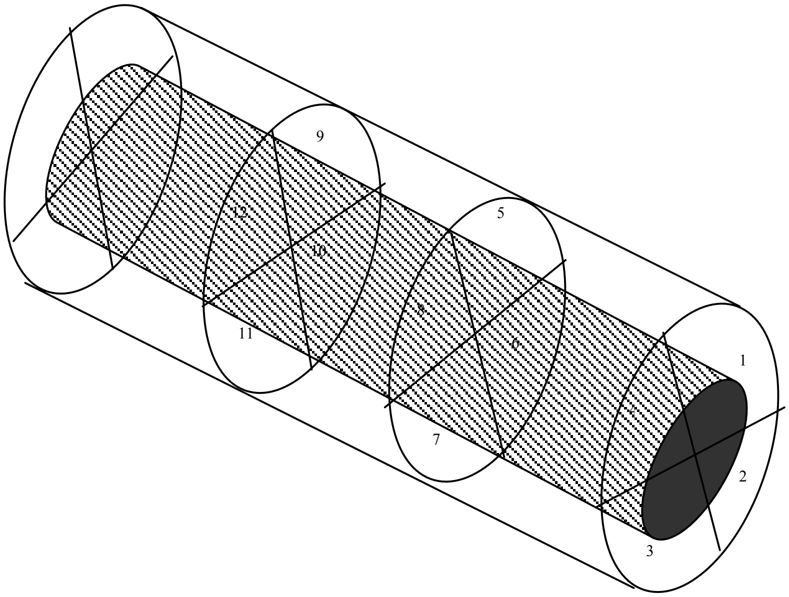

Figure 7. Nacelle Concentration Measurement Quadrants (numbered at upstream edge of each zone).

The same measurement approach will be used within the extinguishers as with Phase I, including pressure transducers in the extinguishers to estimate transient flow rates.

Approach:

It is planned to use HFC-227ea as the representative extinguishant – by adjusting the relative temperatures to its boiling point, its dispersion characteristics should be representative of all clean extinguishants.

Analysis:

DOX Approach – The test data will be analyzed using ANOVA (analysis of variance) and other established protocols for orthogonal arrays. The data will first be analyzed with response to the average and standard deviation of the extinguishant concentration duration at cup burner values for all twelve measured remote locations in the engine nacelle (or a substituted parameter such as area under the concentration-time curve if so determined from Phase I), for a given mass of extinguishant for all runs. An analysis will also be performed using the curves developed using the four mass values for each run that define the relationship between the mass and the average and standard deviation for the probes, and the mass at which all probes meet the minimum extinguishing concentration, for each run. The analysis of multiple discharge mass levels will reveal how the variability in average and standard deviation with factor changes varies according to the mass of the extinguishant charge. The determination of which factors influence these response variables, as opposed to factors that do not offer appreciable or statistically significant sources of variance, will be a significant outcome of this analysis.

Modeling – The test nacelle will be modeled in VULCAN or other CFD codes, and some of the same conditions run to determine if agent concentration profiles are similar to that seen in test, and if estimates of droplet distributions in the nacelle and local estimates of condensation from the instrument readings are consistent with computational codes.

Analysis - Other computational analysis will be performed, based upon the key dimensionless parameters and other criterion established earlier in the NGP program, related to distribution and transport of gaseous and mixed phase extinguishants. This includes studies on the degree of condensation or pressure drop measured or predicted through various types of clutter and obstacles. The results of the required flame zone concentrations and durations for various operational conditions in Phase I, coupled with the extinguisher system requirements to create identical conditions everywhere in the nacelle from Phase II data, will allow an integrated analysis to determine which factors most affect the entire multi-faceted process in total, and a means of optimizing the extinguisher system conditions for different operating conditions to achieve the best overall performance. The ability of the DOX process to estimate effects for factor settings that haven't even been tested, in support of proposing a "paper champion" most optimal design that may comprise factor combinations as well as settings that would not have been tested, for a range of different operating conditions (or the best overall design to support a range of conditions within one flight operating envelope), provides the capability to develop formulations to support the design of the most optimal system for any set of conditions.

Phase III – Follow-On Tests and Special Topics

Data reviews with the various NGP contributors will be held at the end of Phase I and II, to review the data and subsequent analyses, and to plan the results for the next phase. It is intended that a significant portion of remaining test facility time will be available at the end of Phase II to address a number of special topics that do not fit acceptably within the strict DOX protocol, or perform follow-on tests to clarify data collected from Phases I and II (although the results from Phases I and II will comprise a complete set of information successfully fulfilling the original intent and mission of this project). These areas of interest will need to be prioritized by the review team, based upon the results at the end of Phase II, to focus the remaining test time on subject areas of greatest interest. Some of the areas expected to be of interest at that time to consider include the following:

(1) Additional testing to “un-confound” confounded two-factor interactions shown to be significant in Phase I and II.

(2) Repeats or specially modified tests to resolve poorly understood results or conditions where the test results differ significantly from predictions.

(3) Multiple additional settings of significant factors, where additional settings are meaningful, to provide quadratic or higher order relationships, and maxima or minima.

(4) Additional special measurements for a few select test conditions, using laser diagnostics or other means where desirable and practical.

(5) Additional data with “fixed” dimensionless number values, to better compare to fundamental analyses and supplement the existing data.

(6) Data with extinguishants or varying quantities of bromine, to determine if extinguishing efficiency of chemically-active extinguishants is based predominantly upon the relative amount of “bromine loading” per unit mass, regardless of the structure of the molecule.

(7) Testing of pure inert or hybrid gas generators, to determine if the heating of the stored extinguishant can overcome cooling once it is discharged.

(8) Different clutter arrangements to perform tests consistent with conditions evaluated by Disimile and Presser.

(9) Test a “next generation” Halon replacement with chemical activity and performance similar to Halon 1301, in a select number of comparative tests.

(10) Small “witness fires” could be placed in various sites in the nacelle, to confirm that a proven “balanced” (with respect to concentration uniformity) system can indeed extinguish actual fires anywhere in a nacelle.

(11) The “witness fire” approach would facilitate the evaluation of condensed phase extinguishant systems, such as water mist, dry chemical and chemically active gas generator or aerosol units. This new approach, in a manner consistent with Underwriters Laboratory tests of enclosed space fire protection systems, would offer a means for the aerospace community to take advantage of the performance enhancements of these types of systems, many of which have shown promise in the NGP program.

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