ASSESSMENT OF FIRE-SUPPRESSION SIMULATIONS USING FULL-SCALE ENGINE NACELLE TESTS[1]

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ABSTRACT

Results are presented for a series of fire-suppression tests conducted in a full-scale nacelle along with the results of pretest predictions carried out using the Vulcan fire-physics simulation code. The purpose of these tests was to assess the utility of using a CFD fire-physics computer code (Vulcan) to predict the performance of a fire-suppression system. The test plans and test matrix were made to correspond to Vulcan simulations previously run to predict the test results. Twenty-five fire tests were conducted successfully in the NAVAIR ground nacelle simulator to validate this fire-modeling code. This simulator is a full-scale 'iron bird' mockup of an engine nacelle assembly typical of a combat aircraft with a four-nozzle suppressant-distribution system. JP-8 pool fires in a variety of locations were considered, and both the suppressant and the overall air flow rates through the nacelle were varied to simulate a wide range of operating conditions. In addition, the effects of varying the inhomogeneities were investigated by capping individual nozzles. The pretest Vulcan simulations correctly predicted the success or failure of extinction in nearly all cases. In only two cases were there disagreements between the Vulcan predictions and the test results. In both of these cases, when either of the two forward nozzles was capped, the test results found that the fires were suppressed using a bottle pressure 25% lower than the Vulcan simulations had predicted. This indicates that the Vulcan simulations were somewhat conservative in their predictions of the mixing in the forward nacelle region. Detailed data analyses of the twenty-five fire tests are presented in this paper.

INTRODUCTION

Advances in computational power and physics models relevant for fire-suppression applications have reached the point where predictive modeling of fire suppression in complex geometries is feasible using Reynolds-Averaged Navier-Stokes (RANS)

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Computational Fluid Dynamics (CFD). At this level, it is possible to account for inhomogeneities as the mean flows are resolved and mixing is treated using well-established models [1-3] having a sound physical basis. This is in contrast to zonal models where the composition is assumed to be constant over larger regions, with empirical mixing rules between zones.

In fire-suppression applications, the ability to predict inhomogeneities in the suppressant concentration is a key requirement for optimizing fire-suppression systems. If regions of the flow field exist where the suppressant concentration is locally below the value that leads to suppression (referenced to the cup-burner value or the strained flame-extinction value), then combustion can continue in those regions. In certain applications where the objective is to reduce the fire until fire-fighting crews can attack it, such behavior is acceptable. However, this is not acceptable for fires in aircraft nacelles and other inaccessible areas. Three factors come into play in aircraft nacelles and similar spaces: First, the quantity of fire suppressant that can be carried is severely limited in weight and space in order to satisfy the mission requirements. Second, the need to eliminate trace combustible vapors requires ventilation that also quickly sweeps suppressant out of the nacelle as it sweeps out combustibles. Third, a failure to completely suppress a fire can be catastrophic, since small pockets of fire can quickly propagate through the remaining premixed gases in the nacelle leading to accelerated burning under certain conditions. The present work under the Next Generation Program has focused on developing a set of models and tools to predict suppressant distributions in order to meet these challenges [4]. The results discussed herein are focused on suppressants with boiling temperatures well below operating temperatures, such as HFC-125 (C_2HF_5). Other work has addressed issues related to higher-boiling point agents [5-8].

The purpose of the tests described here is to assess the utility of CFD models like Vulcan to predict the outcomes of a fire-suppression system's performance. The tests and simulations are conducted in the context of a full-scale 'iron-bird' aircraft nacelle ground-test simulator located at the Patuxent River Naval Air Station. This nacelle simulator is representative of actual nacelles incorporating realistic arrangements of structural support, piping, machinery and other items collectively referred to as 'clutter.' This scenario tests both the fluid flow and the fire-suppression aspects of Vulcan in an application where the flow is under-resolved, and some of the physics is captured in subgrid-scale clutter models. The test sequence was developed based on Vulcan simulations described in [9,10] with the conditions designed to cross from successful to failed suppression. While simulations and tests were conducted in a simulated aircraft engine nacelle as determined by the focus of the NGP plan, the capabilities demonstrated herein are expected to be applicable to a wider range of scenarios including aircraft dry bays, land-based vehicles, and ships.

In this paper, we describe in brief the Vulcan simulations and the test procedures employed. The results of the tests are then compared to the prior Vulcan predictions, and the performance of the CFD model is assessed.

DESCRIPTION OF THE NACELLE GROUND-TEST SIMULATOR

Figure 1 shows the fire test simulator. The air inlet source is seen in the lower left coming up into the lower, forward end of the nacelle. The air is supplied from an electric-motor-driven centrifugal compressor and measured with a calibrated turbine meter. There is adequate straight pipe, according to ASME Standards [11] and a flow straightener between the compressor and the turbine meter to provide uniform flow profiles for flow measurement. Likewise there is adequate straight pipe downstream of the turbine meter, and downstream of the 45 degree elbow there is an Etoile swirl-removing conditioner in the straight pipe leading to the nacelle providing uniform velocity profiles similar to those in flight.

Suppressant is introduced into the nacelle through as many as four nozzles each on different streamlines and fuselage stations. The nozzles orifices have diameters ranging from 3 to 5 mm and are indicated with identifying numbers in the text where the numbers increase from nozzle 1 to nozzle 4 moving from the forward to the aft end of the nacelle. The suppressant flows to the nozzles from a bottle located on the inboard side of the nacelle through a piping structure. The bottle is filled with suppressant as described in the Test Method section. The nozzle characteristics and the suppressant concentrations generated by these nozzles are detailed in [10].

There are two vents in the top: a diamond-shaped vent all the way aft, and a balance piston round vent at the forward third. There are also four small holes (2 to 3 in. dia.) in the front face simulating vents and connections to the AMAD bay. Air, products of combustion, and suppressant can leave the nacelle through these vents and holes as described in [10].

An array of 21 type ‘K’ thermocouples was installed over the bottom of the nacelle in three rows, 8 each on the sides and 5 along the center, spaced approximately equally streamwise about 2 inches above the ribs. These were used to measure the temperatures above the pool fires and to detect the presence of the flames. These also provide some indication of the flow patterns that can be compared to the Vulcan model predictions.

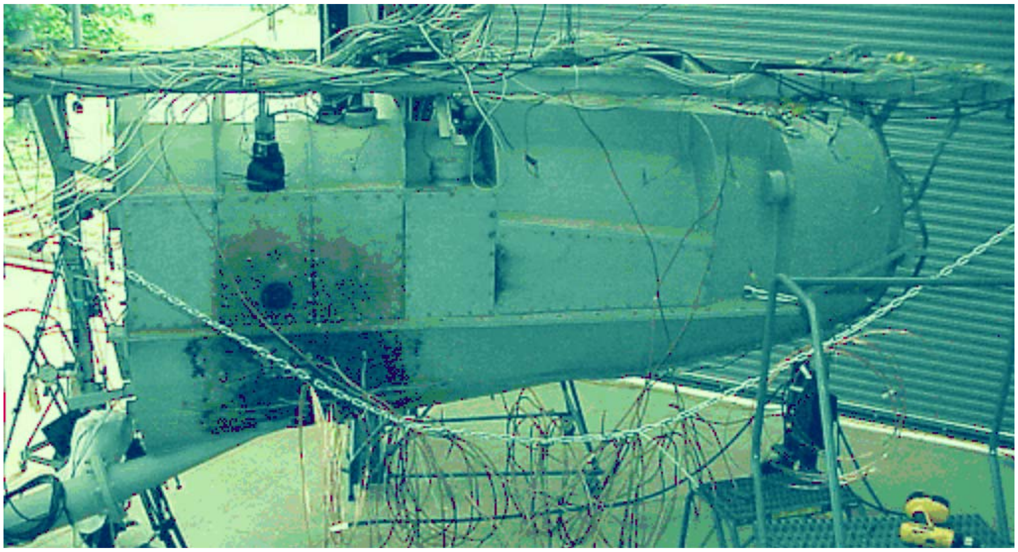

Figure 1. The F/A-18 Nacelle Ground Test Simulator, Outboard Side.

Instrumentation employed in the tests and their uncertainties:

1.Supply Air Flow Measurement: 6-inch Turbine Meter, Sponsler Co. Inc., Model SP6-CB-PH7-C-4X. S/N 130619 Calibrated in water 3 Sep 04: ± 0.75% systematic, ± 0.06% random.

2.Temperature Measurements: 21 Type K thermocouples, calibrated at ambient: ±1.1 deg. F systematic and ±1.8 deg. F random.

3.Digital Stopwatches (2): Calibrated error less than 0.1 sec over 15 minute period

4. Graduated Cylinders for measuring tares and final fuel quantities from the pools, ± 5 ml.

5. Video Cameras (4) to record the existence of fire and its extinguishment inside the nacelle.

6. Pressure Gauge, NoShok, 0-1000, ± 6 psi. (0-71 ± 0.4 bar)

7. Dead Weight Tester, Druck Co., 0-10,000 psi. ± 2.5 psi.(0-710 ±0.2 bar)

8. Pressure Transducer, Patriot Gage Co. 0-3000 psi. ± 15 psi.(0-207 ± 1 bar)

9. Digital Data Acquisition System integral with the ground test nacelle.

10. Calibrated Weigh Scale for the HFC-125.

TEST METHOD

This test series focused on extinguishing JP-8 pool fires contained by structural ribs and longerons along the lower nacelle surface. Prior to the testing, the bottom of the nacelle was lowered and the spaces between the ribs were sealed from their normal drain holes so that each could become a container for fuel. In the test series, three pools were used, beginning at the front of the nacelle and progressing in order to the middle of the nacelle. These pools are designated B1, B2 and B3 (or B3C3 indicating that the pool crossed one longeron). Prior to the tests, measured quantities of water were added to each pool, and the dimensions of the resulting pools were recorded to document the surface area of each pool as a function of liquid contained in the pool. The areas measured are tabulated in [9].

In most of the tests, all three pools were ignited because this provided the strongest fire source. In several tests only the first or third pool was used in conjunction with a reduced number of agent-distribution nozzles in order to assess the spatial distribution of the agent in both the Vulcan model and the real nacelle. The fuel burning rate and the nacelle temperatures were observed to be substantially lower when a single pool was burned as predicted in the Vulcan pretest simulations [9].

The mass of agent to be used in each test was measured by the difference over the tare of the empty 'bottle' on a calibrated scale. HFC-125 was the agent used in all tests. The rate of injection was controlled by the nitrogen pressure level in this bottle, and three rates of injection were targeted by setting the bottle pressure to one of three values. These values targeted injection rates that were expected to roughly correspond to a designed system (515 psig, 35.5 bar), a rate roughly 75% of the designed system (275 psig, 19 bar) and a rate roughly 50% of the designed system (122 psig, 8.5 bar); at these ambient temperatures the vapor pressure of HFC-125 was about 122 psig (8.5 bar) so that no nitrogen charge was added for the lowest pressure. Nitrogen is somewhat soluble in this agent, and consequently the fire-suppression agent in these tests was a mixture of both HFC-125 and nitrogen; the latter is ignored in the Vulcan simulations. The suppressant bottle discharges downward so that the initial discharge is driven by the nitrogen pressure, which drops as liquid agent is displaced from the bottle. At an intermediate pressure the rate of pressure change slows; this is associated with agent discharge being driven largely by the boiling of the agent or the dissolved nitrogen. Note that for the lowest bottle pressure there is no initial nitrogen-driven stage. The last stage of the discharge follows, in which the gaseous agent and nitrogen in the bottle flow from the bottle. The pressure profiles from several tests, where discharge was through all of the nozzles, are shown in Fig. 2. The discharges from the two tests denoted 1a(21) and 1a(25) are essentially the same conditions, as are the four tests denoted 1b(21), 5b(25), 8a(26) and 1b(26). The spread in these pressure profiles is indicative of uncertainties attributable to, for example, ambient temperature changes that may heat the bottle during the few minutes that the test is being set up. Such uncertainties are thought to be the most significant and are estimated to be roughly ±10%.

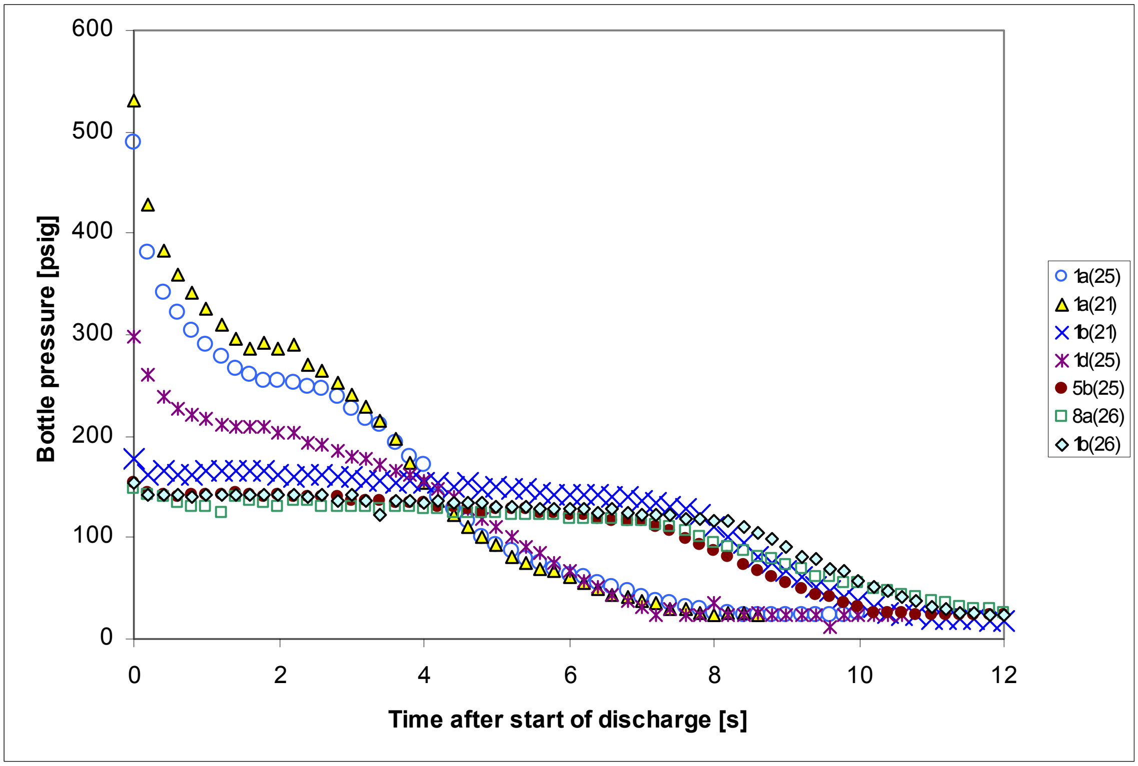

Figure 2. The suppressant discharge pressure, measured at the bottle, for various initial pressures with all nozzles discharging and a total of 3.2 kg of agent.

Attempts to model this discharge based on the pressure data with simple pipe flow network models has proven challenging, and the results indicate that the flow at the nozzle where most of the pressure drop occurs is most likely multiphase flow. We estimate somewhat more gas than liquid phase at the nozzles, with our best estimate being 60% gas and 40% liquid by volume. This volume ratio is expected to vary during the evolution of each discharge, moving towards 100% vapor at the end of the discharge. Note that the majority of the agent mass remains almost entirely liquid, but the presence of the gas phase dramatically reduces the rate at which the agent flows into the nacelle.

Once the bottle was filled, it was installed into the distribution piping on the nacelle, and its manual safety valve was opened. Predetermined quantities of fuel were poured from graduated cylinders into the pools chosen for each test. At the end of each test, the remaining fuel was drained from each pool so that the amount consumed could be accounted; these data, along with the elapsed time of the test, gave an estimate of the heat-release rate during the test.

Igniting the pools of JP-8 fuel at ambient temperatures is not trivial. The bottom of the nacelle was warmed with hot air to enhance the volatility of the fuel and to reduce heat losses. A minimum air flow from the blower was established to provide sufficient air for combustion. An electric igniter was inserted over each pool in turn while a more volatile fuel, pure ethyl alcohol, was sprayed onto the pool. Once the pool ignited, it required about 30 seconds to become vigorously inflamed. After all pools had established a durable flame, the air flow was ramped up to the predetermined rate—either1 kg/s or 0.5 kg/s according to the turbine meter. This steady flow was maintained for about 15 to 30 seconds before the agent was released. The elapsed period of burning was recorded with stopwatches as well as the digital data acquisition system. Four video cameras recorded the views inside and outside the nacelle by which elapsed times for extinguishment were recorded. This data acquisition system also recorded the signals from the array of 21 thermocouples in the nacelle. The temporal response of these thermocouples was not sufficient to determine the temperatures in the interior of the nacelle; the indicated temperatures had not attained steady state over the duration of the fires.

After each release of agent, a reduced air flow was maintained to cool the nacelle and remove potentially inflammable vapors. Then the remaining fuel was collected and measured in the graduated cylinders.

KEY RESULTS FROM THE PRETEST SIMULATIONS

Certain results from the Vulcan pretest simulations and simplified analyses helped guide the design of the experimental test plan and matrix. These results estimated the overall concentration of suppressant in the nacelle, the duration of the transients as the concentrations rise and fall, and the magnitude of the distribution of suppressant. To begin with, a simplified analysis of the relative masses of air and suppressant flowing into the nacelle can provide some guidance on the overall suppressant concentration and the transients. The suppressant mass-injection rate relative to the total injection rate provides a characteristic mean mass fraction within the nacelle, Y_{ss}. The injection must proceed for a long duration for the mean mass fraction to reach this characteristic steady-state value, but the mean mass fraction approaches this value in an exponential manner with an exponential time constant that is proportional to the total nacelle volume divided by the total volumetric influx. This time constant indicates the time scale for transients. In the tests conducted here, it was found that suppression is less sensitive to the total injected mass than it is to the rate of injection.

The Vulcan predictions indicate, and the test results confirm, that the overall or average mass fraction of suppressant resulting in fire suppression is substantially greater than the cup burner value, which is Y_{cb}=0.28 [12]. In general, the estimated average fraction required for suppression is on the order of 30% to 40% greater than the cup-burner value, according to the Vulcan simulations. A similar excess was required for the tests. The fact that a greater overall mass fraction is required indicates that inhomogeneities are significant. In other words, the suppressant's mass fraction in certain regions of the flow is substantially less than the mean. It is noted that the high rates of mixing present in the nacelle tend to reduce the mass fraction required to suppress the fire. It is found for HFC-125 that strained laminar flames are indicated to be suppressed at mass fractions as low as 0.16 [12].

One of the primary objectives of the present study is to ascertain the predictive capabilities regarding the degree of inhomogeneity in the nacelle. To this end it is noted that predictions with the Vulcan models were very successful at reproducing extinction in a geometry where the suppressant was introduced in a uniform manner and the only mixing processes were related to a fire-stabilizing recirculation zone [3]. The present geometry is appreciably more complicated, and the leading challenge was expected to be the transport of the suppressant rather than the well-established suppression model itself. In order to evaluate the mixing process for several scenarios, simulations and tests were conducted with different rates of injection and with different nozzle configurations. As an added variable, the air inflow rate was varied to simulate varying flight conditions. As indicated above, the ratio of the suppressant's injection rate to the combined, total mass rates is indicative of the mean of the suppressant mass fractions in the nacelle.

TEST PLAN

From the Vulcan model simulations of various test conditions, it was predicted that the suppression would be more sensitive to the rate of injection of agent than the amount of suppressant, or equivalently the duration of injection. Further, suppression is indicated to be sensitive to the distribution of agent via the distribution of nozzles about the nacelle. With these results, a test plan was generated in the form of a rule-based sequence of tests. The test sequence is initiated with an approximation of the production suppression system, which is expected to result in successful suppression. From this point subsequent tests reduce the effectiveness of that system by either:

- reducing the suppressant injection rate by reducing the suppressant bottle pressure so that the suppressant's mass fraction is likely to be reduced or
- removing a nozzle so that the distribution of suppressant is likely to be less uniform, or
- reducing the mass of suppressant injected for a given bottle pressure so that the fraction is reduced and held for a shorter duration.

As indicated above, tests were run also for reduced air flow rates. However, because of limitations on the rate of injection imposed by the HFC-125 vapor pressure, it was not possible to reach a condition where suppression failed at lower air flows. That is in agreement with predictions for lower air flows: the overall mass fraction of the agent for the physically attainable injection rates is always sufficiently high to extinguish the fires.

For the tests in which a nozzle was removed (by capping the end), the sequence was repeated also by lowering the bottle pressure until suppression failed. The general sequence for changing the injection rate was to reduce the injection rate by 50% if the previous attempt succeeded and to increase the injection rate back to 75% of the original rate if the previous attempt failed to extinguish. The lowest injection rate that is attainable is 50% of the nominal design injection rate, so this process results in bracketing the suppression in proximity to 100%, 75%, and 50% of normal injection rates. The nominal pressures corresponding to these tests were 122, 275, and 515 psig (8.5, 19.0, and 35.5 bar) though these pressures vary somewhat with the mass of agent in the bottle. While these are relatively wide margins, the available resources did not allow for additional tests to narrow these bands. The tests actually conducted are summarized in Table 1.

Table 1. Summary of Tests Conducted.

Variations from the baseline conditions, apart from pressure, are indicated in bold.

Test indicator	air inflow rate [lb/s]	pools	nozzles	supp. mass [lb]	bottle press. [psig]	targ supp rate [lb/s]
1a(25)	2	all	all	7	515	2.33
1a(21)	2	all	all	7	515	2.33
1b(21)	2	all	all	7	122	1.16
1d(25)	2	all	all	7	265	1.75
5d(25)	**1**	all	all	7	265	1.75
5b(25)	**1**	all	all	7	122	1.16
7a(26)	2	all	all	**4.84**	458	2.33
7d(26)	2	all	all	**4.84**	270	1.75
8a(26)	**1.5**	all	all	7	121	1.16
1b(26)	2	all	all	7	131	1.16
2a(27)	2	**3**	**not 2**	7	515	1.6
2d(27)	2	all	**not 2**	7	275	1.2
2b(27)	2	all	**not 2**	7	515	1.6
2c(27)	2	**3**	**not 2**	7	275	1.2
3d(27)	2	all	**not 1**	7	275	1.35
3b(27)	2	all	**not 1**	7	515	1.8
3e(28)	**1.5**	all	**not 1**	7	275	1.35
3f(28)	2	**1**	**not 1**	7	275	1.35
3g(28)	2	**3**	**not 1**	7	275	1.35
4a(28)	2	all	**not 3**	7	275	1.2
4b(28)	2	all	**not 3**	7	122	0.8
7e(28)	2	all	all	**3**	515	2.33
7f(28)	2	all	all	**2.25**	600	2.33

SUMMARY OF MEASUREMENTS AND OBSERVATIONS

A total of twenty-five tests were conducted following the plan to explore the edges of the extinguishment envelope for this ground test nacelle simulator. Two of these tests were conducted to determine whether or not individual pools (B1 and B3) could stabilize a fire. It was demonstrated that these pools could sustain a fire. This is in agreement with Vulcan simulations, although the Vulcan simulations indicated that the stability of fires in individual pools was sensitive to heat losses. Specifically, if the heat losses associated with conduction through the pool to the nacelle are as great as 50 % of the heat flux to the pool (essentially reducing the vaporization rate by 50 %), then certain pools not employed in the present series of tests could fail to sustain themselves. In the tests it was necessary to apply heat sources (heat lamps) to the nacelle under the pools to minimize heat losses just to get the fires stabilized, and this lends support to the Vulcan observations.

Of the remaining tests, two tests were replications of the first two tests in order to gain confidence in the results; in each replication, the results of repeated tests were identical. Because of the physical limitations, namely the vapor pressure of the HFC-125 and the inability to light or stabilize fires in certain pools, certain Vulcan simulations could not be reproduced. Consequently certain tests were run without pretest simulation results, but by using the arguments in the section on 'Key Results from the Pretest Simulations' a similar range of parameter space was identified, and these results were in agreement with the Vulcan simulation trends. The results of the testing are described now for:

(1) tests with all nozzles in which the ratio of the suppressant mass injection rate to the total mass injection rate was varied,
(2) tests where the total mass of agent was reduced, and
(3) tests where one of the nozzles was capped.

The results will be presented in terms of the *target* ratio of the suppressant mass injection rate to the total mass injection rate. Ideally, the pressure data indicated in Fig. 2 would be used to determine the actual suppressant discharge rate to a level of accuracy similar to the accuracy of the inlet flow meter. However, the unknowns associated with the phase transitions occurring both in the bottle and in the distribution piping prevent such a determination. Instead, the discharge rate is estimated. For this purpose, discharge rates identical to those in the Vulcan simulations are employed. Specifically, with all nozzles discharging, the 3.2 kg of HFC-125 was presumed to discharge uniformly over 3, 4.5 and 6 s for bottle pressures of 515 (35.5 bar), 275 (19 bar), and 122 psig (8.5 bar). The discharge rate was presumed to be reduced in accordance with the reduction in the total nozzle area when nozzles were capped. Clearly, the assumption of constant discharge rates in the Vulcan model will be a source of test uncertainty. This uncertainty varies over the duration of the suppressant injection period, and the errors in the estimates provided here are likely to be greatest in the earliest (fraction of the first second) and latest periods of the injection. If the rate of suppressant injection is considered averaged over the significant couple of seconds, say the first 2-3 s of the injection process, then based on the results of our analysis, we estimate uncertainties on the order of ±15 %.

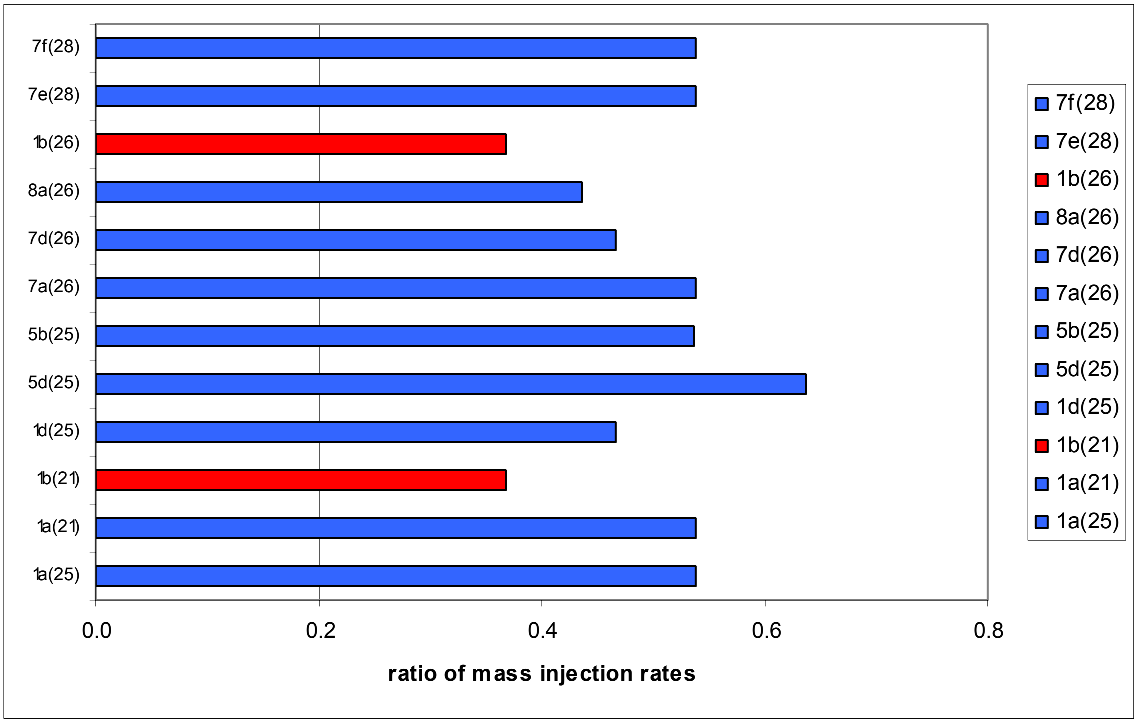

Figure 3. A summary of results for tests with all nozzles. Blue bars represent successful extinction, while red bars represent a failure to suppress the fire. In all of these cases, the Vulcan predictions were in agreement with the tests.

The results of the tests employing all nozzles are shown in Fig. 3. We first discuss the results of tests with labels starting in ‘1’ ‘5’ or ‘8’ because they correspond to baseline cases using approximately seven pounds (3.2 kg) of suppressant at varying bottle pressures and air flows. This series can be viewed as varying the ratio of the suppressant’s mass injection rate to the total mass influx rate. Suppression is observed to fail when this ratio is below (approximately) 0.4 (± 10% uncertainty in this value, but the total uncertainty is estimated at ±19%). This corresponds to those cases where the air flow rate is greatest (2 lb/sec, 0.9kg/s) and the bottle pressure is lowest (122 psig, 8.5 bar). For reduced air flow rates (1.5 lb/sec, 0.68 kg/s) or increased bottle pressures (265 psig, 18.2 bar) suppression is successful. The Vulcan predictions are in agreement with the test results for all of these tests. The fact that the ratio of injection rate exceeds the cup burner mass fraction by a factor of 1.4 (0.4/0.28) is indicative of the degree of inhomogeneity in the system.

The results in Fig. 3 with labels starting ‘7’ are those tests where the mass of suppressant was reduced from 7 lbs, to 4.84 lbs, 3 lbs and 2.2 lbs (from 3.2 kg to 2.2, 1.4 and 1 kg). All of these tests resulted in successful suppression of the fire. In all of these cases, the rate of injection was close to that for the designed conditions; in other words, the suppressant was injected just as fast, but for a shorter duration, in these tests. It is estimated that the bulk of the suppressant is injected in 3 s for 7 lbs, in 2 s for 4.84 lbs, and in 1 s for 2.2 to 3 lbs. These results reinforce the importance of the ratio of mass injection rates. The Vulcan simulations were conducted with 7 and 4.84 lbs (3.2 and 2.2

kg) of agent, and the results were in agreement with the tests. No Vulcan simulations were run for agent masses less than 4.84 lbs (2.2 kg).

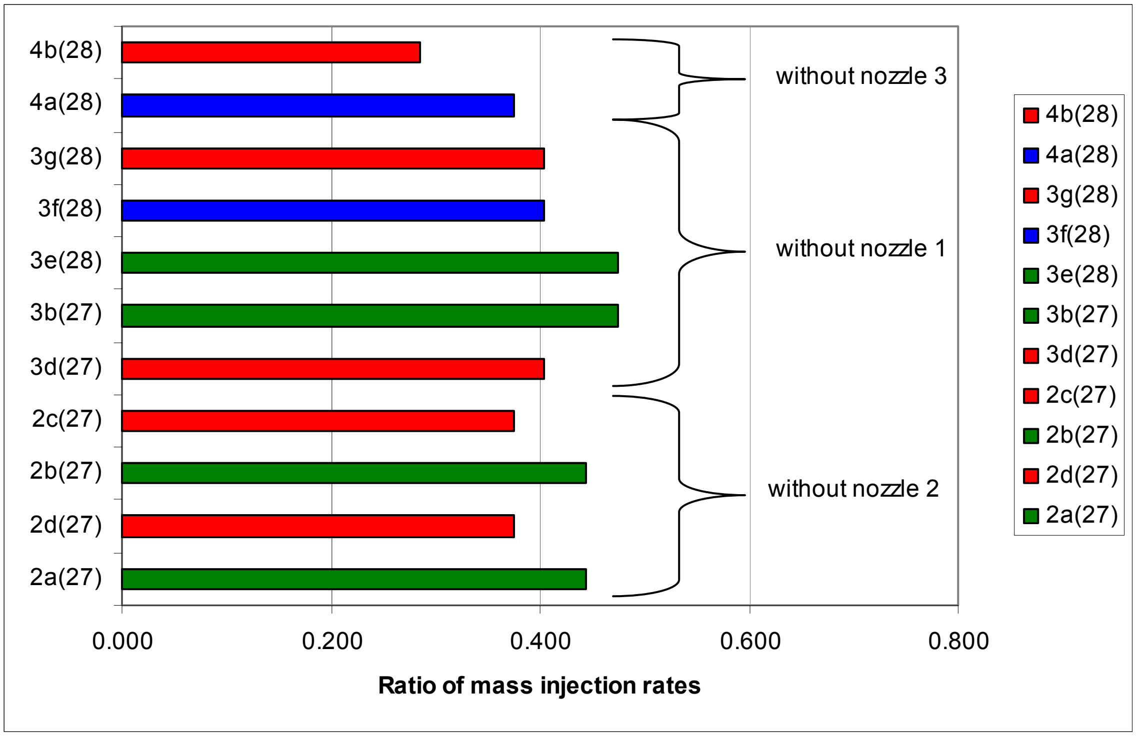

Figure 4. A summary of test results with specified nozzles capped. Those cases shown with the blue bars represent successful extinction, and those shown with red bars represent a failure to suppress the fire. In all of these cases, the Vulcan predictions were in agreement with the test results. Green bars indicate cases where suppression was successful in the tests, but Vulcan indicated failure to extinguish.

Figure 4 summarizes results for those tests in which one of the four nozzles is capped. Capping a nozzle has two effects: First of all, the total nozzle area is reduced so that, for the same nominal bottle pressures employed, the suppressant's injection rate is reduced. The reduction depends on each specific nozzle orifice diameter, but the reduction is on the order of 25%. This effect is captured by the indicated ratio of the mass injection rates. The second effect of capping a nozzle is the increased inhomogeneity inside the nacelle. More inhomogeneity would require a greater ratio of injection rates to define the boundary between successful and failed suppression. In the Vulcan simulations, it was predicted that higher inhomogeneity would be associated with capping either nozzles numbered 1 or 2,--but not 3.

The results of tests when nozzle 3 is capped are indicated by the labels with the prefix '4' at the top of Fig. 4. It is seen that the mass ratio where suppression fails is moving towards lower values than observed when all nozzles are employed. It is not certain whether or not the degree of inhomogeneity actually decreases and performance of the system increases by capping nozzle 3, and this conclusion should not be drawn based on the present results even if this is implied in the test results. Nozzle 3 injects suppressant into the upper nacelle, far from any of the pool fires considered here. For this reason, reduced suppressant in the upper nacelle may not impact suppressant levels in the lower nacelle where the fires are. The uncertainties in the suppressant's injection rate and the lack of replicate tests prohibit drawing firm conclusions for these cases.

Tests where nozzle 1 is capped are indicated with the prefix '3' in Fig. 4. For these tests, it is necessary to refer to Table 1, because in some tests only specific pools were ignited to find the locations where fires failed to extinguish. The tests where all pools are ignited are discussed first (3b, 3d, 3e). In cases 3b and 3e the Vulcan simulations and the tests showed different outcomes. Specifically, the Vulcan predictions indicated a failure to suppress the fire in test 3b (the Vulcan prediction for 3e was not actually run, but extrapolated) whereas the fire was extinguished in the tests. Reducing the injection rate so that the ratio of mass rates is 20 % less leads to a successful prediction as in case 3d. This implies that Vulcan tends to predict failure to suppress before it actually occurs. This may be because the mixing rate within the Vulcan simulation errs on the low side, thereby tending to underestimate mixing in highly cluttered areas bounded by walls. This is thought to be the case because the current clutter model does not account for enhanced mixing properly near the wall. Improvements to the clutter model may improve these predictive capabilities, but the fact that Vulcan predictions tend to be conservative, with a safety factor on the order of 20% as indicated here, is viewed to be preferable and acceptable. In terms of the ratio of the mass injection rates, the tests indicate a critical value between 0.4 and 0.45, a statistically insignificant increase over the 0.4 (+/-15 %) estimated for tests employing all nozzles. The Vulcan predictions indicated that the critical ratio of mass injection rates was between 0.45 and 0.55. In tests 3f and 3g, only pools B1 and B3 were filled, respectively. This was done to ascertain the location of the inhomogeneity that led to failed suppression. Here it was found that low concentrations of agent occur in the vicinity of pool B1 and not pool B3. This agrees with the Vulcan simulations. We view the ability of Vulcan to identify the region where the fire could not be suppressed as favorable.

The results of tests for which nozzle 2 is capped are indicated by the labels with the prefix '2' in Fig. 4. As with the previous examples, the Vulcan simulations indicated a failure to suppress at the higher injection rates due to increased inhomogeneities. The test results show that the failure to suppress occurs at the next step down in the injection rate (or the suppressant bottle pressure), the same as when nozzle 1 was capped. This again indicates a 20 % safety factor relative to the Vulcan simulations. It is noted that the failure to suppress when either nozzle is capped occurs at a ratio of injection rates that is again spanning 0.4 which is the same value indicated in the tests employing all nozzles. This implies that the degree of inhomogeneity in the tests where nozzles were capped is not significantly greater than those where all nozzles were open; in the Vulcan simulations capping nozzle 2 did indicate greater inhomogeneities in the fire region.

CONCLUSIONS

The results of a series of fire suppression tests in the complex environment of a simulated aircraft engine nacelle have been compared quite favorably with CFD simulations using the Vulcan code. The test plan was developed based on the pretest Vulcan predictions, and increments of roughly 25% in the air flow rate and the suppressant injection rate were investigated. In addition, the effect of varying the arrangement of suppressant-distribution nozzles was investigated by removing nozzles one at a time. The Vulcan predictions were generally successful in predicting the results of the tests (in all but 2 cases). In general, success or failure in extinguishing the fires is largely correlated with the ratio of the rate of injection of suppressant to the total inflow rate (air plus suppressant). In agreement with this finding, significant reductions in the total mass of suppressant used still resulted in successful extinguishment, in which the 'standard' mass of 3.2 kg was reduced to just over 1 kg.

For those cases where all four of the nozzles were employed and for those cases where the nozzle towards the middle of the nacelle was capped (#3), all of the test results agreed with the Vulcan predictions. For those cases where either of the nozzles in the forward section of the nacelle was capped, the test results indicated successful suppression using a bottle pressure commensurate with a 25% reduction in the suppressant's injection rate relative to that predicted in the Vulcan simulations—that is, it was easier to suppress than predicted. This suggests that the Vulcan simulations are somewhat conservative in predicting the mixing of the suppressant into fire regions towards the forward end of the nacelle. Thus, Vulcan presents a factor of safety of about 20% relative to the tests conducted here. The largest uncertainty in these results resides in the variance between the assumed uniform injection rate of suppressant in Vulcan and the difficulties in determining the actual two-phase injection rates during the tests.

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