FIRE SUPPRESSANT DISTRIBUTION IN AN ENGINE NACELLE[1]

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ABSTRACT

The flow inside an engine nacelle ground test simulator is studied for the purpose of understanding and optimizing the distribution of suppressant. One objective of this study is to identify conditions for which suppression will and will not be successful in order to test the model's ability to discriminate between various scenarios. To do this, the distribution of suppressant during cold flow is studied to identify regions of low concentration.

Available measurements are coupled with predictions using Sandia National Laboratories' Vulcan fire-field model. Some measurements are required to help design the computational model, such as the inlet and outlet flows, which are boundary conditions for the simulation. Specific suppressant-concentration profiles as a function of time are helpful in evaluating the model's performance. To create scenarios with insufficient distribution in regions of potential fire, the removal or capping of individual agent nozzles is used. The test matrix has been constructed by varying the loci and number of discharge nozzles, the mass of suppressant, and the air flows. Vulcan's predictions of suppressant-concentration profiles to date are in qualitative agreement with test measurements and show that the suppressant is well-distributed.

Empirical Boundary Conditions

In the autumn of 2002 tests were conducted on the ground in a full-scale 'iron bird' nacelle simulator to determine the distribution of air flows, without fire, across the boundary of the fire test nacelle. [1] (numbers in brackets denote references). These data were to provide the boundary conditions for the Computational Fluid Dynamic (CFD) and Vulcan models of this nacelle simulator effected by Sandia National Laboratory. It was found that the distribution of

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effluxes among the vents remained a nearly constant proportion of the inlet flows, and consequently the actual mass flows are nearly proportional to the total influx as well. The second finding was the rather large variation, proportionately speaking, in the steady-state pressures measured inside the nacelle with the range being greater than the mean. The third observation was a severe velocity profile across the top aft diamond vent. Most of the flow was exiting from the port side of the diamond-shaped area; the velocity out the starboard side was estimated at only ~20% of that out the port side. The pitot rake apparatus was designed to observe an overall average of that efflux from this vent.

Nacelle Simulator Test Apparatus This ground test, 'iron bird' simulator is designed for testing at one flight condition ---- 0.55M, sea level flight, on a standard day. Given this physical constraint, three nominal ventilation flows were selected to correspond to three major flight conditions: high-speed, high-altitude cruise, loiter, and precision approach. These flows are 2.1, 1.5, and 1.25 lbm/sec respectively, and were derived from flight tests [2]. The air is supplied from a centrifugal compressor which is driven by a gas turbine. The inlet flow is measured by a calibrated turbine meter. There is adequate straight pipe, according to ASME Standards [3]; a flow straightener is inserted between the compressor and the turbine meter. Likewise, there is adequate straight pipe downstream of the turbine meter, and downstream of the 45-deg elbow there is an Etoile conditioner in the straight pipe leading to the nacelle to remove swirl. The supply air pressure was measured with a water manometer immediately downstream of the turbine meter. The air effluxes were measured at each of the outlets separately under steady state. The air temperatures in the nacelles were measured with thermocouples at four locations, one on each side and near each end of the nacelle. The airflow out the aft diamond vent was measured with a pitot rake. The airflow in the other outlets was measured with a calibrated vane anemometer and stopwatch. Air pressures in the nacelle were measured at three locations using an inclined water manometer. All airflow data were corrected to ambient conditions at the time of test in order to determine the mass balance.

Table 1: Summary of Test Results of Flow Distribution

	Air Inflow	Air Out-Flows	Air Out	Flows are	All shown	As ratios		Leaks
	lbm/s	Aft Top	BalPist	Stb.2" vent	Center 3.6"vent	Port,top Vent	Port,Bottom Vent	
Distribut'n	2.024	0.6651	0.0975	0.0260	0.1424	0.0199	0.0474	0.00127
of flow	1.418	0.6397	0.0958	0.0263	0.1658	0.0234	0.0474	0.00122
(ratio)	1.152	0.6442	0.0931	0.0264	0.1680	0.0196	0.0472	0.00123
Average	**Distr. %**	64.973	9.5526	2.6275	15.879	2.1024	4.7395	0.12442

As can be seen, there were air leaks, but their cumulative effect was less than 1.3% of the total flow.

In discussing the agreement between model and test in the total flow and average pressures, this test was also a calibration of the nacelle simulator. In constructing the model, it was assumed that the balance piston vent and aft top vent would behave as parallel orifices and that the AMAD vents would behave more like nozzles. A weighted average of these coefficients of discharge was predicted to be 0.733. By actual test and calibration, it was determined that the effective coefficient of discharge equals 0.614. This value implies that all the vents behave essentially as sharp-edged orifices. This value of the coefficient of discharge correlates very well with published values for the coefficient of discharge of orifices at these Reynolds numbers. By correcting these coefficients of discharge in the boundary-flow model, it may be used with confidence in setting up future tests.

Agent Concentration Testing

Three phases of testing were performed with the ground test nacelle simulator at NAS Patuxent River [4]. Phase One measured fire extinguishing agent concentration using an agent-distribution system which had been proven to extinguish live fires in previous Qualification testing. Phase Two used various bottle and distribution system configurations to validate concentration measurements acquired during previous risk-reduction testing. Phase Three utilized various Halonyzer sampling probe configurations to quantify associated effects on agent concentration readings. A total of twenty-three test runs were conducted.

Both HFC-125 and Halon 1301 concentration measurements were observed, but only the HFC-125 test results are compared to the Vulcan model.

Halonyzer II System

The Halonyzer II (S/N 3), was used to acquire and record agent concentration data. The system was manufactured by Pacific Scientific, Inc., HTL Div., of Duarte, California. It is capable of measuring concentrations of Halon 1301, HFC-125, and other fire-extinguishing agents. This system consists of the following major components:

- Three ”Quad” units each containing four sensor assemblies for four probes
- Twelve agent sampling probes
- Power supply/vacuum pump unit
- Data acquisition system

The operation of this instrument is based on a linearized viscosity mixing theory using the weighted viscosities of the constituent gases. Since the viscosity of pure air differs from that of pure fire-extinguishing agents, readings will show that a mixture of gases is present and the ”relative” concentration of extinguishing agent will be indicated by the differential pressure reading obtained. The processor also converts relative readings to volumetric readings based on the unique calibration of each Halonyzer and extinguishing agent.

The vacuum pump draws the gas samples through the sampling probes into the respective sensor assemblies in the “Quads”. In each sensor assembly, the gas passes through filter screens, a heat exchanger, a capillary tube differential pressure sensor section, and finally through a sonic flow orifice. The heat exchanger section ensures uniformity of monitoring conditions, and tests are performed only after thermal equilibrium is achieved. The sonic flow orifice ensures a constant flow while the capillary tubes create the pressure drop measured by a transducer. The transducer transmits the pressure signal to the processor unit which performs the necessary calculations and then records and displays relative concentrations. A scan rate of 10 Hz. was used.

<u>Test Procedures</u> Field calibrations and calibration verifications using 100% agent were performed on site prior to testing and whenever agents were changed.

The general step-by-step procedures followed during the tests were:

- Set engine simulator air flow and allow to stabilize
- Conduct Halonyzer calibration
- Initiate NAVAIR data collection
- Initiate Halonyzer recording and confirm data acquisition
- Discharge engine fire-extinguishing system
- Record concentration data for at least 30 seconds

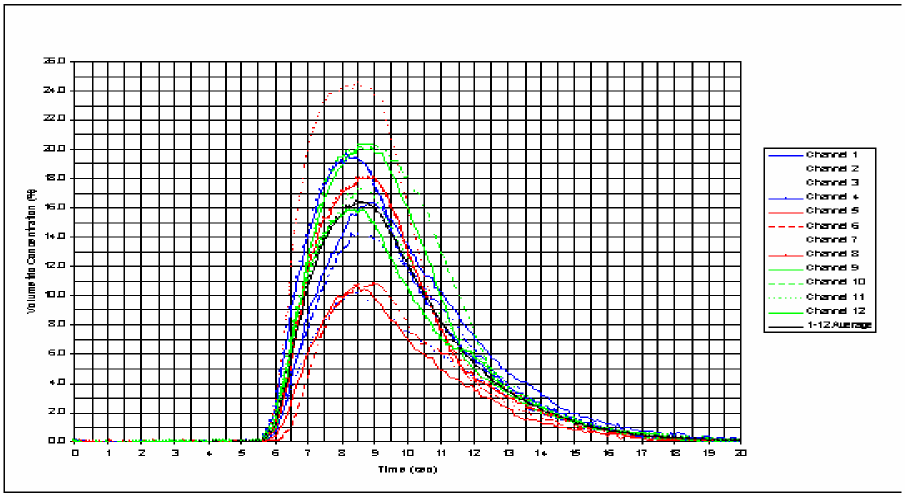

Figure 1 HFC-125 Transient Injection Test Results

A total of twenty-three test runs were conducted during the test program. Two test runs were conducted for Phase One, with average HFC-125 volumetric concentrations peaking at approximately 20%, with all channels exceeding 10% for 0.5 seconds. (These concentrations should guarantee extinction.) Thirteen test runs were conducted for Phase Two plus eight test runs for Phase Three. Figure 1 shows the test results used for comparison with the Vulcan modeling described below. These data show that the rate of injection decreases between 2.70 and 2.75 seconds, while the bottle discharge data shows a 3 to 4 second injection interval. Note also the great variation in agent concentrations observed between all of the 12 sampling tubes—from 10% to 24% by volume in various parts of the nacelle, simultaneously. These clearly show the great nonuniformity in the flow profiles throughout the nacelle caused by four nozzles discharging high-momentum jets in contrary directions. These nonuniformities make model validation quite difficult near the nozzle discharge loci.

Vulcan Model Comparisons

Measurements from the agent concentration tests are compared with simulations in which 3.2 kg of HFC-125 is injected over 3 and 4 seconds. Air flow into the nacelle is 1.0 kg/s and suppressant mass flow is proportional to the nozzle area for four nozzles. To evaluate the predictive capability of the Vulcan simulations in describing the suppressant distribution in the nacelle, we have compared HFC concentration-time traces with those measured using a Halonyzer II. The locations of Halonyzer II probes are shown in Table 2 below:

Table 2: Nozzle characteristics.

No.	Dia. (cm)	X,m	Y,m	Z,m
1	0.396	0.09	15.78	1.02
2	0.475	0.09	15.84	1.15
3	0.475	0.19	16.82	.41
4	0.330	1.03	17.7	.46

In these simulations, the suppressant has been assumed to enter the nacelle in the vapor phase or to vaporize instantly upon entrance. Other simulations, not reported here, indicate that there is a finite vaporization time. Actual vaporization times depend on the square of the initial particle diameters, assuming a vaporization rate proportional to the surface area. For reasonable droplet diameters (100 to 500 micron), estimated evaporation times can vary from 0.1 to 2.5 seconds. These estimates assume flash vaporization of roughly a third of the suppressant which then cools the remaining liquid suppressant to its boiling point. While relatively few large droplets are expected, the droplet size distribution leaving the suppressant nozzles does affect the simulation results. The effects of finite-rate evaporation are clear in the qualification test measurements in the following figures in which the suppressant concentrations drop off more gradually than comparable simulations after the end of the 3 or 4-second injection.

Table 3. Concentration Sampling Probe Locations

Probe No.	**Location: (fuselage sta.(in), o'clock looking fwd., cm aft of bulkhead)**
1	(Sta 604; 7:00, 31.75cm)
2	(Sta 604; 12:00, 31.75cm)
3	(Sta 645; 3:00, 136cm)
4	(Sta 645; 12:00, 136)
5	(Sta 680; 2:30, 224.8cm)
6	(Sta 680; 6:00, 224.8cm)
7	(Sta 680; 10:30, 224.8cm)
8	(Sta 722; 12:00, 331.5cm)
9	(Sta 722; 4:30, 331.5cm)
10	(Sta 722; 7:30, 331.5cm)
11	(Sta 617; 7:30, 64.75cm)
12	(Sta 625; 7:30, 85cm)

Channel 1 is in the forward lower end of the nacelle on the port side. The injection period is 2.75 seconds, and therefore the more relevant results from Vulcan are those of the 3-second injection.

Figure 2 shows that the rise characteristics follow quite closely up to the peak, but after that the calculated decrease is faster than the test data. Most of this can be attributed to the simulation method. The injection simulated using Vulcan was a square wave, 3 seconds long, but during the actual bottle blow-down the flow tapers off as the pressure in bottle decreases—particularly in the latter phase where the discharge is no longer sonic. The response curve calculated for the 4-second injection illuminates the difference in peak time and its subsequent rate of decrease. Channel 3 is almost half way aft located on the starboard side. Results for channel 3 are reasonably good, with 3 and 4-second injection periods closely bounding the test measurements.

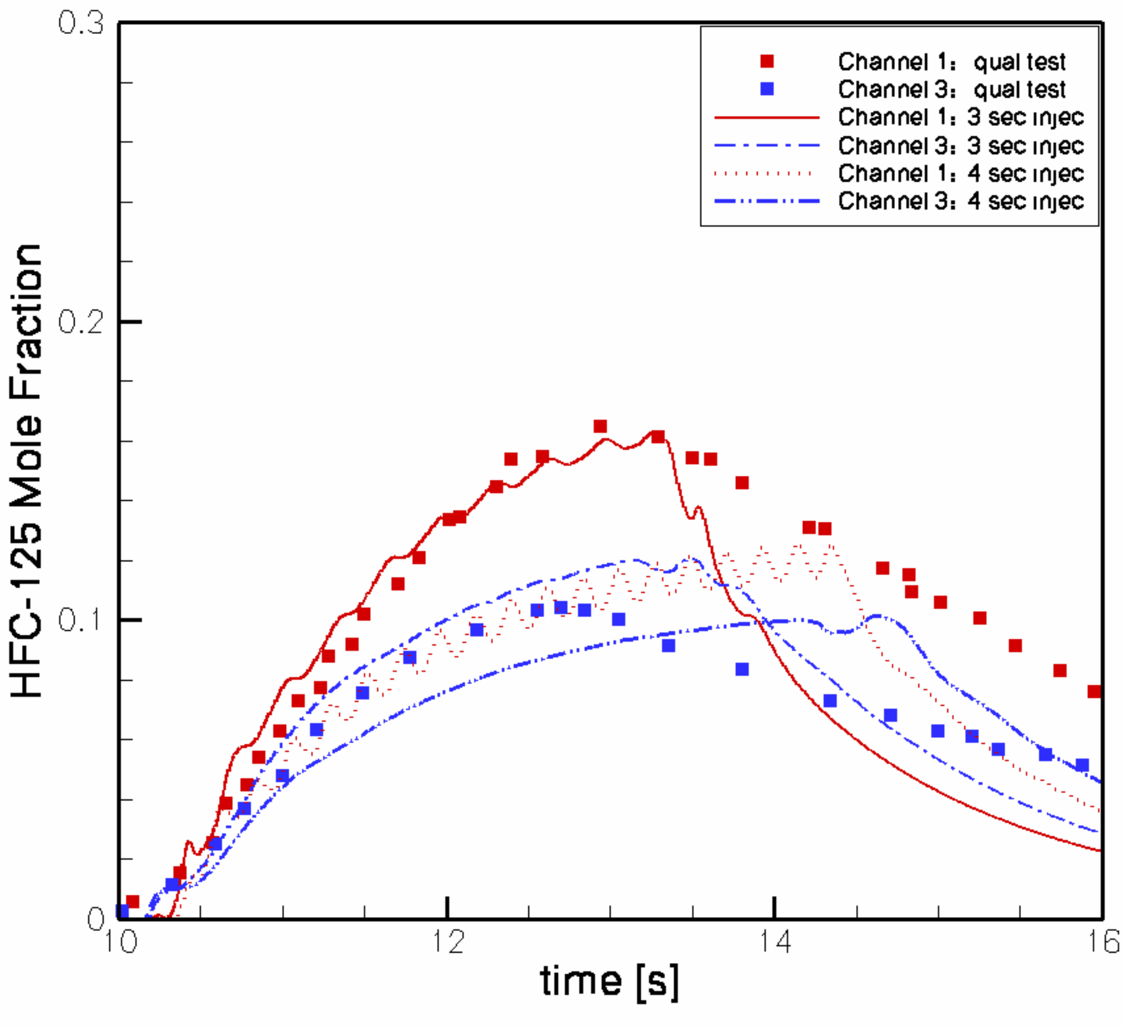

Figure 2 HFC-125 mole fractions at Halonyzer II sensor locations 1 and 3.

Suppressant comes from nozzle 1 (over the top of the engine) and from nozzle 2 (under the engine). Sensors are located between nozzles 3 and 4, roughly two-thirds of the way aft.

Channel 6 has been located below the engine and just in front of one large rib while channel 5 is located on the upper starboard side. Simulated results for channels 5 and 6 are relatively insensitive to the rate of injection and these simulations bound the measurements for those channels.

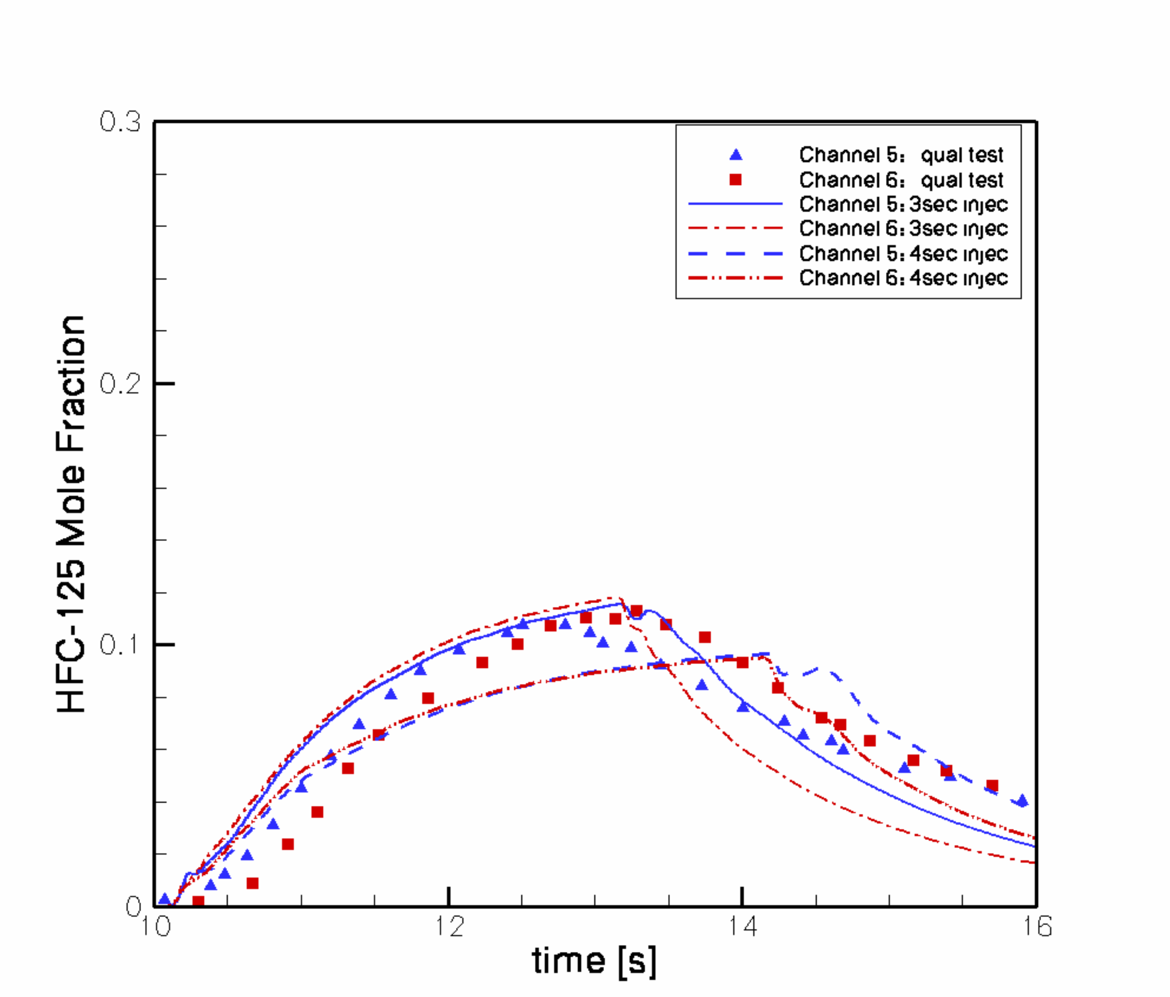

Figure 3 HFC-125 mole fractions at Halonyzer II sensor locations 5 and 6.

Uncertainty and Sensitivity Estimates

Boundary Condition Flow Model When comparing the calibrated model of the influx-efflux tests to the means of these test results, given the flow, the mean nacelle pressures agree within ±4.5%. If given the supply pressure, the total flow agrees within ±2.3%. As a check on the overall accuracy of these flow measurements, a mass balance was performed as well. In the mass balance calculations of the means, the difference between the inflow and the sum of all effluxes ranges from 0 to 1.11% in the worst case. Almost 2/3 the total flow exited from the aft, upper diamond vent. Before calibrating the discharge coefficients of the several vents, the influx-efflux model predicted about 6.5% more flow leaving via the Balance Piston Valve and 8.5% more by the four AMAD vents in the front bulkhead than was observed. After calibration, the above uncertainties were obtained. The Halonyzer II instrumentation tends to smooth the concentration data because there is ~ 6 m of 6mm tubing leading to the 'quad' sensors (which also causes a transport delay in the data), and the length of capillary sensing tubes within them further mix and smooth the viscosity variations of the incoming gas mixtures. Since the flow of sampled gases was not reported, further estimates of uncertainty from this source are not possible.

Agent Concentration Testing There is an unknown uncertainty associated with the Halonyzer II concentration measurements, both in terms of the absolute concentration measured and in the locations where the measurements were taken. The indications from the agent concentration test report [ref] are that the measurements are fairly repeatable so that significant errors are most likely of the systematic type. The probe locations are not specified in detail in the report; for example, the probe corresponding to channel 1 is identified as being 604 inches aft of the aircraft nose and at 7:00. This places it roughly in front of the upper port edge of the gearbox assembly, but there is some latitude on the exact placement. The stated locations and the coordinates used in the simulations are indicated in Table 3. Each probe location within the Vulcan simulation averages over a cubic inch of volume.

Vulcan Sensitivity Analyses and Observations Model sensitivities in the areas of the suppressant spray momentum vector and magnitude relative to the air inflow and the rate of suppressant vaporization indicate the effect of the relative momentum. Simulations are conducted with the 3.2 kg of HFC-125 injected in the gas phase over either a 3 or 4-second injection period; this difference in the period effects a 30% change in the jet momentum. It is evident that this modest change in the suppressant momentum can lead to as much as a 50% change in the concentration predicted at a specific point because the high-concentration suppressant jets either hit a measurement cell or are shifted by ~10 cm away from it. A typical example of these sensitivities is shown in Figure 4, which highlights the model's sensitivity both to the spray momentum and to the Halonyzer II probe locations. Because of this enormous sensitivity, there is more of a qualitative significance to the agreement or disagreement in many of these detailed results.

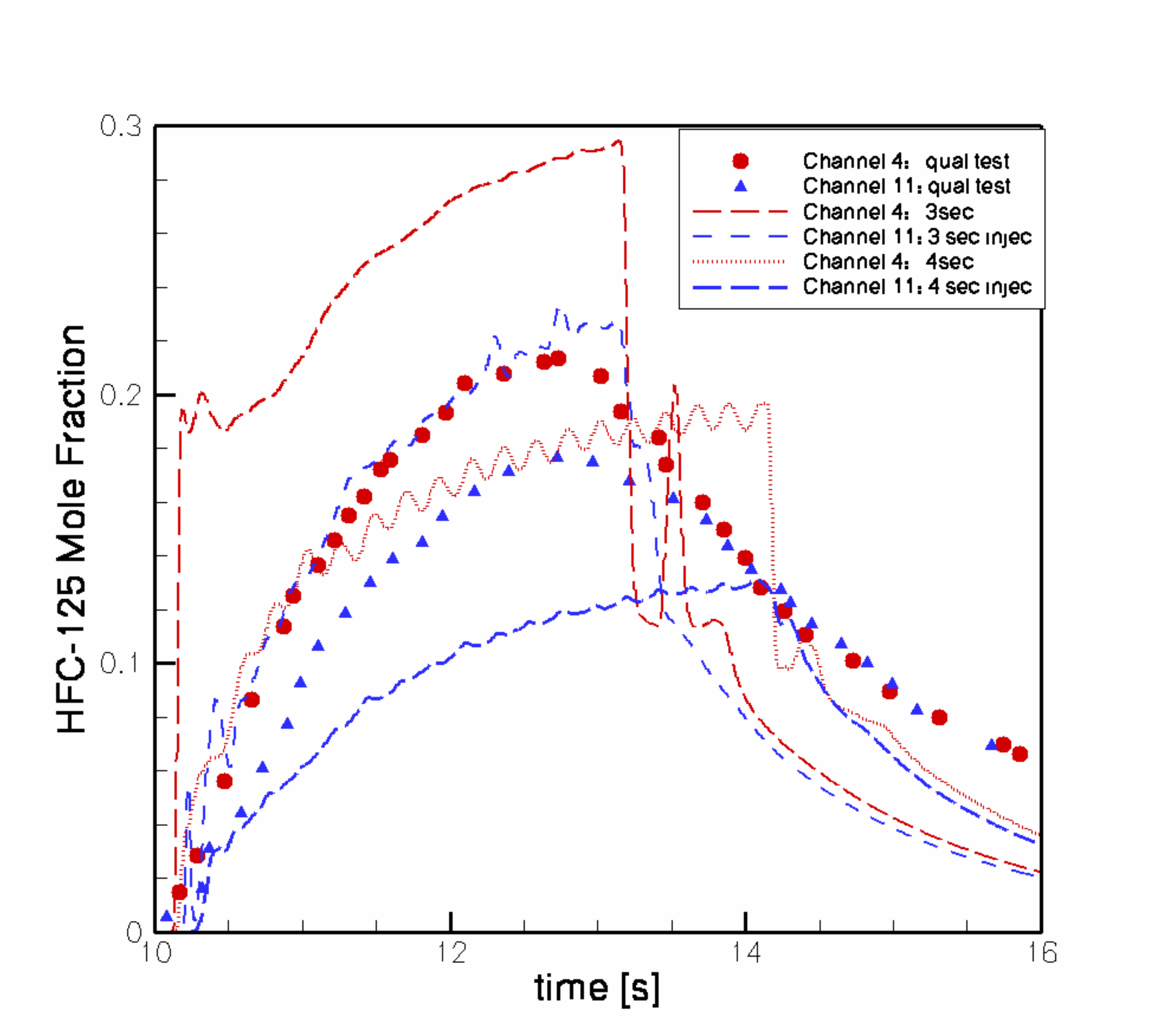

Figure 4: Typical Variations caused by Sensitivity to Jet Momentum and Turbulence

Because the turbulence generated by the suppressant injection is not known very well, this parameter was varied to determine its sensitivity. The concentrations measured by probe channels 4 and 11 do show some sensitivity to turbulence levels generated by the spray nozzles. There are two orders of magnitude between the levels of turbulence caused by 3 vice 4-second injection, which bracket the concentration profiles for channels 4 and 11 in fair agreement with the Halonyzer II measurements. There is a correlation here: whenever a channel exhibits a high sensitivity to jet momentum, it also shows similar sensitivity to high turbulence. *We conclude that the sensitivity to the injection momentum and the turbulence generated as the suppressant mixes is more substantial than the sensitivity to the turbulence imposed as a boundary condition.*

Conclusions

For the boundary flow model and testing, it was found that the distribution of effluxes among the vents remained a nearly constant proportion of the inlet flows, and consequently the actual mass flows are nearly proportional to the total influx as well. Almost 2/3 of the total flow exited via the aft, top diamond vent, which was not expected. The reason for this most likely was the discovery that the screen over diamond vent opposite it on the bottom of the nacelle was virtually closed by particles resulting from the combustion products.

The discrepancies noted between Vulcan calculations and the measured concentrations do not indicate a change in final results from where suppression is expected to where suppression is not expected, or vice versa. When the Vulcan simulations and the Halonyzer II probe measurements differ noticeably, one shows a concentration that is sufficient to suppress a fire while the other shows a markedly higher concentration, but still sufficiently concentrated when it reaches that probe location to extinguish the test fires.

References

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