Total Flooding Fire Suppressant Testing in a 56 m^3 (2000 ft^3) Compartment

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ABSTRACT

We previously evaluated eight different halon and 'halon-like' agents for minimum extinguishing concentration requirements in our 56 m^3 (2000 ft^3) compartment under total flooding conditions. Three agents for occupied spaces were selected for further evaluation: du Pont FE-13, Great Lakes FM-200, and 3M PFC-410. Another agent, an aerosol generating material, was evaluated at the manufacturers' test site and is now being included in intermediate size chamber tests.

The test facility, including the discharge system, has been modified to allow shorter duration well characterized liquid discharges. Agent distribution and halogen acid production are analyzed during the discharge time interval itself. The fire threats employed have been varied to obtain a more severe, realistic, extinguishment challenge. A significant concentration increase above cup burner requirements must be used to achieve rapid extinguishment and to assure against energized reflash.

An evaluation of test considerations and result interpretation is included within the format of our test program.

PROGRAM CONSIDERATIONS

Key points in performing comparison evaluations with different products are knowing what the critical criteria are; selecting the products for evaluation that may satisfy the requirements; performing tests that evaluate the relevant parameters (not other known or unknown influences); and being able to interpret the results.

The basic dogmas (not always adhered to) are: performing tests where 'all other things are equal' and, comparing 'apples to apples', not 'apples to oranges'.

Usually, not all variables are controlled, controllable, or even known. The breakdown of the above dogmas is likely within one test series performed by one research group. This is much more likely to be a significant consideration between different test series, and especially different test groups.

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Many of the points raised in our paper entitled "Halon Replacement Agent Testing: Procedures, Pitfalls, and Interpretation"[1], are discussed within the framework of the intermediate scale test series performed by the Naval Research Laboratory.

TEST CONDITIONS

The primary fire threat the Navy surface fleet is protecting against is a rapidly developing, high energy releasing, three dimensional liquid organic fuel fire, anywhere in the protected volume. This necessitates a total flooding agent, added quickly to minimize damage, and sufficient to prevent reignition from residual energy sources. Successful extinguishment has to be achieved quickly, on the order of discharge time. This is a very stringent requirement not necessary for some other fire threat scenarios. The spaces are normally occupied, so agent toxicity is an issue. Space (and weight) restrictions exist as well.

The test compartment is 4 x 3.4 x 4.3 m (13 x 11 x 14 ft) with a volume of 56 m^3 (2000 ft^3). It is made of cinder block and concrete with a metal ceiling. All surfaces were coated with water sealant paint. A key feature is large gravity closed explosion roof vents. The roof opening allowed strong chimney effect ventilation during preburn to steady state (non-oxygen depleted) conditions, and high voltage spark reflash initiation attempts. The fireballs that sometime resulted under our 'test to failure point' protocol would probably have damaged a more sealed compartment.

FIRST TEST SERIES

Our initial test series[2] was performed with the following chemicals:

3M	PFC-410
Du Pont	FE-13
Du Pont	FE-25
Great Lakes	FM-100
Great Lakes	FM-200
Great Lakes	FM-100/FM-200 (1:5 Blend)
References	Halon 1301
	Halon 1211
	Sulfur Hexafluoride

All agents were pressurized with nitrogen to 42 bar (600 psig), except for high vapor pressure FE-13. Discharge times were modified by changing nozzle orifice sizes. We did not test candidate agents that would not have met our specific shipboard requirements. For example, Inergen is stored as a high pressure gas. The agent volume (at 40 % design concentration) is over an order of magnitude greater than that of halon 1301 (at 6 % design concentration). Shipboard space is not available. Ship lifetime is long - 30 to 40 years. Candidate alternatives must have sufficient projected availability. CFCs, HBFCs and HCFCs are subject to environmental limitations; other candidates were eliminated due to toxicity constraints. Global warming continues to be a concern in that there is uncertainty in future restrictions.

The fire threats employed n-heptane pool and spray fires, and wood crib fires. We continuously monitored agent, oxygen, carbon dioxide, and carbon monoxide concentrations at four different heights in the compartment. Additional 'grab' samples for agent were taken near the fire area (for agent concentration at fire extinction), and for halide acids in the overhead space. Acid sampling at low height gave lower acid concentration values. Temperatures and agent discharge line pressures and temperatures were computer recorded to provide discharge characteristics data, as well as to establish a data base for future discharge system design. Videos from both inside and outside the compartment were also recorded.

The desiderata were the minimum concentration values that would effect extinguishment. The tests were a true learning experience in how, and how not, to perform such evaluations. A major factor was the desire to keep equipment and personnel physically removed from toxic and explosive situations. This meant a long agent transfer piping system that increased the significance of pipe volume and two-fluid flow. The candidate agent thermodynamic properties, especially pressure-temperature and nitrogen solubility, strongly determined fluid flow. It became difficult to make valid agent comparisons as agent delivery rates followed different functionalities. That is, liquid run-out discharge time lost some of its fundamental significance. Differences in agent distribution within the compartment were also present[3].

SECOND TEST SERIES

The major change was a redesign of the discharge system from employing a tank with a dip tube and a long (significant volume) horizontal pipe run, to a tank partially inverted above the test compartment without a dip tube. The piping distance to the nozzle is approximately 2 m (7 ft) with a resulting total pipe volume much less than agent liquid volume, including for halon 1301. In addition to the previous instrumentation, a number of kerosine lanterns were distributed in the compartment. Thermocouples were used to determine when their flames were extinguished.

The agents included in this (continuing) series are:

3M	PFC-410
Du Pont	FE-13
Great Lakes	FM-200
Reference	Halon 1301

The desiderata are the minimum concentration values that would effect extinguishment as well as the effect on extinguishment times and halogen acid gas production of short and long discharge times and increased agent concentrations. Agent concentration values, calculated based on agent weight, have been used only for loading cylinders for tests. The concentrations reported in the compartment are measured values.

DISCHARGE TIMES

Extinguishment times and halide acid product concentrations depend on agent concentration and addition rate. Characterizing the discharge process is of key importance. However, the concept of a specific discharge time is not correct. The time interval for discharge of liquid can be determined visually, from discharge pipe pressure, or from temperature inside the discharge pipe near the nozzle. The transition from liquid flow to gas flow depends on the thermodynamics of the agent, ambient conditions, the particular discharge system employed, and volume ratios of agent, pressurant gas, and system piping. These all affect the transition region of the various forms of two-fluid flow. Thus, even with the same transition point time from liquid flow, the time dependence of the subsequent flow rates of liquid, vapor, and pressurant gas mixtures would not be the same for different agents or conditions.

The functionality of agent delivery into the compartment with time is required. A discharge time determined by time to a set percentage of total agent discharged is probably the most practical simplification. It may be necessary to model the discharge process to obtain this information. Figures 1 and 2 show discharge time indications from pressure-time and temperature (agent energy transfer)-time curves, i.e., time to curve break-point. Figure 3 shows the calculated agent delivery rate as modeled by MPR[4] using NRL discharge profile data. While the liquid run-out was completed in approximately 3.5 seconds, the 95% agent delivery interval was greater than 9 seconds. This agrees with the slowly decreasing pressure and temperature after the less sloped initial period in Figures 1 and 2 respectively.

Figure 4 shows the agent concentration high and low in the compartment as determined by grab sampling with subsequent gas chromatograph analysis. While the discharge time was short as determined by liquid run-out, the agent concentration increased long after that point, in agreement with the calculated agent delivery rate. Fire extinguishment likewise did not occur until the higher concentrations were reached well after liquid run-out.

A further complication is illustrated by Figures 5 and 6 showing piping and compartment pressure during and following a 3+ second discharge. The compartment is not leak tight, but significant rapid volume changes are measurable. All tested agents initially reduced pressure due to cooling effects from flash evaporation, followed by pressure increases from further gasification. PFC-410, a relatively high boiling point chemical, can exist in significant fraction as a mist which evaporates for several seconds following its discharge. This is shown by the elevated compartment pressure well after agent discharge. The transition from agent liquid to pressurant gas is fairly sharp for high boiling PFC-410 in our second test series delivery configuration with much shorter piping. Slower evaporation does not necessarily translate into less efficient suppression, as the heat of vaporization could contribute to energy abstraction.

AGENT DISTRIBUTION INHOMOGENEITIES

Figure 4 also demonstrates the mixing delay between high and low heights with agent discharge high in the compartment from a horizontal dispersing nozzle. There is a two-to-three second delay in initial agent dispersal, and an initial overshoot high agent value and temporary drop (reproducible) in concentration at nozzle height. Very pronounced nozzle effects with inhomogeneities in both time and space do occur. Their significance will vary for the same factors mentioned above with regard to discharge time considerations.

Figures 7 and 8 show the significant difference of nozzle types with PFC-410 as an example. The Bete N series nozzles project a downward full cone dispersed over 90 or 120 degree full cone angle. Significantly higher agent concentrations quickly result low in the compartment. A similar discharge with a 'Navy' nozzle, four perpendicular horizontal orifices, gives more uniform coverage.

Peak agent concentrations (transients) can occur in particular volume elements due to nozzle type and orientation. The agent-air mixture would then 'homogenize' to a lower average concentration. In this way, fires at some locations could be extinguished by a quantity of agent insufficient to extinguish fires at all points in a space (true total flooding). The fires could subsequently be reignited without the capability of the agent to effect their extinguishment. Examples of heptane pool fire extinguishment times as functions of final agent concentration and nozzle type from our first test series include:

The following data show some very rapid "successful" extinguishments were at agent "concentrations" well below the amount needed for cup burner extinguishment. The concentrations listed are the 'final' steady state values determined by gas chromatography.

Agent	%	Discharge Time, sec	Extinguishment Time, sec	Nozzle	Reflash
1301	2.7%	9	2	Downward	Yes
1301	2.7%	7	74	Horizontal	
1301	2.9%	10	3	Downward	Yes
1301	3.4%	7	19	Horizontal	
FM-100	2.4%	5	3	Downward	Yes
FM-100	4.2%	7	9	Horizontal	
FM-200	6.0%	2	4	Downward	Yes
FM-200	8.0%	8	13	Horizontal	

The variation in time-to-extinguishment data in the preceding Table is clearly attributable to nozzle discharge orientation. The downward directed Bete nozzle produced extinguishment times of 2 to 4 seconds whereas the horizontal discharge nozzle extinguishment times are in the range 9 to 74 seconds and the agent concentrations are significantly higher at extinguishment in three of the four horizontal discharge nozzle tests. Since the heptane pool fire was located near the floor (40 cm elevation), the downward discharge should be expected to effect earlier suppression requiring a correspondingly lower enclosure-average agent concentration. This was observed even with the metal partial shield situated between the nozzle and the 0.23 m^2 (2.5 ft^2) heptane pool fire in all these tests. Extinguishment occurred well before discharge was completed in three of the four reported tests with downward directed discharge, but did not occur until well after discharge in the tests with the horizontal discharge nozzle.

The most difficult fire to extinguish is the smallest pool fire that is of sufficient size to be turbulent. A spray fire, where the vaporization rate is not limited to flame heat feedback, is the easiest to ignite. The heptane spray fire reflash that occurred subsequent to pool fire extinguishment with the downward discharge nozzle indicates that the lower agent concentrations at extinguishment in these tests were not adequate to provide fire suppression of the enclosure. In fact, initial "extinguishment" concentrations were well below cup burner values.

AGENT REQUIREMENT FACTORS

Since the roof vent remained open until immediately prior to agent discharge, there was no significant preheating of air in the enclosure. This is important because air preheating can cause a substantial reduction in the number of moles of air in the enclosure at agent discharge, with a corresponding increase in the mole fraction of agent produced by discharging a given number of moles of agent. For example, doubling the enclosure air temperature from 300 °K to 600 °K at agent discharge can cause a nominal mole fraction of 5% to increase to an actual mole fraction of about 10% for the same amount of agent discharged.

A ramification of keeping the roof vent open prior to discharge is that the oxygen concentration at agent discharge (typically in the range 20 to 21 v%) will not significantly inhibit the fire. This is important as a fire in a depleted oxygen environment will require measurably less agent to effect extinguishment. Agent concentrations that would successfully extinguish in a vitiated environment will not be adequate to safely extinguish with adequate air supply. This factor (together with air heating, mentioned above) is why larger fires are easier to extinguish and are not suitable for determining minimum agent requirements. The NRL "free oxygen" model[5] can be used to predict agent requirement increase (or decrease) for oxygen increase (or decrease). A decrease from 21% to 19% oxygen is a relative decrease of 10%, but the 79% inerts in air have already "neutralized" 2/3 of the oxygen. Only approximately 7 v% oxygen is available to generate the additional energy required to propagate a flame. A decrease from 21 v% to 19 v% oxygen is thus a decrease from 7 v% to 5 v% "free oxygen." An agent requirement determined at 19 v% can be up to 40% greater (relative) ~~than~~ at 21 v%.

AGENT REQUIREMENTS

The agent concentrations determined here should not be used directly for engineering design concentrations. They do not provide any safety margin to account for discharge time differences, agent leakage effects, or agent distribution inhomogeneities, including those with larger ceiling heights and equipment obstructions. They are concentration values which will extinguish pool fires if achieved at the fire. Suitable design considerations must be employed to generate the required concentrations everywhere in the volume that a fire may occur, within the desired extinguishment time interval. This can require considerably more agent than cup burner plus 20% values would indicate. The following table lists as "Observed" the concentrations at the fire site that will give rapid extinguishment, without reflash. The final column lists the ratios of alternatives' weight and volume relative to halon 1301 that these concentrations would indicate.

HYDROGEN FLUORIDE

The zero ODP fluorocarbons and hydrofluorocarbons except for tetrafluoromethane, CF_4, will significantly react in a fire environment. Large amounts of toxic and corrosive HF are produced when such molecules are employed as fire extinguishing agents. Acid concentration profiles with time have been obtained in these intermediate scale tests. Concentration values are typically in the thousands of parts-per-million (ppm v/v) for successful extinguishment. Longer extinguishment times and lower agent concentrations result in increased acid production. The HF concentrations were an order-of-magnitude lower (ppm values in the hundreds) in the Halon 1301 extinguishment tests.

AEROSOL AGENT TESTS

The aerosol agent tested (Spectronix S.F.E.) is generated by electrically energizing a propellant of proprietary composition. The propellant is prepared by Spectronix in a variety of configurations including powder, pellet, and preformed charges. The propellant and/or container is placed in one of several types of generators that direct the discharge of aerosol into the test enclosure.

Preliminary tests with several different generators and agent compositions were conducted at the manufacturer's facilities with sparse instrumentation. Tests in the NRL 56 m^3 enclosure are currently underway and preliminary results for heptane pool fires and one generator design are reported here. Instrumentation for the NRL tests included thermocouple and video data as in the gaseous agent tests, and optical density meter data to indicate the temporal and elevation variations of relative aerosol concentrations,

Tests with one generator configuration and nominal agent loadings of 54 to 72 g/m^3 indicated that the heptane pool fire could indeed be extinguished but only after a delay time due the buoyant rise of the exothermally generated aerosol cloud. Other tests are now underway with a water cooled generator that produces a much less buoyant cloud and more uniform aerosol concentration.

FUTURE PROGRAM

The intermediate scale tests with halon-like alternatives are continuing to scope out the parameters for suppression and acid production. Characterization of flow properties will allow the modeling and designing of a full scale total flooding system. The NRL ship, the ex-USS SHADWELL in Mobile Bay, AL, will be used as an instrumented testbed.

Evaluation of replacements, including aerosol agents, will continue in our 56 m^3 (2000 ft^3) Compartment.

ACKNOWLEDGEMENTS

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HALON REPLACEMENT

Preliminary Halon Comparison

Efficiency Compared to Halon 1301

AGENT [Agent %] = X/(1-X)	Observed	Required	Cup	Observed	Required
Halon 1301	3.9%	4.0%			
Weight	30.2 lb	31.4 lb	1.0	1.0	1.0
Volume	0.31 cu ft	0.33 cu ft	1.0	1.0	1.0
Great Lakes FM-200	8.1%	8.8%			
Weight	71.6 lb	78.0 lb	2.4	2.4	2.5
Volume	0.80 cu ft	0.88 cu ft	2.7	2.6	2.7
du Pont FE-13	15.6%	18.5%			
Weight	56.8 lb	67.3 lb	1.8	1.9	2.1
Volume	1.01 cu ft	1.20 cu ft	3.1	3.2	3.6
(compressed)			(2.8)	(2.9)	(3.3)
3M PFC-410	7.3%	7.9%			
Weight	90.4 lb	97.5 lb	2.7	3.0	3.1
Volume	0.92 cu ft	1.00 cu ft	2.7	3.0	3.0

Agent Weight and Volume for 2000 ft^3 Compartment: n-Heptane Pool Fire with Metal in Flame

Figure 1

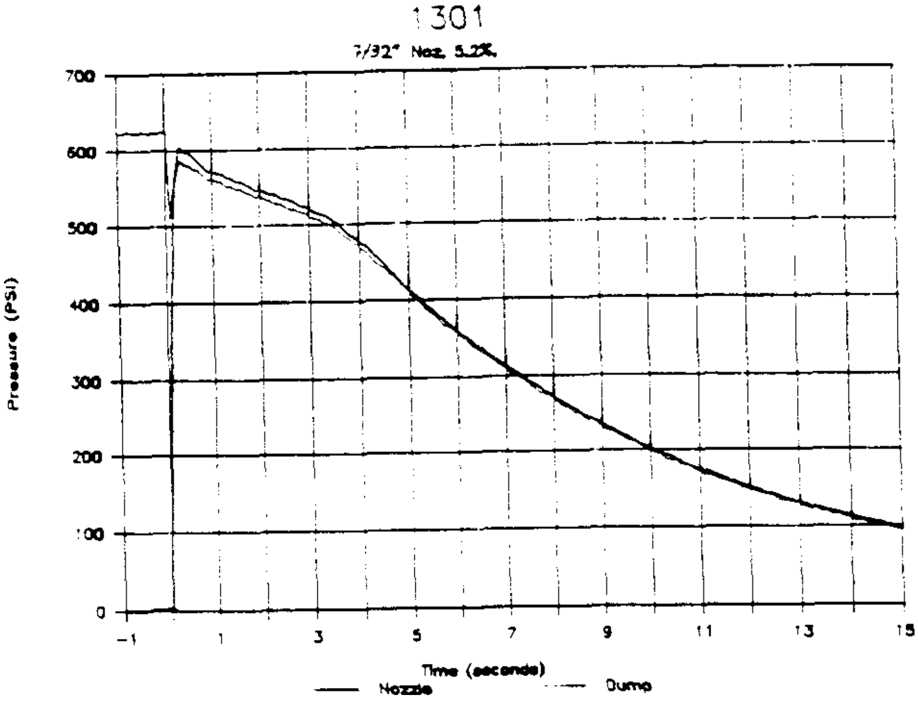


Figure 2

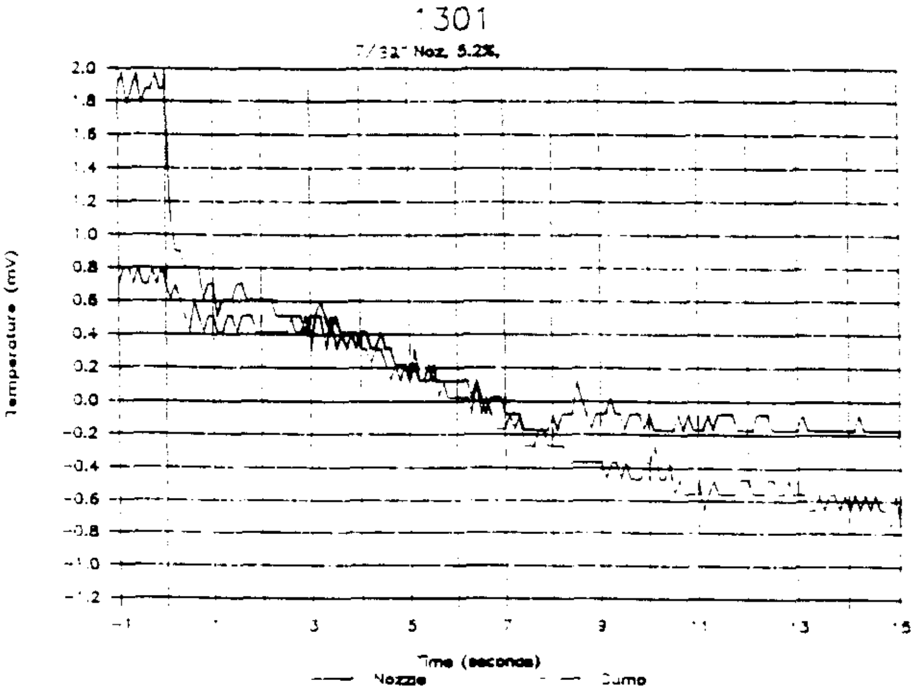
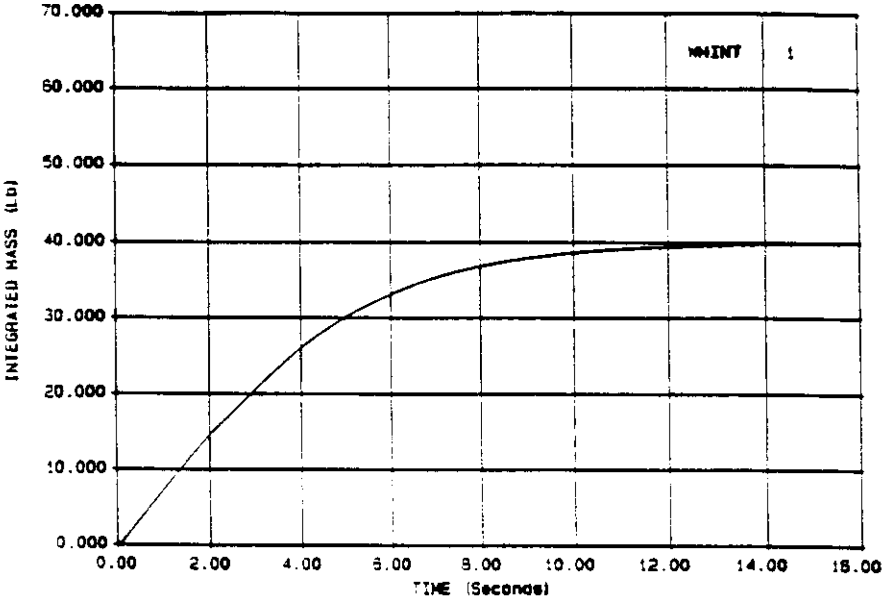


Figure 3



Test 1301 - 7/32 Noz - 5.2%

Figure 4

HALON **1301** (CF$_3$Br) **5.2%**

7132" **Navy Nozzle**

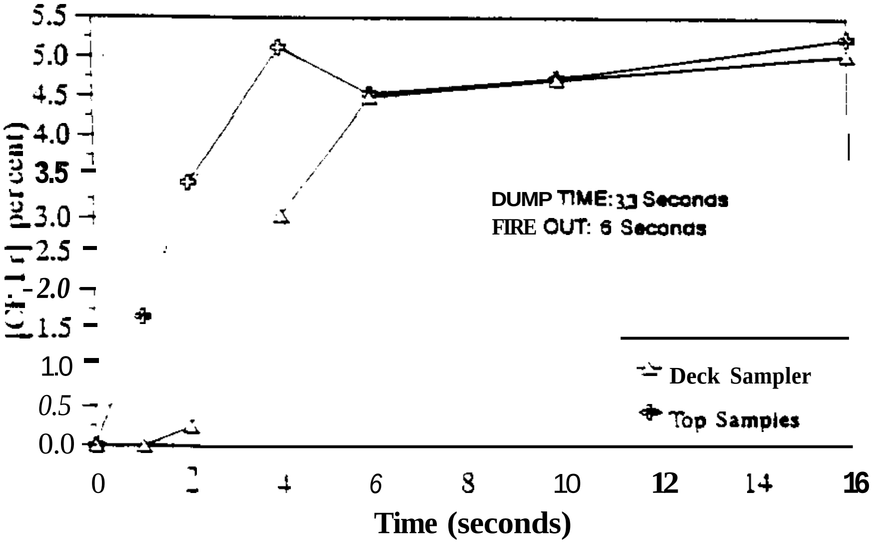


Figure 5

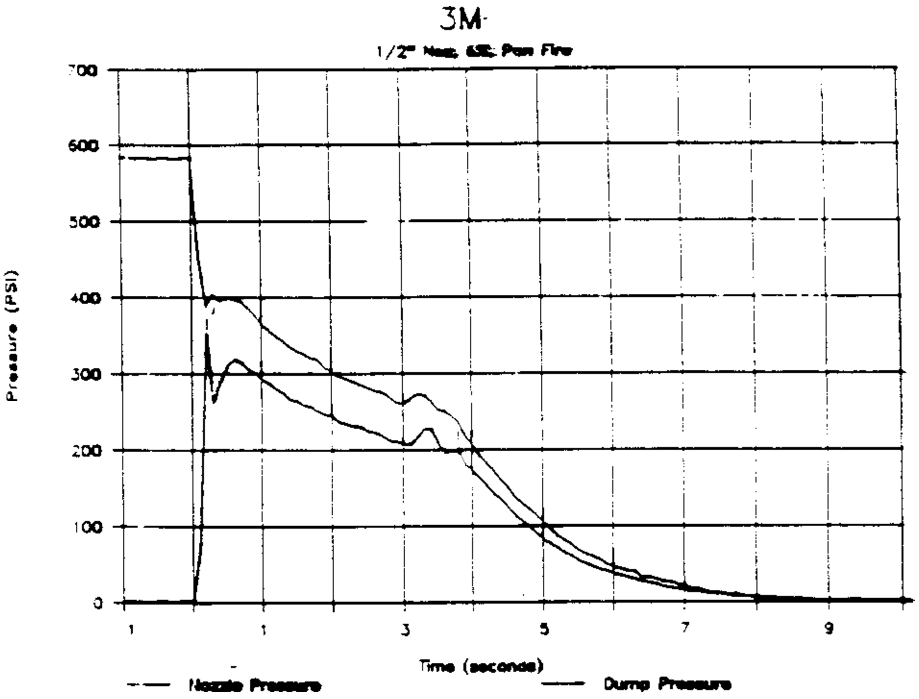


Figure 6

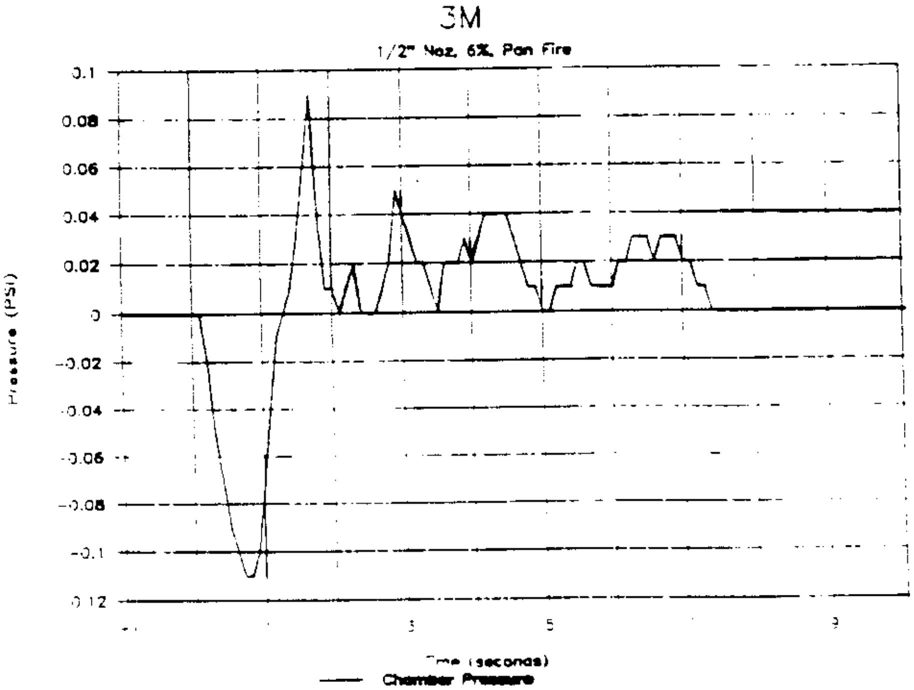


Figure 7

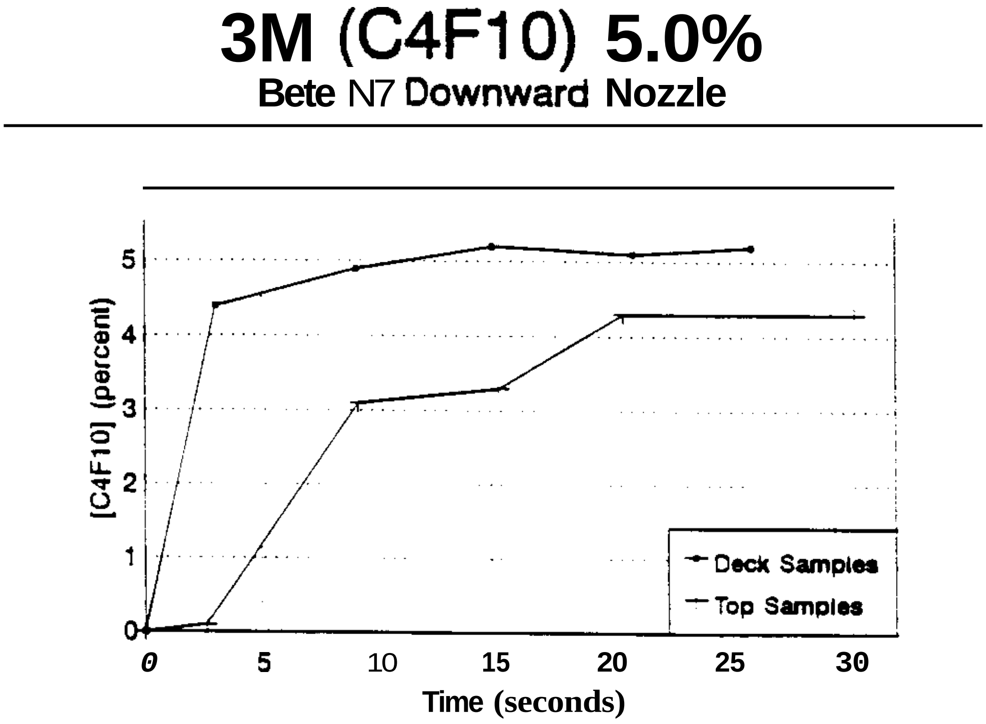


Figure 8