IN: Gann, R.G, Editor, Fire Suppression System Performance of Alternative Agents in Aircraft Engine and Dry Bay Laboratory Simulations, Vol. 2, Section 12, NIST SP 890, 591-621 pp, 1995

12. SELECTION OF A CF_3Br SIMULANT FOR USE IN ENGINE NACELLE CERTIFICATION TESTS

Carole A. Womeldorf and William L. Grosshandler
Building and Fire Research Laboratory

Contents

Page

12. SELECTION OF A CF_3Br SIMULANT FOR USE IN ENGINE NACELLE CERTIFICATION TESTS 591
12.1 Introduction 592
12.1.1 Background 592
12.1.2 Engine Nacelle Fire Suppression Systems 592
12.1.3 Suppression System Certification 593
12.1.4 Previous Simulant Work 594
12.2 Thermophysical Screening of Candidate Simulants 594
12.2.1 Thermophysical Comparison and Analysis 594
12.2.2 Three Final Candidates 596
12.3 Experimental Testing of Candidate Simulants 597
12.3.1 Test Methodology 597
12.3.2 Fill Conditions 597
12.4 Results 599
12.4.1 Comparison of Pressure Results 599
12.4.2 Spray Discharge Results 604
12.5 Conclusion 605
12.6 Acknowledgments 620
12.7 References 620

12.1 Introduction

This section describes the requirements and selection of a simulant of CF_3Br for the purpose of certification testing engine nacelle fire suppression systems. To illustrate the storage, delivery, and distribution requirements of CF_3Br, relevant characteristics of engine nacelle fire suppression systems and certification tests are briefly summarized. An initial screening of over 1300 chemicals based on the boiling point, critical temperature, and molecular weight of CF_3Br is described, and the nine potential candidate simulants that were found are listed. Three final candidates (SF_6, C_2HF_5, and $CHClF_2$) were selected for experimental testing based upon their saturated vapor pressures, Jakob numbers, and the requirements of this application: ozone depletion potential, flammability, corrosiveness, toxicity, stability, and atmospheric lifetime. To evaluate the hydraulic properties of the simulants, as compared to CF_3Br, pressure traces of discharges through a piping system into cooled recovery bottles and to atmosphere are compared with like tests of CF_3Br. To compare the discharge spray distribution of the simulants with CF_3Br, high speed movies of the plumes at the end of the piping system were taken and are described. Results and conclusions from comparisons of the three candidate simulants with CF_3Br are presented and discussed.

12.1.1 Background. The Department of Defense and the Federal Aviation Administration require certification testing of the fire suppression system for each aircraft engine design to ensure that the required concentration of halon 1301 is distributed throughout the nacelle. Historically all halon 1301 systems have been tested by discharging an installed bottle of halon 1301 into the engine nacelle. The concentration of the agent is then measured to determine whether the system passes the certification test. The Montreal Protocol of 1987 increased awareness of the harmful effect of halon 1301 on the environment; consequently national (European Communities Regulation 3093/94, 22 December 1994) and local regulations (e.g., South Coast Air Quality Management District Rule 1418, Section (d)(2)(B), 10 January 1992) are bringing this procedure to an end.

Given the continued need to test engine nacelle fire suppression systems, the United States Navy initiated a search for a simulant of halon 1301 that would have an acceptable (preferably zero) ozone depletion potential (ODP). An effective simulant would need to mimic halon 1301 and could be used during system development or a certification test to evaluate the discharge performance of the fire suppression system. The Building and Fire Research Laboratory of the National Institute of Standards and Technology was contracted to identify and test three possible simulants and make a final recommendation to the Navy for an appropriate simulant. This section describes the work defining the requirements of a simulant, a review of relevant thermophysical properties to identify three candidates, and experimental testing which led to the selection of C_2HF_5 (HFC-125) as a simulant of halon 1301 for certification and development testing.

12.1.2 Engine Nacelle Fire Suppression Systems. Though the details of engine nacelle fire suppression systems vary from aircraft to aircraft, their fundamental configuration is basically the same. The agent is stored in a spherical or cylindrical pressure vessel with a volume as small as 0.7 L or as large as 15.5 L. The N_2 pressurization is in the range of 2.5 MPa to 6.4 MPa at 21 °C. The *percent liquid fill*, which describes the volume of CF_3Br present in liquid phase at room temperature divided by the total volume of the bottle, is usually between 40 % and 75 % and typically 50 % on Navy aircraft. When a bottle is only 40 % filled with liquid there is a sizable weight and space penalty on board an aircraft. At the other extreme, when a bottle is filled to 75 %, less N_2 is available to propel the agent from the bottle and into the nacelle. The fill conditions of the bottle are determined by the size and

geometry of the nacelle and the volume of air flowing through it, as well as the distance the bottle is stored from the nacelle. In practice designers refer to the *fill density* of the storage bottle which is the total mass of the agent divided by the volume of the bottle, rather than the percent liquid fill. The fill density when given in U.S. Customary Units, pounds per cubic foot, is nearly identical to the percent liquid fill because the density of CF_3Br at saturation pressure and room temperature is 97.3 lb/ft^3 (1.56 x 10^3 kg/m^3). If the density is rounded up to 100 lb/ft^3 then the fill density divided by 100 lb/ft^3 gives a ratio very close to the percent liquid fill.

Once the design parameters are selected for a particular engine and nacelle, a fire bottle is filled with the correct mass of CF_3Br and pressurized with the appropriate amount of N_2 to achieve the desired pressure at room temperature. During this process the bottle is agitated to equilibrate the N_2 with the CF_3Br. The charged bottle is then mounted in an aircraft with the discharge head usually pointed downward. This is done to allow the N_2 gas to force the agent out from above when the aircraft is flying level, as is required when the engine nacelle fire protection system is triggered by the pilot.

The agent release mechanism is typically a small explosive device, known as a squib, which ruptures a small closure disk and produces an opening that allows the agent-N_2 mixture to flow through the discharge head and into the tubing. The N_2 that was in solution at the higher storage pressure begins to degas, while the CF_3Br boils. At atmospheric pressure, the boiling point of CF_3Br is -57.8 °C. The detonation of the squib also promotes nucleation in the N_2-saturated agent. This turbulent, highly transient mixture of dense vapor and evaporating liquid travels through usually less than 3 m of pipe, though as much as 24 m, from the storage location to the targeted nacelle. The mixture sprays into the nacelle through tubes, sometimes with supplementary holes, mounted in the nacelle and located to distribute the CF_3Br simultaneously and evenly throughout fire zones in the nacelle.

12.1.3 Suppression System Certification. Based upon years of testing and experience, a system that generates a 6 % by volume concentration of CF_3Br, held for at least 0.5 s during the test procedure, has been found sufficient in practice to extinguish an engine nacelle fire under most conditions (Tedeschi and Leach, 1995). Any redesign of an engine nacelle with a halon fire suppression system requires that tests be run to re-certify that the 6 % level can still be maintained throughout the nacelle for the 0.5 s requirement. Military aircraft are tested according to the Military Specification MIL-E-22285, while the Federal Aviation Administration is responsible for the certifying of commercial aircraft. The FAA test requires that a 6 % concentration be achieved with the bottle cooled to -54 °C (FAA Advisory Circular Number 20-100). For the military certification process, the discharge of the calculated amount of agent must occur in one second or less, timed from the entrance of the agent into the nacelle.

The concentration of agent is usually measured using 12 probes located throughout the nacelle while in flight or with air flow conditions to simulate in-flight conditions. The probes are attached to a halon analyzer, (see Section 11, this publication) which measures the change in concentration of the air-agent mixture. Any change in concentration affects the fluid properties of the mixture and causes a pressure variation that is detected by a strain gauge mounted on a bellows. The strain gauge resistance is calibrated against a known concentration of CF_3Br. The required concentration must be reached at all 12 probes and held for 0.5 s simultaneously for the system to pass the certification test.

During the process of certifying an aircraft, as many as 50 bottles of CF_3Br can be discharged to the atmosphere. The specific number discharged depends on the type of aircraft, the different flight attitudes, velocities, altitudes, and bottle temperatures that the certifying agency requires, as well as the amount of design modification required to achieve a successful certification test. The Environmental Protection Agency has defined the certification process to be a "non-essential" atmospheric discharge

of the very high ozone depletion potential chemical, CF_3Br. Because of the significant amounts of CF_3Br used, its deleterious effect on the environment, and resultant regulations, it is important that any simulants identified for modeling CF_3Br during future certification procedures possess an ODP defined as acceptable by the 1990 amendment to the Clean Air Act with a value of 0.2 or less.

12.1.4 Previous Simulant Work. Previous studies (Moore, 1989; DiNenno *et al.*, 1990; BA^{e}SEMA, 1992) have examined different halocarbons and refrigerants to determine their suitability as CF_3Br simulants. $CHClF_2$ and SF_6 were both tested for use in shipboard room flooding applications as simulants of CF_3Br by the Navy (DiNenno *et al.*, 1989, 1990). This work found that SF_6 outperformed $CHClF_2$. Though $CHClF_2$ was not selected, the Navy tests demonstrated that its pipe flow behavior (i.e., the slope of pressure decline) was similar to that of CF_3Br, although the absolute timing was different. Only BA^{e}SEMA (1992) tested C_2HF_5 as a simulant. BA^{e}SEMA and the British Ministry of Defense were also concerned with a total flooding application and also selected SF_6. For engine nacelle fire suppression systems, the dynamic flow characteristics are more important than the suspension-in-air characteristics. These earlier studies concerned total flooding applications where leakage and suspension-in-air timing, on the order of 30 seconds to 15 minutes, were of primary importance. For the current application in engine nacelles, the time scales are much shorter, on the order of 500 ms, and the dynamic pipeline properties and spray plume characteristics dominate the process.

12.2 Thermophysical Screening of Candidate Simulants

12.2.1 Thermophysical Comparison and Analysis. Given the dynamic phase change, from a liquid saturated with N_2 to a gas detected by a halon analyzer, any simulant should match as closely as possible the thermophysical characteristics of CF_3Br listed in Table 1. In an effort to broaden the scope and focus on essential physical properties, NIST selected explicit criteria for an extensive search. These physical properties were molecular weight, normal boiling point, and critical temperature. The molecular weight was selected as the broadest of screening tools to eliminate those chemical compounds that were less suitable than the two previously tested simulants: SF_6 and $CHClF_2$. A range of ± 65 g/mol about the molecular weight of CF_3Br was selected, based upon the difference between the molecular weights of CF_3Br and $CHClF_2$. The normal boiling point and the critical temperature of CF_3Br were selected as the other two criteria based on their contributions to the phase change process. The acceptable range about both these temperatures was defined as ± 25 °C.

An examination of the halogenated compounds and other refrigerants listed in REFPROP (Gallagher *et al.*, 1993), a database complied by NIST, located three new candidates in addition to the previously tested $CHClF_2$ and C_2HF_5. A second, more general database, DIPPR (Daubert and Danner, 1993) was searched also. This covered 83 different families of chemicals, including all classes of pure hydrocarbons; hydrocarbons containing halogens, nitrogen, sulfur, and/or oxygen; as well as silanes and inorganics. From these two databases only nine chemicals met the screening criteria: $CHClF_2$, C_2ClF_5, C_2HF_5, $C_2H_3F_3$, C_3F_6, C_3OF_6, C_3F_8, ClO_3F, and SF_6. Their properties are summarized in Table 1.

In addition to the candidates' resemblance to CF_3Br, they must also be appropriate for the application, a discharge into an engine nacelle. For broad acceptance a candidate to be discharged into the atmosphere must possess an ozone depletion potential less than 0.2, preferably zero. C_2ClF_5 was removed from consideration because it has an ODP of 0.4. For discharge into the fire zones of a running aircraft engine, it is important that the chemical be non-flammable. $C_2H_3F_3$ is not suitable

Table 1. Thermophysical Properties of CF_3Br and Potential Candidate Simulants

Candidate Simulants Chemical Compounds	Chemical Formulas	Refrigerant Number	Molecular Weight (kg/kmol)	Normal Boiling Point[R,D] (°C)	Critical Temperature[R,D] (°C)
Bromotrifluoromethane	CF_3Br	R13B1	148.9	-57.8	67.1
Chlorodifluoromethane	$CHClF_2$	R22	86.5	-40.9	96.2
Chloropentafluoroethane	C_2ClF_5	R115	154.5	-39.2	79.9
Pentafluoroethane	C_2HF_5	R125	120.0	-48.6	66.2
1,1,1-Trifluoroethane	$C_2H_3F_3$	R143a	84.0	-47.4	73.1
Hexafluoropropene	C_3F_6	R216	150.0	-29.7‡	94.8
Hexafluoroacetone	C_3OF_6	-	166.0	-27.3	83.9
Octafluoropropane	C_3F_8	R218	188.0	-36.8	72.0
Perchloryl Fluoride	ClO_3F	-	102.5	-46.7	95.2
Sulfur Hexafluoride	SF_6	-	146.1	-64.0	45.5

The reliability is better than 5 %, except where noted.

References/Key:
R REFPROP: Gallagher *et al.*, 1993.
D DIPPR: Daubert and Danner, 1985.
‡ Reliability quoted in reference as < 10 % error on a Kelvin scale.

because it has a lower flammability limit of 13 % by volume in air (MSDS, 1994), and as such it could be a fire hazard during testing. In addition, the chemical must not be corrosive, unstable, nor toxic. Both C_3OF_6 and ClO_3F fail on these points because of the ease with which they hydrolyze into highly toxic and corrosive acids: HF and HCl (MSDS, 1994).

The five remaining candidates were evaluated based on saturated vapor pressure, Jakob number, experimental history, and atmospheric lifetime (Refer to Table 2). Saturated vapor pressure is an indicator of the relative pressure reached during a discharge in the pipeline and the force that will expel the chemical in addition to the nitrogen. At 22 °C, both C_3F_6 and C_3F_8 have saturated vapor pressures more than 46 % lower than CF_3Br. As a result, these candidates may not achieve the same pipeline pressures as CF_3Br. At the other extreme, SF_6 has a saturated vapor pressure 50 % greater than CF_3Br. This may result in SF_6 dispensing more quickly than CF_3Br. Of all the five possible candidates, C_2HF_5 has the saturated vapor pressure closest to CF_3Br.

The Jakob number (*Ja*) (Pitts *et al.*, 1994) is the difference in enthalpy of a liquid between the normal boiling point and the ambient temperature (evaluated by the integral of the heat capacity of the liquid over that temperature range), divided by the heat of vaporization at the boiling point:

$$Ja = \frac{\int_{T_{bp}}^{T_{ambient}} C_{p,l}(T)dT}{\Delta H_{vap}(T_{bp})}$$

Table 2. Thermophysical and Environmental Properties of CF_3Br and Potential Candidate Simulants

Chemical Formulas	Vapor Pressure[R,D] (kPa) at 22 °C	Jakob Number[P] at 22 °C	Ozone Depletion Potential[B]	Atmospheric Lifetime[B] (years)	Reasons for Exclusion
CF_3Br	1496	0.51	16	110	*Baseline*
$CHClF_2$	957	0.31	0.05	16	*Selected*
C_2HF_5	1271	0.52	0	41	*Selected*
C_3F_6	603	0.40	0	< 1†	Low VP & Low Jakob
C_3F_8	805	0.59	0	10,000	Low VP & High ALT
SF_6	2268	0.66[A]	0	3200	*Selected*

Reliability of values is better than 5 %.

References/Key:
R REFPROP: Gallagher *et al.*, 1993.
P Pitts *et al.*, 1994.
B Braun *et al.*, 1994.
D DIPPR: Daubert and Danner, 1985.
A Jakob Number was calculated using thermodynamic values from AlliedSignal Chemicals.
VP Vapor Pressure
ALT Atmospheric Lifetime. For these chemicals ALT is a predictor of global warming effects.
† Correspondence with Scott Thomas, 3M Specialty Chemicals Division and Robert Huie, NIST.

This dimensionless number is a measure of the fraction of a pure liquid that will flash to vapor when depressurized instantaneously. The *Ja* numbers for these candidates at 22 °C vary from 0.31 for $CHClF_2$ to 0.66 for SF_6, compared to a value of 0.51 for CF_3Br.

Another consideration was the environmental impact of the chemicals based upon their atmospheric lifetime (ALT). Ideally, the selected candidate should have a very short atmospheric lifetime and very low global warming potential (GWP). Global warming gases have been identified by the Environmental Protection Agency as an area of serious concern, although as of yet, chemicals are not regulated based on their GWP. The values in Table 2 show that SF_6 and C_3F_8 have ALTs greater than a millennium. In addition, their S-F and C-F chemical bonds indicate that they will absorb infrared effectively (Ravishankara *et al.*, 1993). The possible advantages of either of these global warming gases as a simulant must be balanced against the possibility of future regulation.

12.2.2 Three Final Candidates. Based on the above thermophysical, application specific, and environmental criteria, C_2HF_5 (also known as HFC-125 or R125), $CHClF_2$ (HCFC-22 or R22), and SF_6 were selected as the three candidate simulants for experimental testing. None of these candidates is flammable, corrosive, toxic, or unstable, and there is sufficient commercial availability of each. $CHClF_2$ has a non-zero ozone depletion potential, at 0.05. The atmospheric lifetime of SF_6 is greater than the 110 years of CF_3Br. Thus, of the three, C_2HF_5 is the most appropriate candidate based on its environmental impact properties: a zero ODP and lower ALT. Because of this and its close thermophysical similarities to CF_3Br, C_2HF_5 was considered the strongest candidate of the three.

12.3 Experimental Testing of Candidate Simulants

Though evaluation of the chemical compounds based upon their thermophysical properties is a strong indicator of their suitability as simulants for CF_3Br in the certification testing process, the relative importance of the thermophysical differences between the candidates and CF_3Br has not been quantified. Accordingly, comparative experiments were performed. NIST performed tests on CF_3Br as a baseline, C_2HF_5, SF_6, and $CHClF_2$, which focused on distinct aspects of the discharge process. An initial round of tests compared dynamic pressures of the compounds to evaluate their behavior inside the fire suppression distribution system. A second set of tests evaluated the discharge characteristics from a simulated fire suppression system through a T-fitting using a high speed movie camera. The width and duration of these plumes are a qualitative indication of how the chemicals will distribute throughout the nacelle relative to CF_3Br. Additional pressure measurements were taken during the spray discharge filming. In the discussion below, the general test methodology and initial conditions will be presented. The pressure traces of the pipeline flow tests and selected prints from the spray tests follow.

12.3.1 Test Methodology. To model an aircraft engine nacelle fire suppression system, these tests used the same basic apparatus described in Section 8.6 (this publication) and earlier work by Cleary *et al.* (1994). Generally it consisted of a fixed cylindrical storage vessel of 4.19 L, charged with a specified mass of CF_3Br and pressurized with N_2 gas. The N_2 gas was slowly bubbled through the agent to pressurize the vessel to 4.41 MPa and to maximize the dissolution of N_2. The vessel was attached to a discharge head and a 3 m long straight piping system, similar in length to a typical Navy aircraft delivery system. The agent release mechanism was a manually engaged, plunger-type solenoid valve. Once the plunger was released, the agent-N_2 mixture traveled through the discharge head, turned 90°, entered a smooth reducing section, into the pipe with a 15.9 mm inner diameter for the entire length. The pressures in the vessel and along the piping were measured by pressure transducers sampling at 1000 Hz. A total of five pressure transducers recorded the pressure decay within the vessel and in the pipeline. Locations are shown at the bottom of Figure 1. The total time of a discharge was no more than 2000 ms.

The first set of tests to compare pipeline behavior used a closed system as in Section 8. The 3 m pipe was terminated into four recovery cylinders in a freezer cooled with dry ice to approximately -57 °C. This temperature, at the pipeline final pressure of about 1 MPa, was sufficient to condense the tested compounds. Two or more shots of compound were discharged, the first with the chemical directly from a supply bottle, the second with chemical condensed and recovered from the freezer cylinders. By recovering and recycling the chemicals less agent was required to run the series of tests. Some minor variation was observed between new agent and recycled agent, as discussed below.

A second set of tests were performed without the recovery tanks attached. These discharges were released through a T-fitting with 7.0 mm diameter outlets to the atmosphere (as shown in Figure 1). The upward plume of each agent was filmed using a 16 mm high speed movie camera at 500 frames per second. The T-fitting used was an actual discharge nozzle provided by Walter Kidde Aerospace, that can be found in some aircraft fire suppression systems. Figure 1 illustrates the location of the pressure transducers and the discharge T-fitting.

12.3.2 Fill Conditions. Previous simulant work for use in shipboard testing for both the Naval Research Laboratory (DiNenno *et al.*, 1989, 1990) and the British Ministry of Defense (BA^{e}SEMA, 1992) matched the moles of the potential simulants with the initial moles of CF_3Br in order to achieve the same concentration by volume in the test chambers. In each test, SF_6 was selected over either

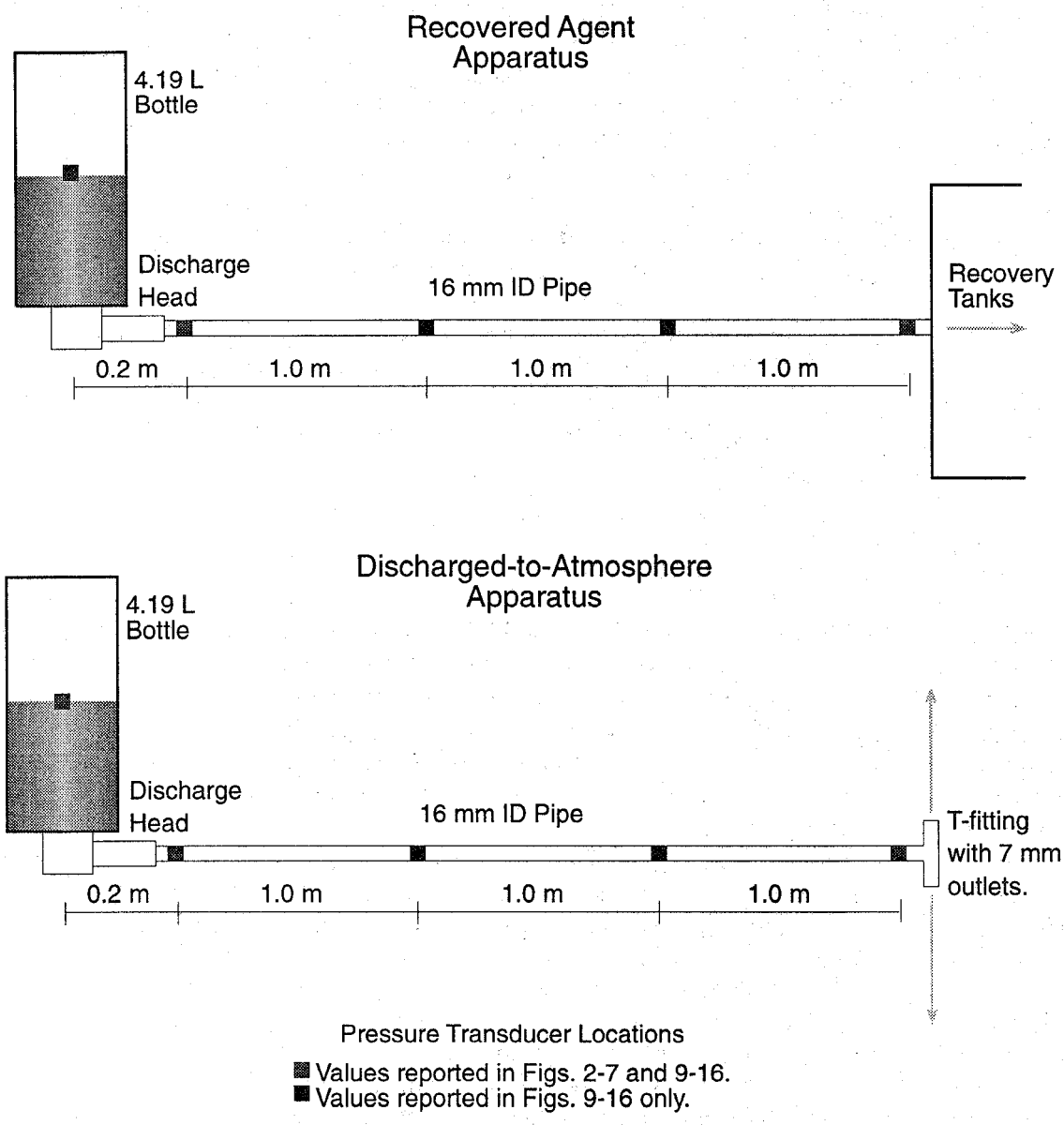


Figure 1. The discharge apparatus with storage vessel and pressure transducers in both configurations, with recovery tanks and with discharge T-fitting.

$CHClF_2$ or C_2HF_5. These tests matched the number of moles in an effort to have 6 % of the simulant equal 6 % of CF_3Br, thereby requiring no rescaling. A significant drawback to this method is that the amount of simulant in liquid volume may be quite different than the corresponding amount of CF_3Br, and as a result there may be either an increase or a decrease in the amount of compressed nitrogen gas available for the discharge process. For example, a four liter bottle with 21 mol (3.2 kg) of CF_3Br at 4.41 MPa has roughly 2 L of liquid and an equal volume of gas. The same bottle filled with the same number of moles of $CHClF_2$ (1.9 kg) will have approximately 20 % less liquid and 20 % more gaseous N_2, due to the difference in liquid molar densities. This increase in gaseous N_2 will significantly impact the discharge pressure and affect the distribution and timing of the discharge independent of the simulant selected.

In these tests the percent liquid fill of CF_3Br was matched rather than the number of moles, thereby conserving the amount of gaseous N_2. Using the chemical's liquid density calculated at saturation pressure and 22 °C, a 51 % liquid fill condition was matched for CF_3Br and each of the different candidates. (The small contribution of the nitrogen in solution and agent in vapor was neglected.) As a result, the volume of agent-N_2 vapor available to force the agent through the pipes was nearly the same for each agent. For each chemical the 51 % liquid fill required a different mass. Specific fill conditions used in both the recovered and the discharged-to-atmosphere tests are described in Table 3.

12.4 Results

12.4.1 Comparison of Pressure Results. The time history of the pressure of each candidate and CF_3Br at different locations in the storage and piping system permits characterization of the complex dynamics that take place during a discharge. These measurements permit quantitative comparison of the magnitude of the pressures as well as the timing of the discharges of the candidates with CF_3Br. Two or more tests of each candidate were performed with the recovery tanks attached. Based on the scatter about the zero points and numerous similar tests with the same apparatus, there is less than 5 % uncertainty in the values presented.

In Figure 2 the pressure traces of both $CHClF_2$ and CF_3Br are plotted. The top pair of lines are the values that were recorded inside the storage vessel. The next pair were recorded at 0.2 m downstream of the discharge head. The lowest pair of traces were taken at the end of the 3.0 m pipe, just before the recovery tanks. (For clarity only these three of the five pressure measurements are shown here.) Figures 3 and 4 show the pressures measured at the same locations for CF_3Br with C_2HF_5 and SF_6, respectively. From an initial inspection, the pressure magnitude and trend of CF_3Br is most nearly matched by C_2HF_5. It is apparent that the close Jakob number and vapor pressures have accurately predicted the pipeline flow similarities of this candidate and CF_3Br.

Table 4 lists the timing and peak pressure values measured at the 3.0 m pressure transducer (PT). These values were calculated by averaging the peaks of each test and their time from discharge. The range is inclusive of pressures and times for all of the peaks of a particular chemical compound. An uncertainty value of about 5 % reflects the human and mechanical variability inherent in the system. The values confirm was what evident by inspection. C_2HF_5 most closely simulates the discharge of CF_3Br. The difference between the peaks is about 2 %. $CHClF_2$ is about 11 % lower and the next closest; while SF_6 is more than 15 % greater.

In addition to these quantitative values there is a qualitative trend that distinguishes the candidates. Inside the storage vessel the initial condition is always 4.41 MPa and the final pressure is approximately 1 MPa, as a result of the back pressure in the recovery tank. The storage vessel

Table 3. Initial Conditions for Both Recovered and Discharged-to-Atmosphere Tests

Properties & Initial Conditions	CF_3Br^R	SF_6^D	$C_2HF_5^R$	$CHClF_2^R$
Liquid density‡ (kg/m^3), at saturation pressure, 22 °C	1574	1354	1207	1204
Mass (kg) used to match 51% liquid fill. ±0.02 kg	3.36	2.93	2.58	2.57
Fraction of CF_3Br mass	1.00	0.87	0.77	0.76
Number of Moles‡	22.6	20.1	21.5	29.7
Fraction of CF_3Br moles	1.00	0.89	0.95	1.31

References/Key:
R REFPROP: Gallagher *et al.*, 1993.
D DIPPR: Daubert and Danner, 1985.
‡ Estimated error is less than 1 %.

pressure traces for $CHClF_2$, C_2HF_5, and CF_3Br have a noticeable inflection point at about 500 ms. It is not present in the SF_6 curves, though there is a short rough plateau at about 100 ms. From the discussion in Section 8, these inflection points are attributable to the delayed degassing of the N_2 within the storage vessel. Due to the lower solubility of N_2 in SF_6 (Huber, 1994) degassing is much less pronounced and occurs earlier in SF_6. The similarity of C_2HF_5 and $CHClF_2$ with respect to the degassing of N_2 is a subtle but possibly important quality of a good simulant.

For both of the pipeline pressure traces at 0.2 m and 3.0 m, there is a steep initial rise in the pressure just after the discharge is initiated. (Refer to Figure 1 for PT locations.) This reflects the swift release of the agent. For the rest of the discharge these curves follow the trend of the vessel pressure trace, at a reduced pressure. The difference between the peaks of these tests and those which were discharged to atmosphere (Table 5) is consistently 0.285 ± 0.013 MPa for each chemical. Consequently the tests with recovery tanks provide reliable predictors of the flow behavior when discharged to atmosphere.

In Figures 5 through 7 pressure traces recorded during the discharges through the T-fitting to atmosphere are plotted. Again each candidate is plotted with CF_3Br for the same three PT locations. Qualitatively, both sets of tests show the same general results. Even the difference in the peaks at the 3.0 m PT is the same, though there is an offset to the tests in which the agent was recovered such that the peaks are about 0.3 MPa higher. Table 5 lists the peak values of the 3.0 m PT of the discharges that were released through the T-fitting to atmosphere. Only one of each of these tests was conducted. Figure 8 is a bar chart of the values tabulated in Tables 4 and 5. The similarity between CF_3Br and C_2HF_5 for both sets of tests is clearly greater than for any of the other candidates. Additionally the differences among SF_6, $CHClF_2$, and CF_3Br are much larger than the error.

Additional tests and the remaining pressure transducer values are plotted in Figures 9 through 13 for both the recovered tests and those discharged to atmosphere. Figure 9 shows the same run of CF_3Br plotted in Figure 2 as well as the run that came before it with the agent directly from the supply bottle. The difference between the two curves is only distinguishable between 500 and 700 ms, and at that point it is less than 0.1 MPa. In Figure 10 three curves from $CHClF_2$ are plotted, one with new agent and two with agent that was recycled. A small amount of variation can be seen toward the end of the test near the end of the discharge at about 900 ms. Three tests of C_2HF_5 are plotted in Figure 11. Here the difference between new and once recycled is more noticeable. This inflection

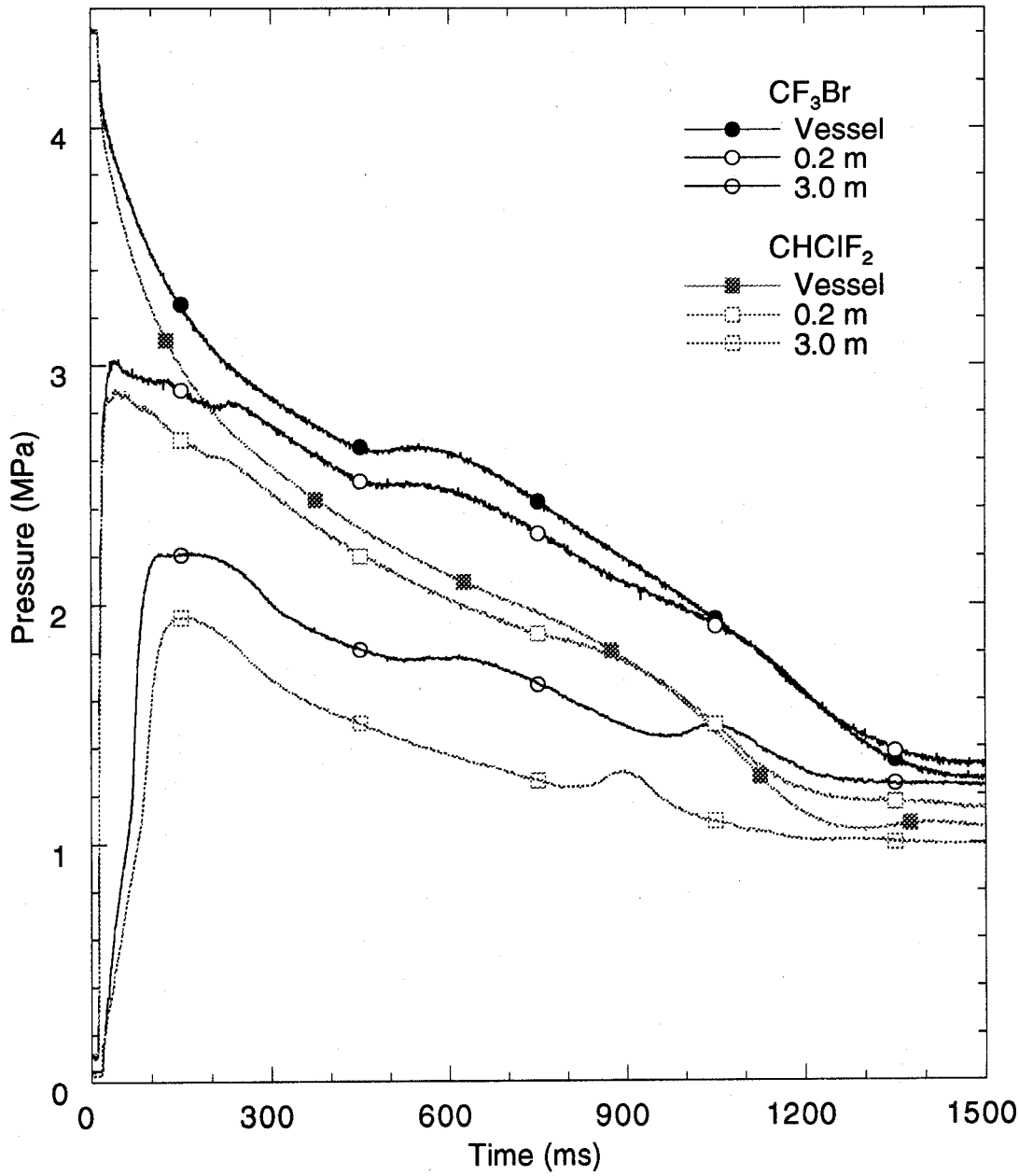


Figure 2. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for recovered discharges of recycled $CHClF_2$ and CF_3Br.

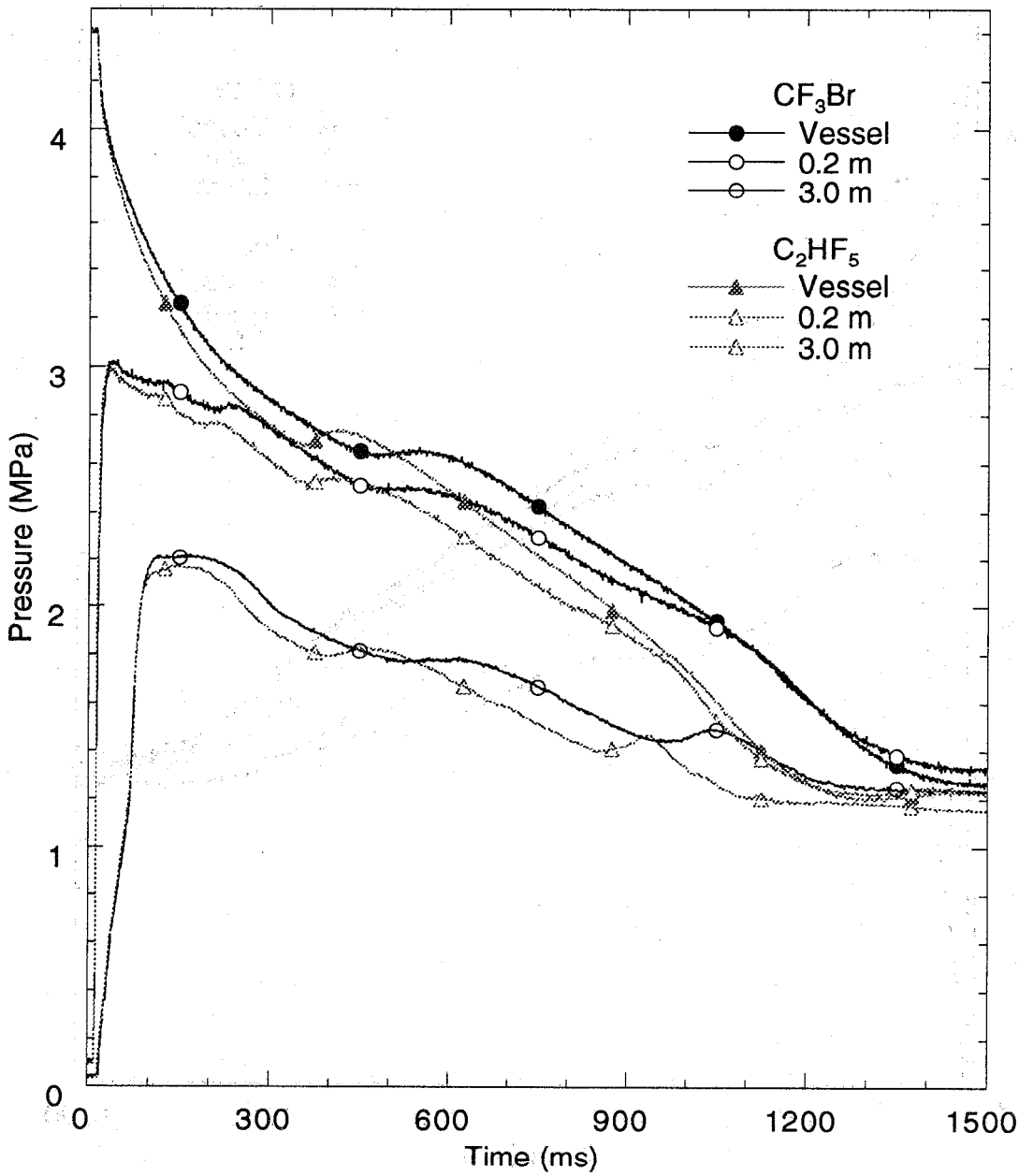


Figure 3. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for recovered discharges of recycled C_2HF_5 and CF_3Br.

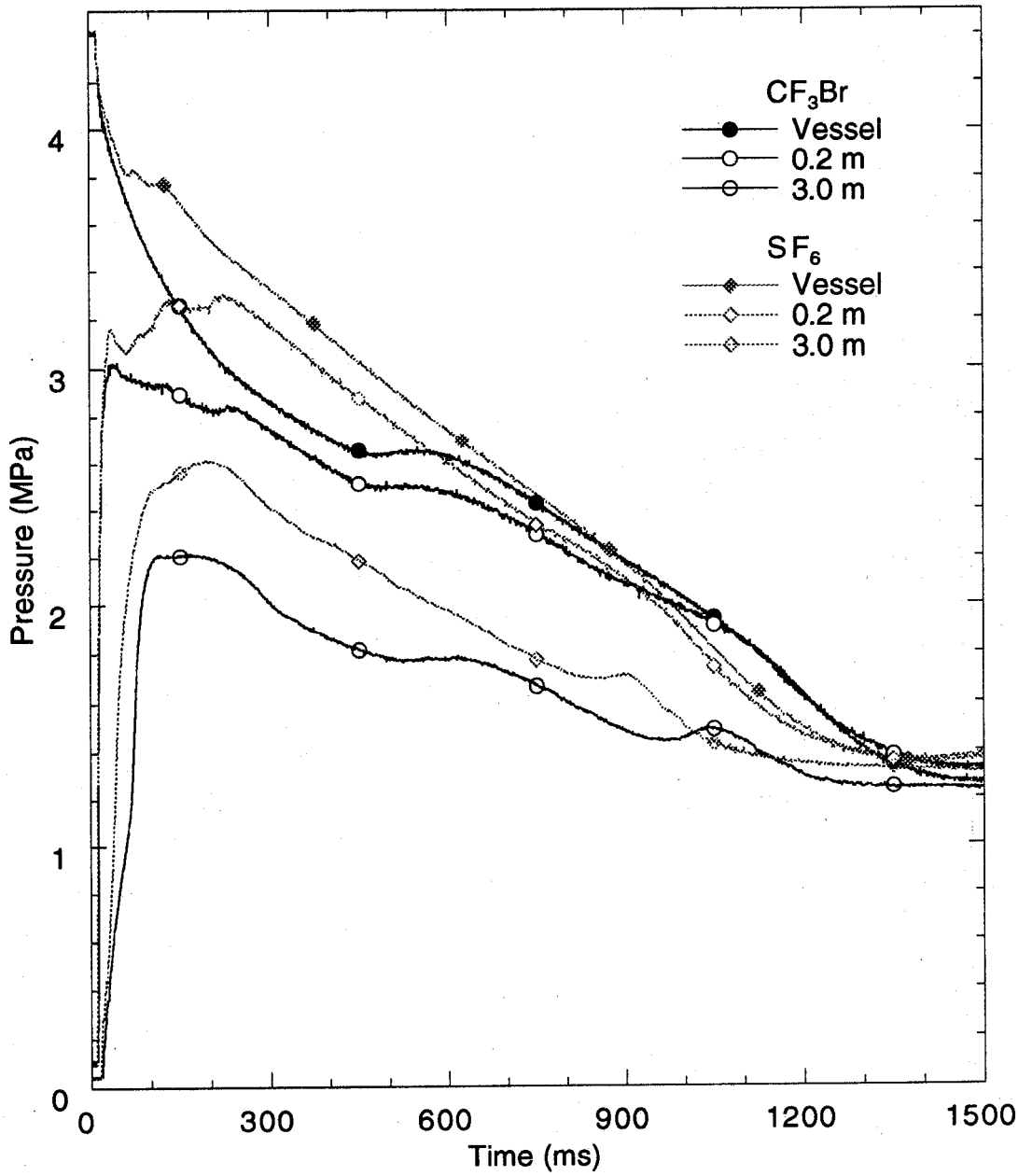


Figure 4. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for recovered discharges of recycled SF_6 and CF_3Br.

Table 4. Peak Values of 3 m Pressure Transducer for All Tests with Recovery Tanks Attached

Chemical Formula	Peak values (MPa)	Scatter of pressure values (MPa)	Time from release (ms)	Scatter in peak timing (ms)	Number of tests	Subset of tests which were recycled
CF_3Br	2.21	±0.01	135	±20	2	1
$CHClF_2$	1.96	±0.02	145	±5	3	2
C_2HF_5	2.16	±0.03	140	±10	5	3
SF_6	2.61	±0.01	180	±5	2	1

point occurs during the dense vapor phase of the flow and may represent a variation in saturation condition with N_2 gas; however it is clear from the peak values from all of the pipeline pressure transducers and the close timing of the final drop off at 900 ms that the differences among chemicals recycled a different number of times has not affected the overall characteristics of this discharge. Figure 12 contains two curves of SF_6, one the first time it was used and the other after it was recycled once. There is no detectable difference between the recycled and initial run. (Note that the pressure transducers at 1.0 m and 2.0 m were not reading the peak pressures properly during the SF_6 discharge.)

Figures 13 through 16 contain pressure plots of all of the tests with discharges to atmosphere. The chemical used in every one of these tests was recycled once before. As it was shown in the tests where the chemical was recovered, there is little difference between tests run with fresh or recycled agent. Figure 13 shows the details of the CF_3Br discharge-to-atmosphere baseline test. The pressure transducer at 1.0 m did not work properly during this test. $CHClF_2$ results are plotted in Figure 14. All transducers appear to have operated properly. Traces from the tests with C_2HF_5 are plotted in Figure 15 and no problems were observed with the pressure transducers during these tests. In Figure 16, SF_6 results are plotted. The same plateau was reached with the pressure transducers located at 1.0 and 2.0 m during these tests, as was seen during the tests with the recovered chemical.

12.4.2 Spray Discharge Results. The second part of the experiment was designed to evaluate and compare the spray characteristics of CF_3Br and the simulants. In this part of the comparison the upward outlet of the T-fitting was filmed for each chemical using a high speed movie camera. Prints of frames taken at 200 ms and 900 ms after the plume began exiting the T-fitting are shown in Figures 17 and 18. Figure 17 represents the discharge during its fully developed phase, just after the peak value was measured at the 3.0 m pressure transducer. Figure 18 shows the discharge near its end.

At 200 ms (Figure 17) the sprays of C_2HF_5 and SF_6 have nearly the same appearance as that of CF_3Br, with C_2HF_5 slightly wider and SF_6 somewhat narrower. The spray discharge of $CHClF_2$ is significantly wider than the CF_3Br discharge. If one recalls the values of the Jakob number for each of these chemicals (*Ja* equals 0.51 for CF_3Br, 0.66 for SF_6, 0.52 for C_2HF_5, and 0.31 for $CHClF_2$) the wider spread of $CHClF_2$ and the narrower spread of SF_6 appears counter-intuitive. A reasonable explanation is that the chemicals with the higher *Ja* are flashing primarily inside the piping. The $CHClF_2$, on the other hand, does not possess the internal energy to flash in the confined environment

Table 5. Peak Values of 3.0 m Pressure Transducer for All Tests Discharged Through T-fitting to Atmosphere

Chemical Formulas	Peak values (MPa)	Time from release (ms)	Number of tests	Number of times recycled
CF_3Br	1.94	109	1	1
$CHClF_2$	1.66	129	1	1
C_2HF_5	1.87	115	1	1
SF_6	2.33	100	1	1

and elevated pressures of the pipe. $CHClF_2$ flashes fully only when it is exposed to atmospheric pressure at the exit of the pipe.

At 900 ms (Figure 18) it is evident that the stronger flashing of SF_6 has either emptied the bottle faster, or it has gasified the agent more rapidly so that it is no longer visible exiting the T-fitting. In either case, the dense vapor cloud of CF_3Br is poorly represented by the SF_6 at this time. The $CHClF_2$ still has a fairly large cloud, but its more conical shape indicates a weaker jet than that of either the CF_3Br or the C_2HF_5. Finally, the jet from the C_2HF_5, though smaller than the CF_3Br, best represents the flashing spray characteristics of the CF_3Br at 900 ms as well as 200 ms.

12.5 Conclusion

The results for this model fire suppression system are conclusive. C_2HF_5 filled to 77 % of the mass of CF_3Br provides an excellent simulant for development and certification purposes. $CHClF_2$ and SF_6 both have similarities, but are inappropriate for reasons brought out by this testing. SF_6 reaches significantly higher pressures in the pipeline, its degassing behavior is unique in these tests, and from the observable spray plumes, it empties or vaporizes too quickly. $CHClF_2$ has a significantly reduced pressure in the pipelines, and though it does have a similar degassing inflection point, the broader spreading of its spray could lead to different distribution when directed into a nacelle.

The similarity between the thermophysical parameters of C_2HF_5 and CF_3Br, particularly the Jakob number, reinforces the conclusion that C_2HF_5 should be an excellent simulant for CF_3Br in different engine nacelle fire suppression systems. Subsequent field testing of C_2HF_5 alongside CF_3Br with a halon analyzer by the Naval Air Warfare Center and Walter Kidde Aerospace (Leach and Homan, 1995), the Boeing Corporation (Kaufmann *et al.*, 1995), and Short Brothers of N. Ireland (Riordan, 1995) has provided additional evidence for the suitability of C_2HF_5 as a simulant in different systems and operating conditions. On February 3, 1995, the U.S. Naval Air Systems Command officially certified an aircraft with C_2HF_5 for the first time. Boeing, at the time of publication, has requested that the Federal Aviation Administration accept C_2HF_5 as simulant for certification purposes on the Rolls Royce 777 engine. The use of C_2HF_5 in sustained total flood applications remains a possible extension of this work.

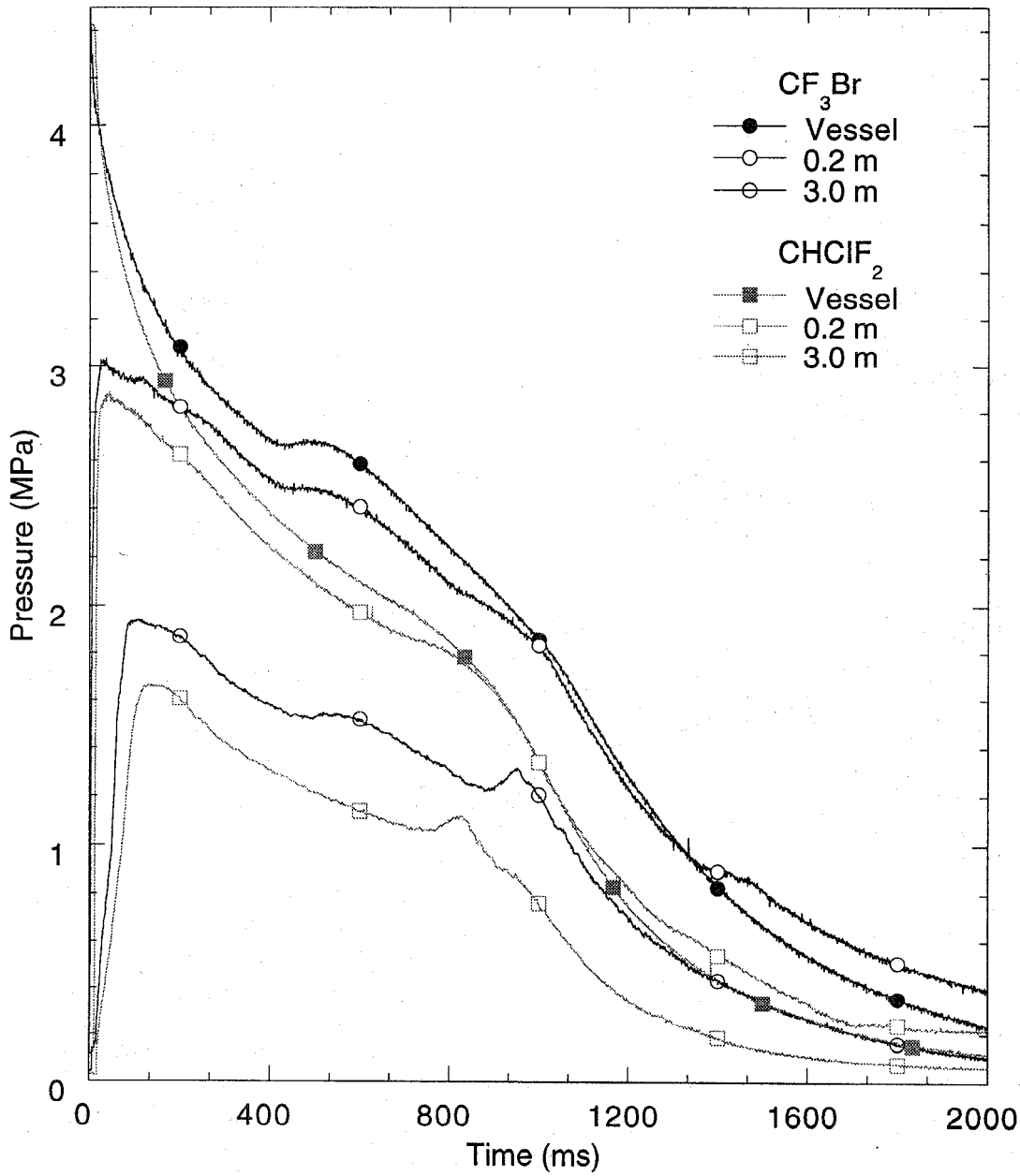


Figure 5. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for the discharges to atmosphere of recycled $CHClF_2$ and CF_3Br.

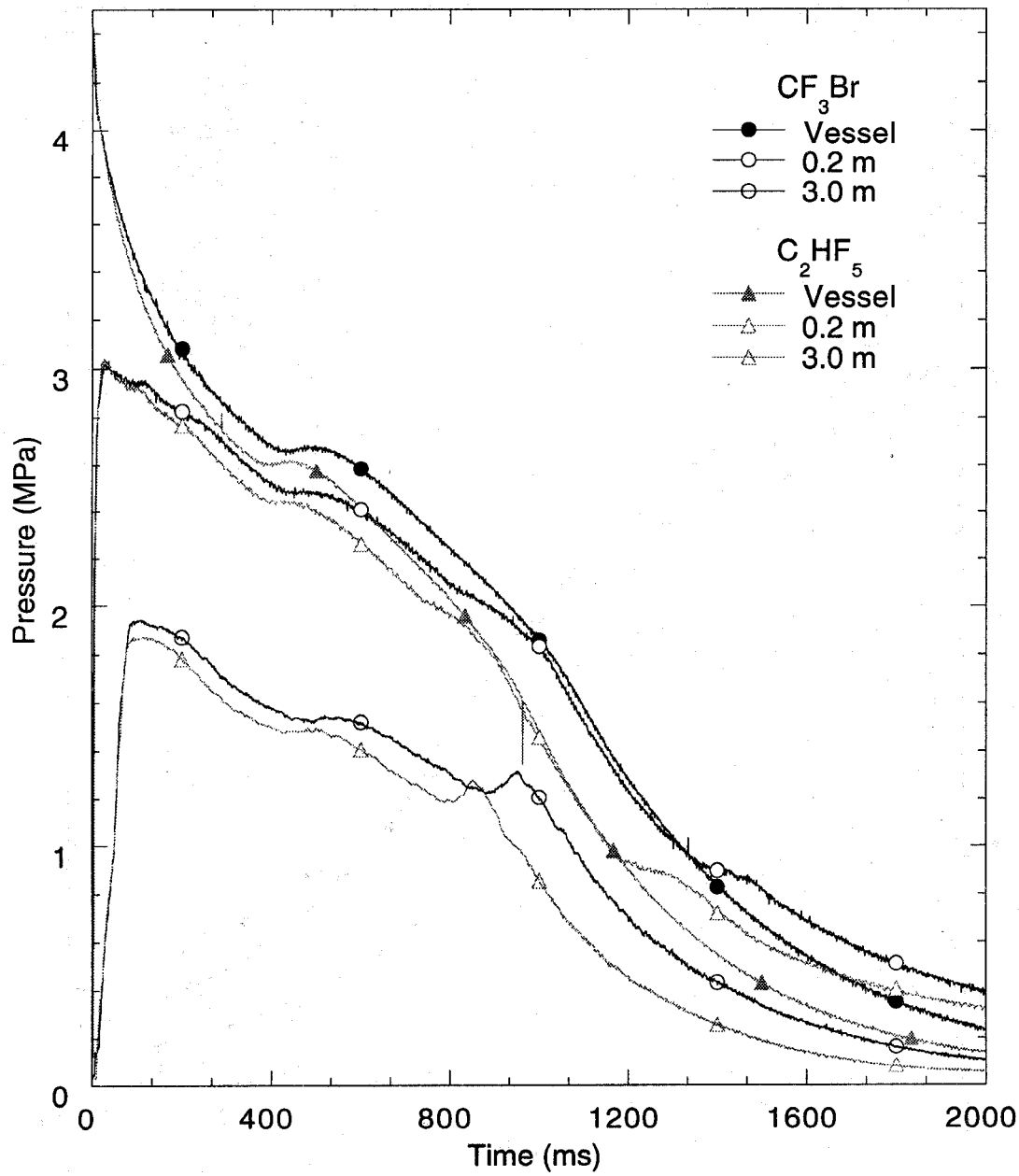


Figure 6. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for the discharges to atmosphere of recycled C_2HF_5 and CF_3Br.

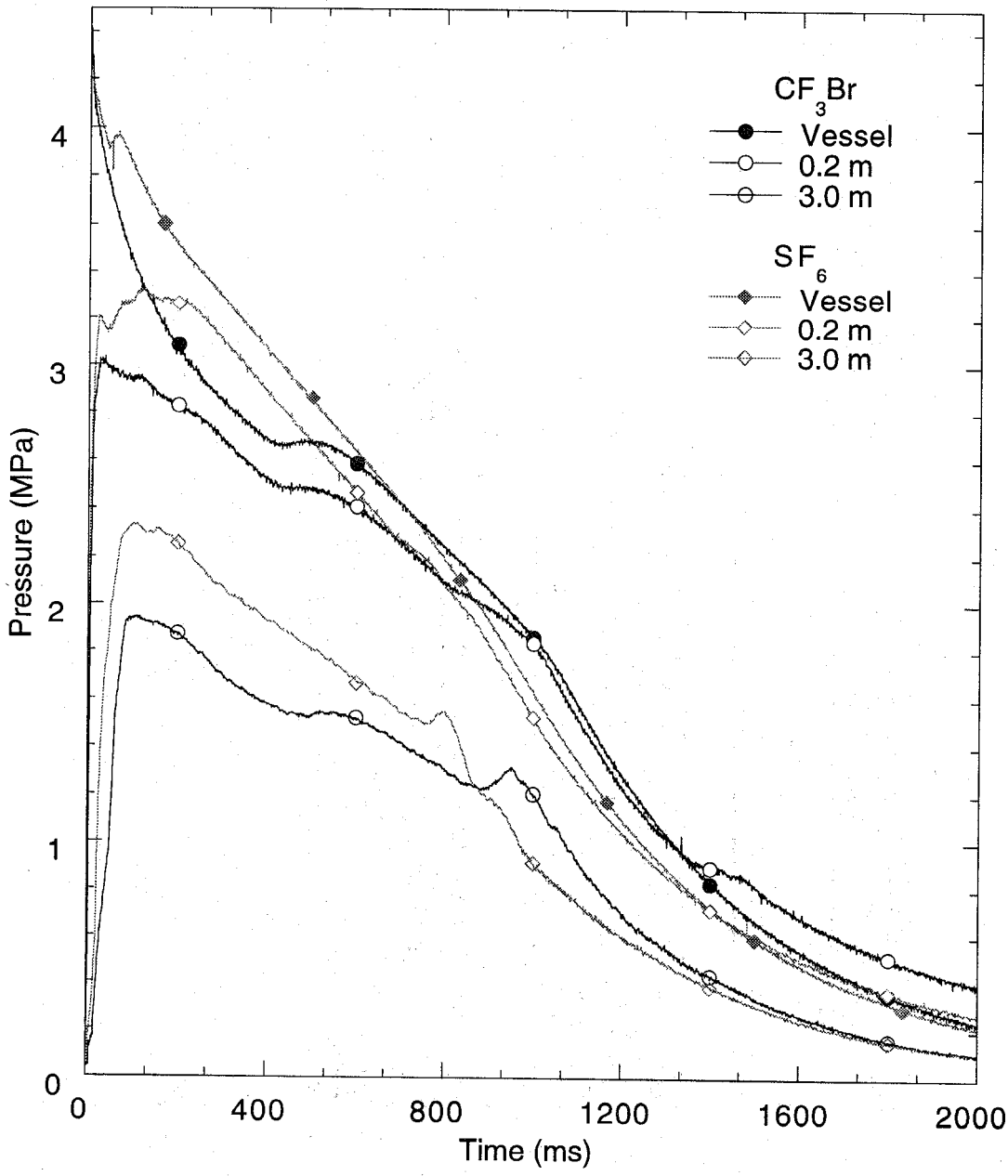


Figure 7. Pressure traces measured in the storage vessel (filled symbols), and at the 0.2 m and 3.0 m pressure transducers for the discharges to atmosphere of recycled SF_6 and CF_3Br.

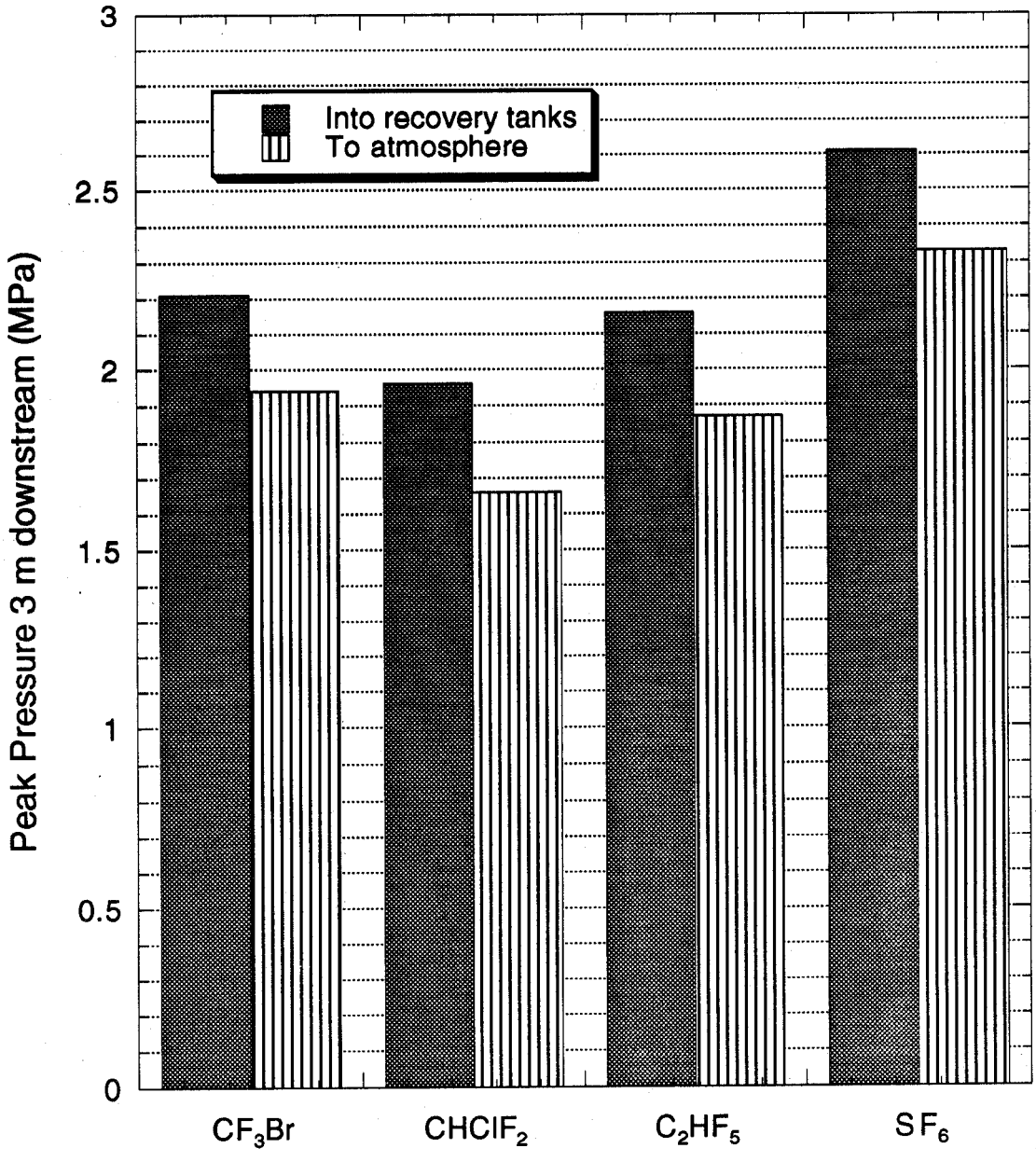


Figure 8. Graph of peak pressures 3.0 m downstream for recovered and discharged-to-atmosphere tests.

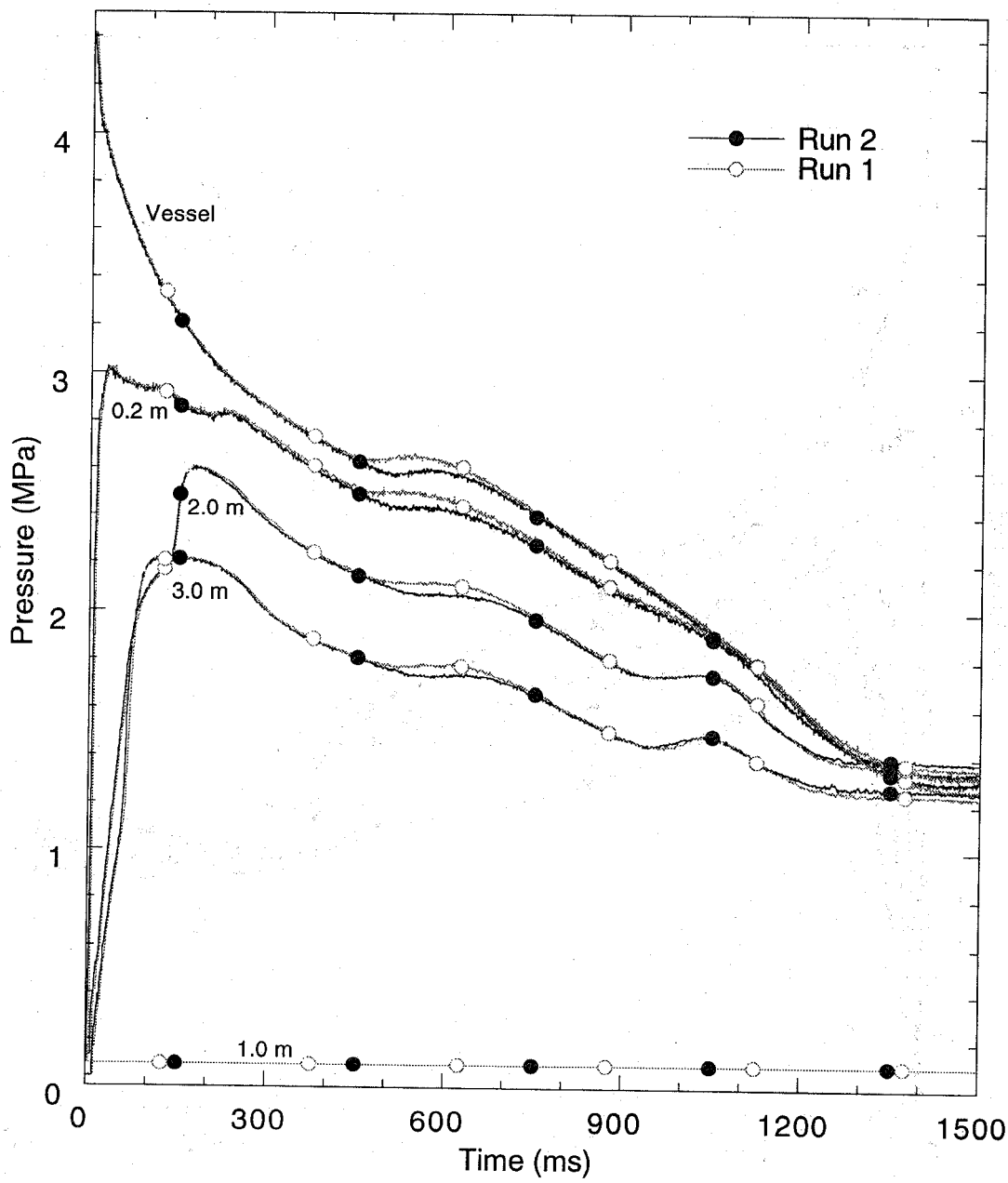


Figure 9. Pressure curves of CF_3Br at five locations using both new (Run 1) and once recycled (Run 2) agent.

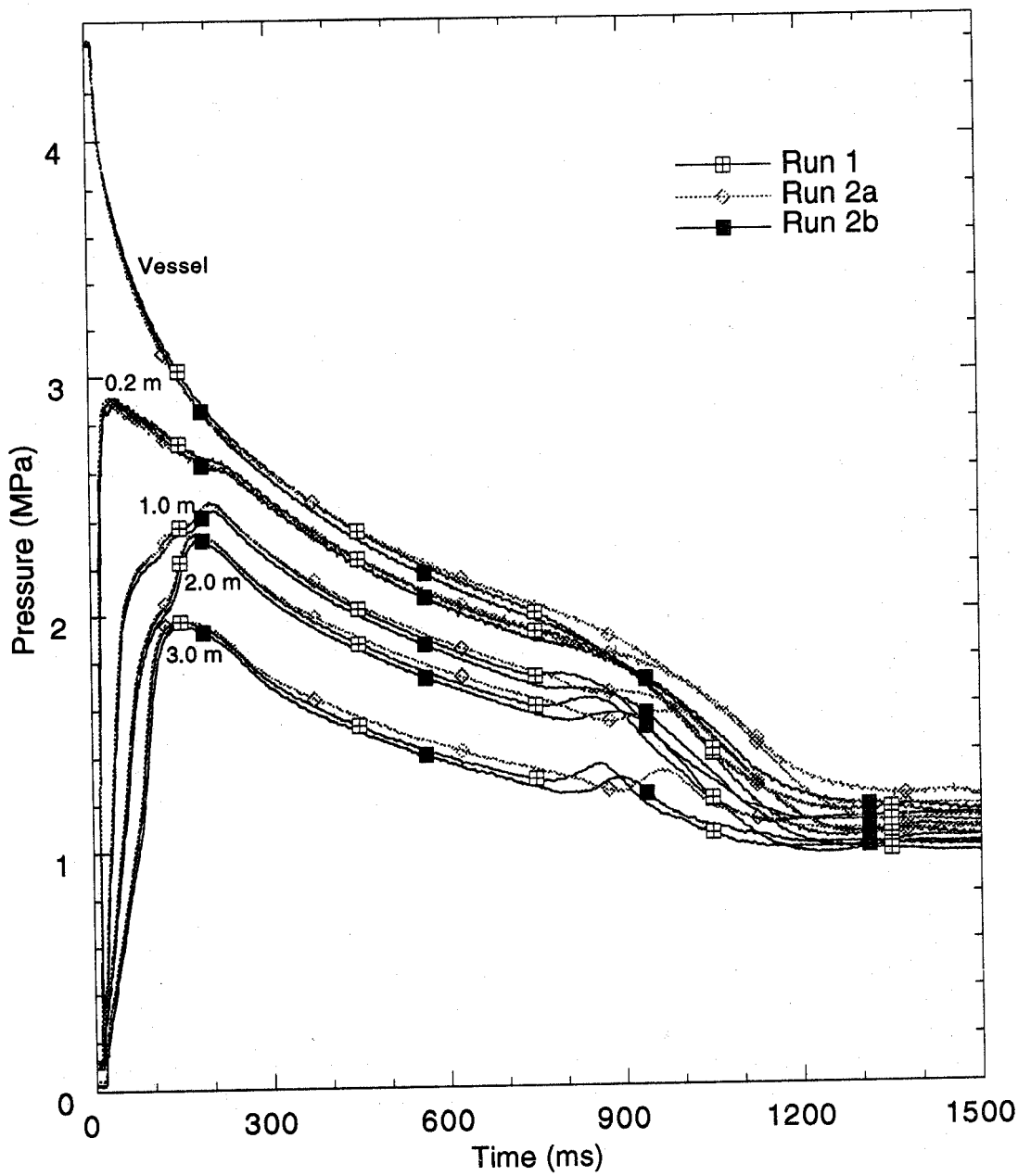


Figure 10. Pressure curves of $CHClF_2$ at five locations using both new (Run 1) and once recycled (Run 2a and 2b) chemical.

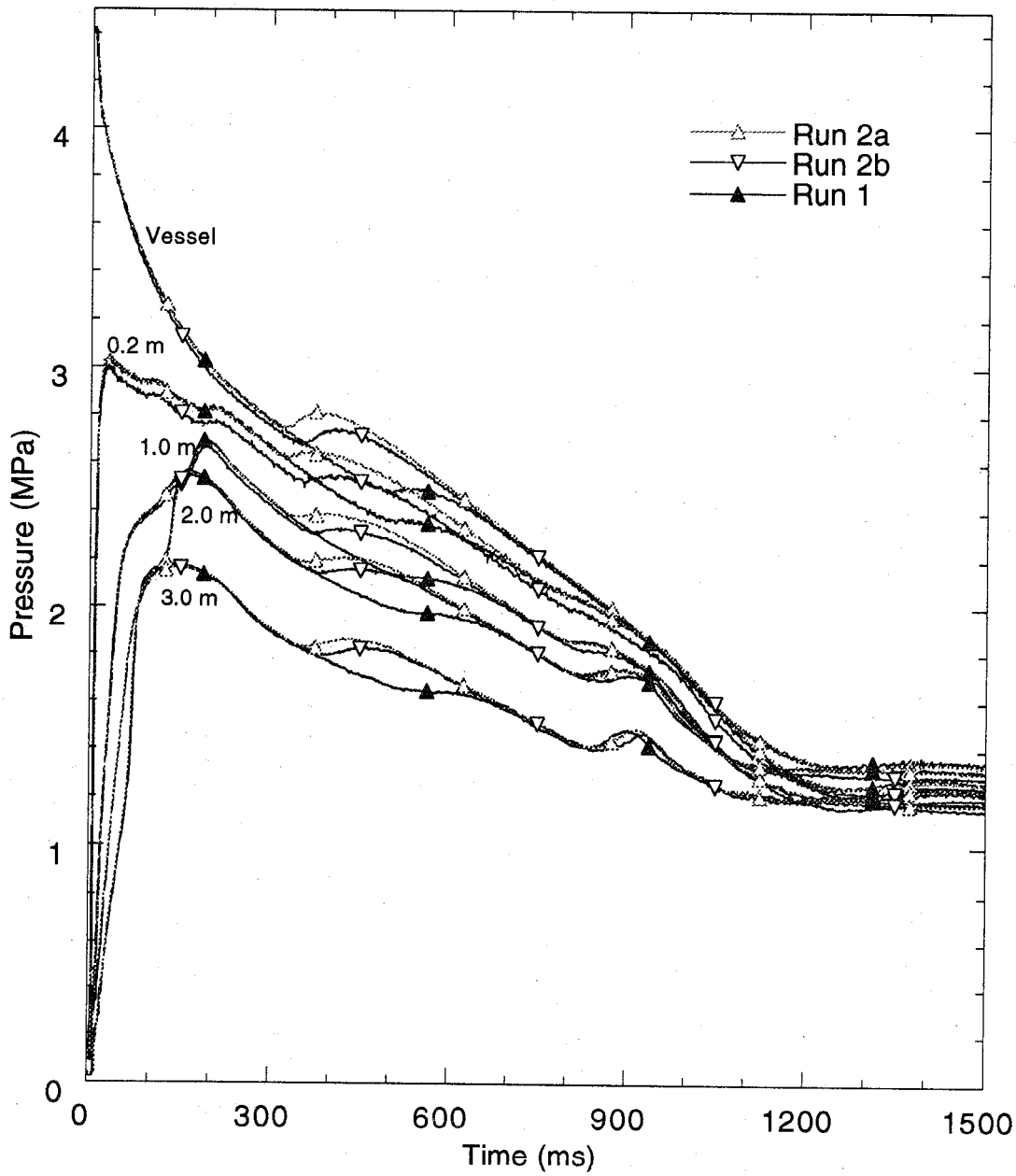


Figure 11. Pressure curves of C_2HF_5 at five locations using both new (Run 1) and once recycled (Run 2a and 2b) chemical.

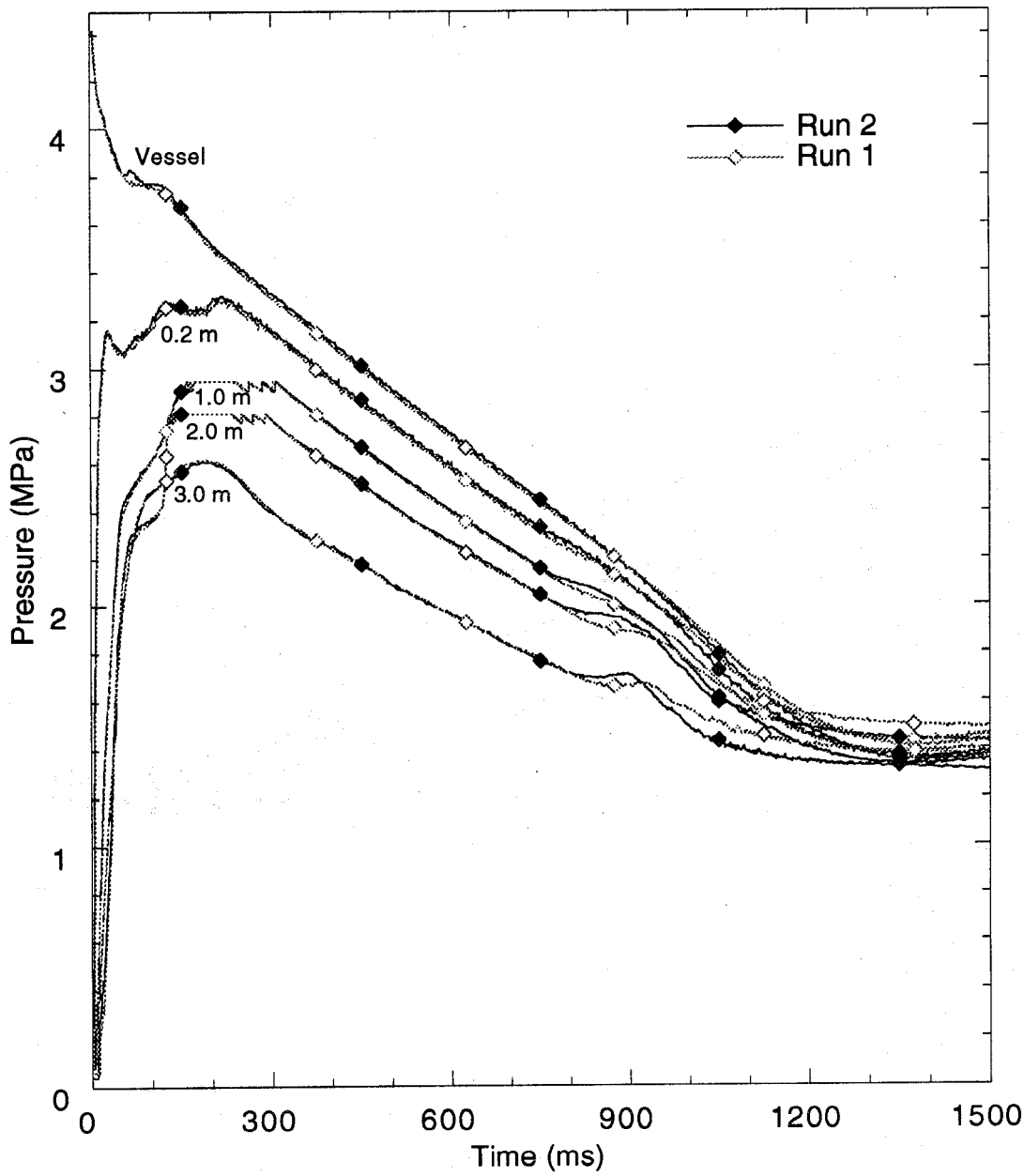


Figure 12. Pressure curves of SF_6 at five locations using both new (Run 1) and once recycled (Run 2) chemical.

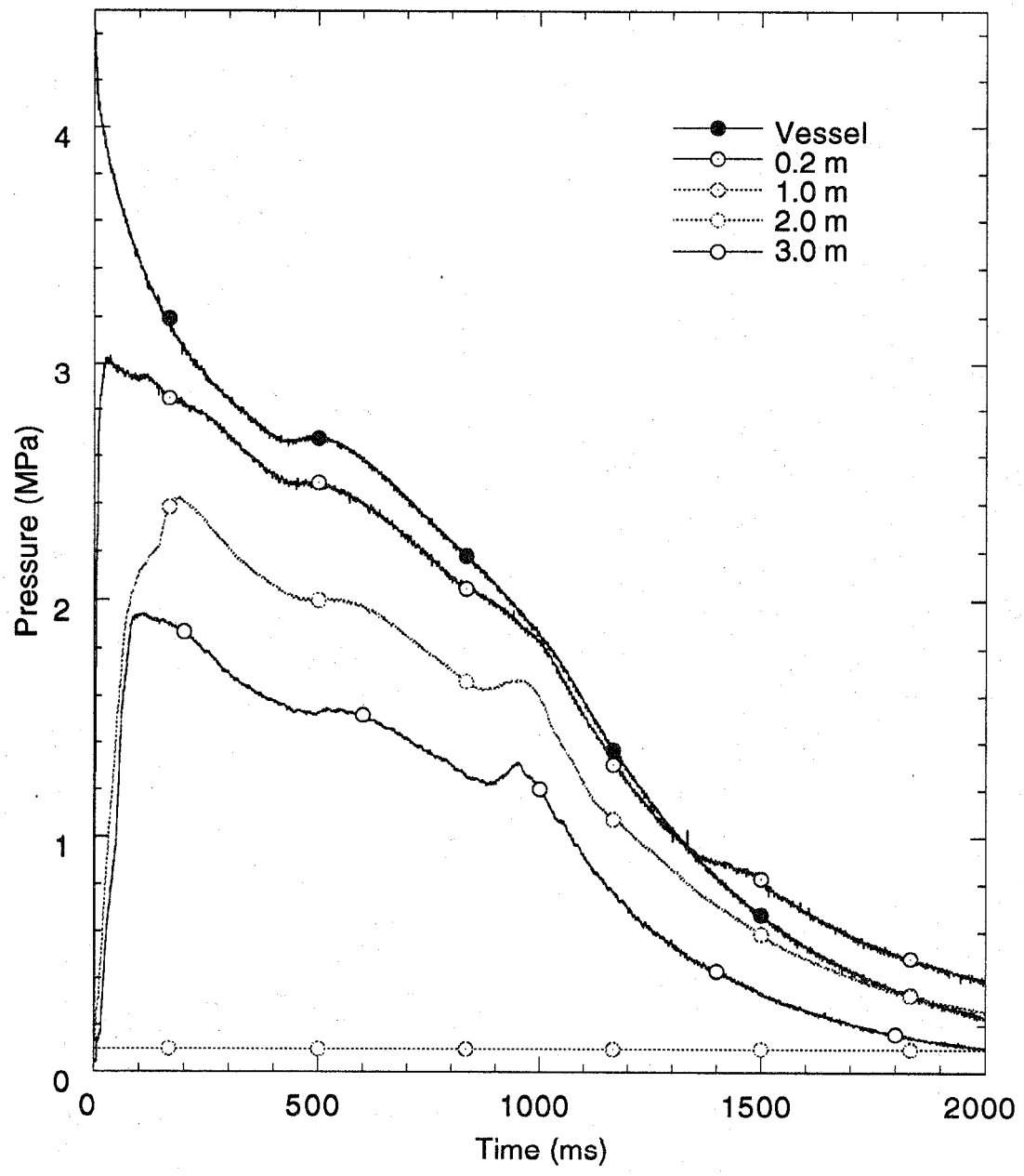


Figure 13. Pressure curves of CF_3Br discharged to atmosphere for five locations with agent that was recycled once. (Note that the 1.0 m pressure transducer malfunctioned.)

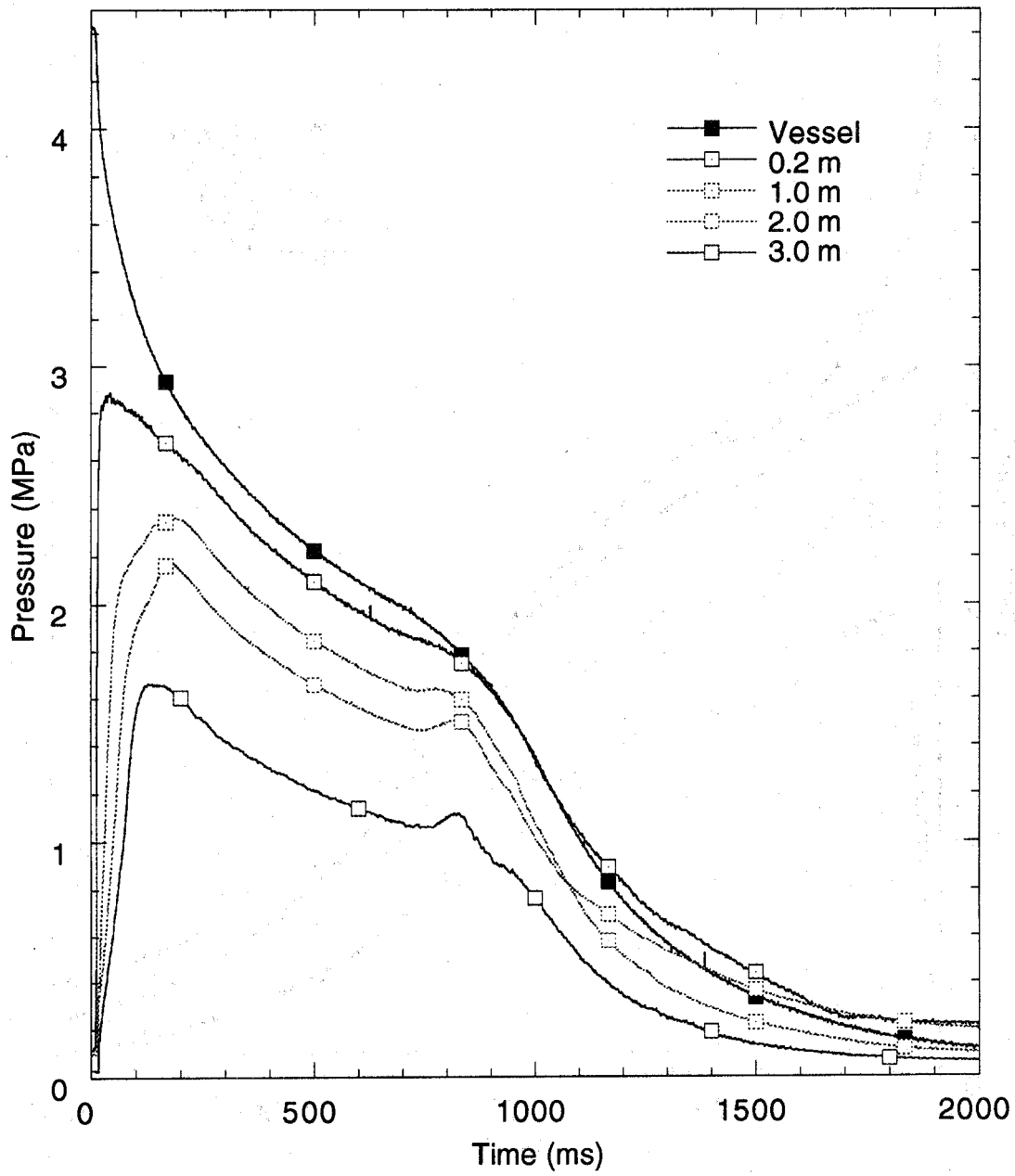


Figure 14. Pressure curves of $CHClF_2$ discharged to atmosphere for five locations with chemical that was recycled once.

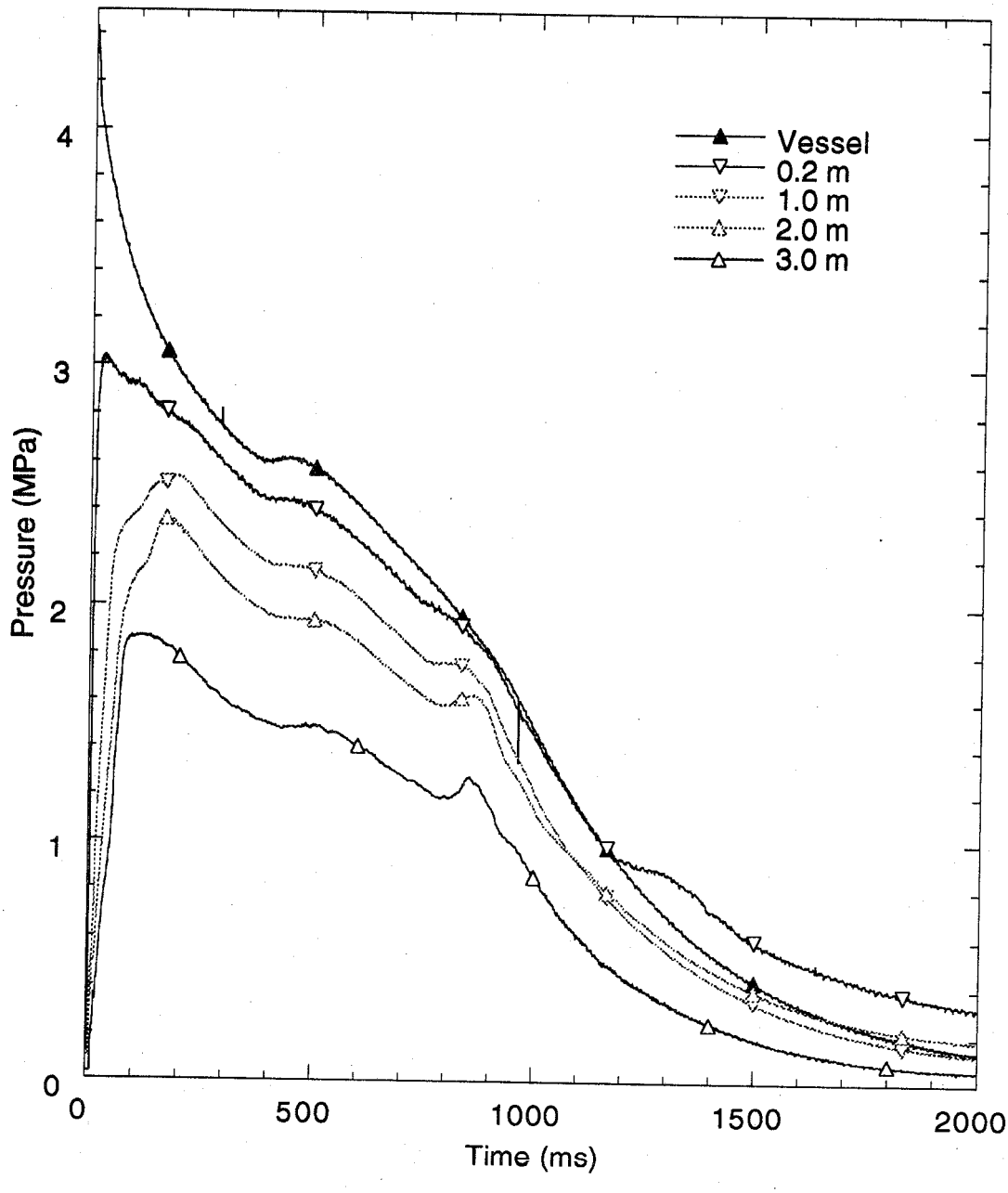


Figure 15. Pressure curves of C_2HF_5 discharged to atmosphere for five locations with chemical that was recycled once.

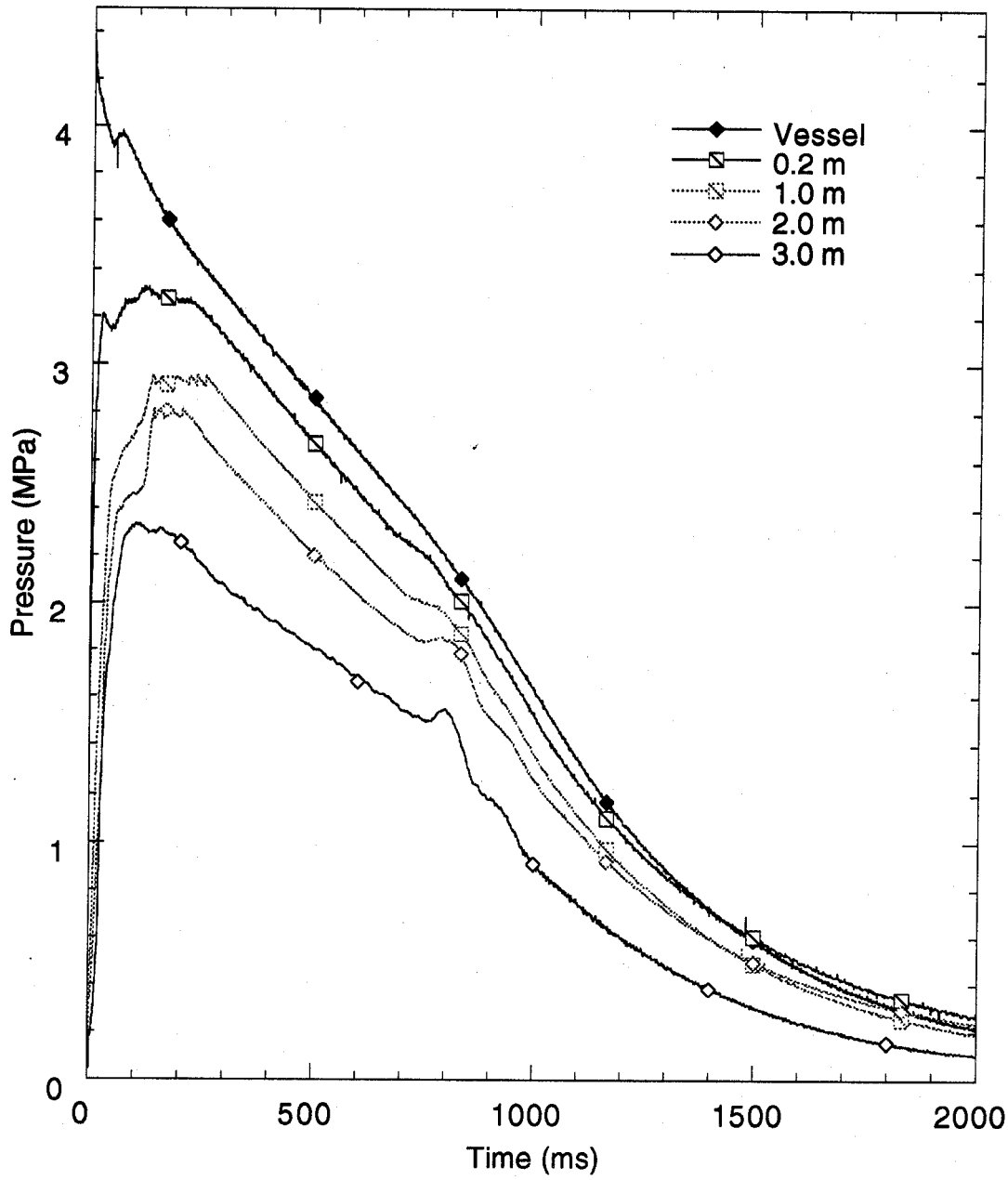
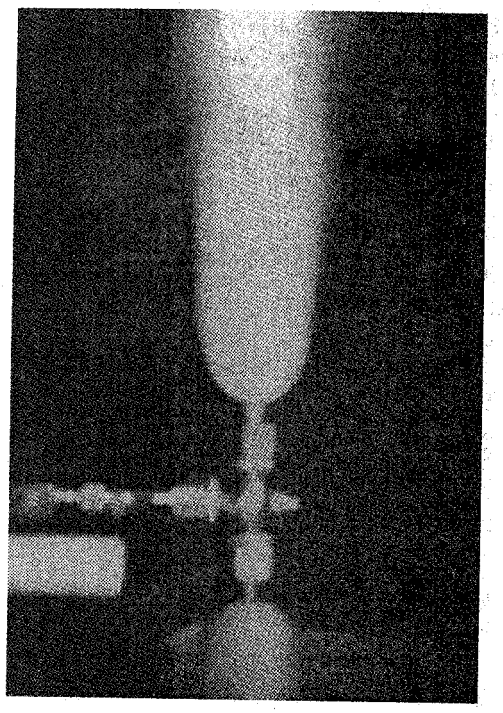
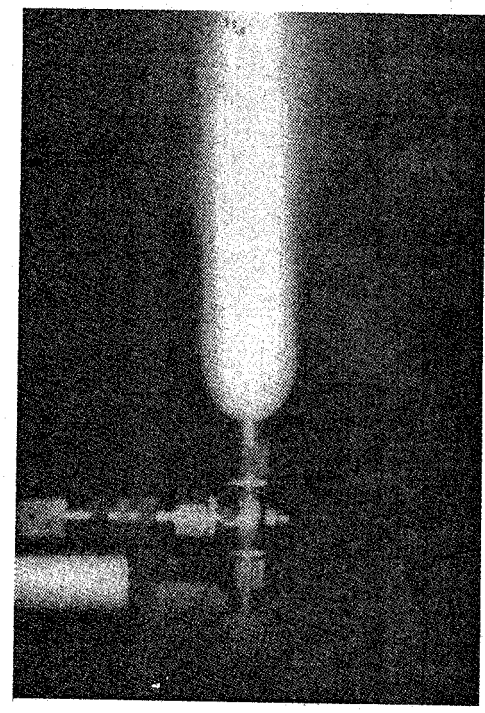


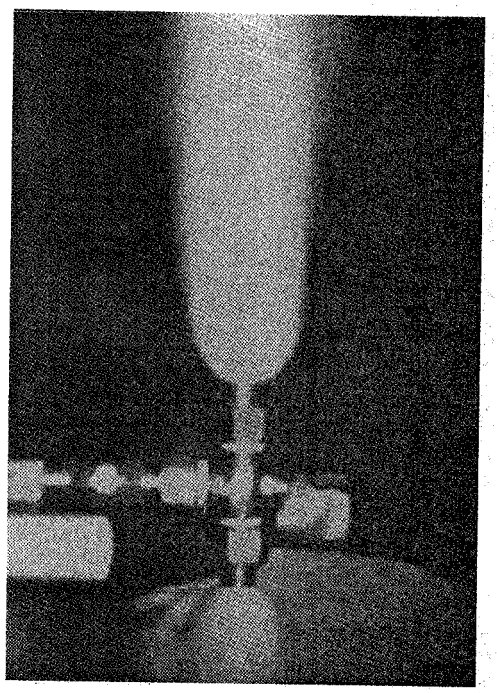
Figure 16. Pressure curves of SF_6 discharged to atmosphere for five locations with chemical that was recycled once.



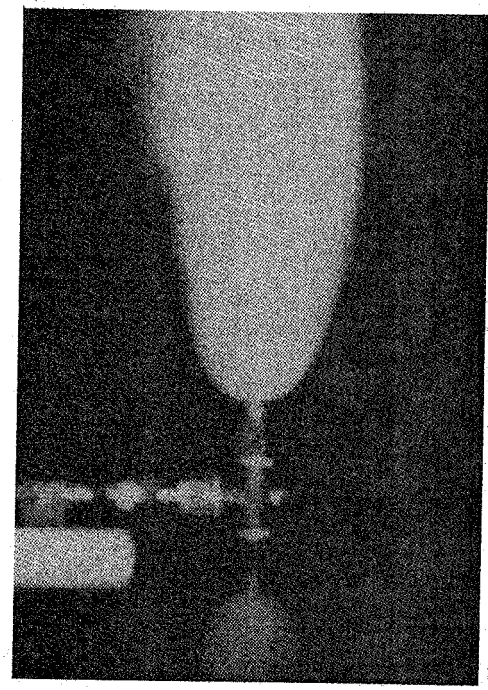
(a) CF_3Br



(b) SF_6

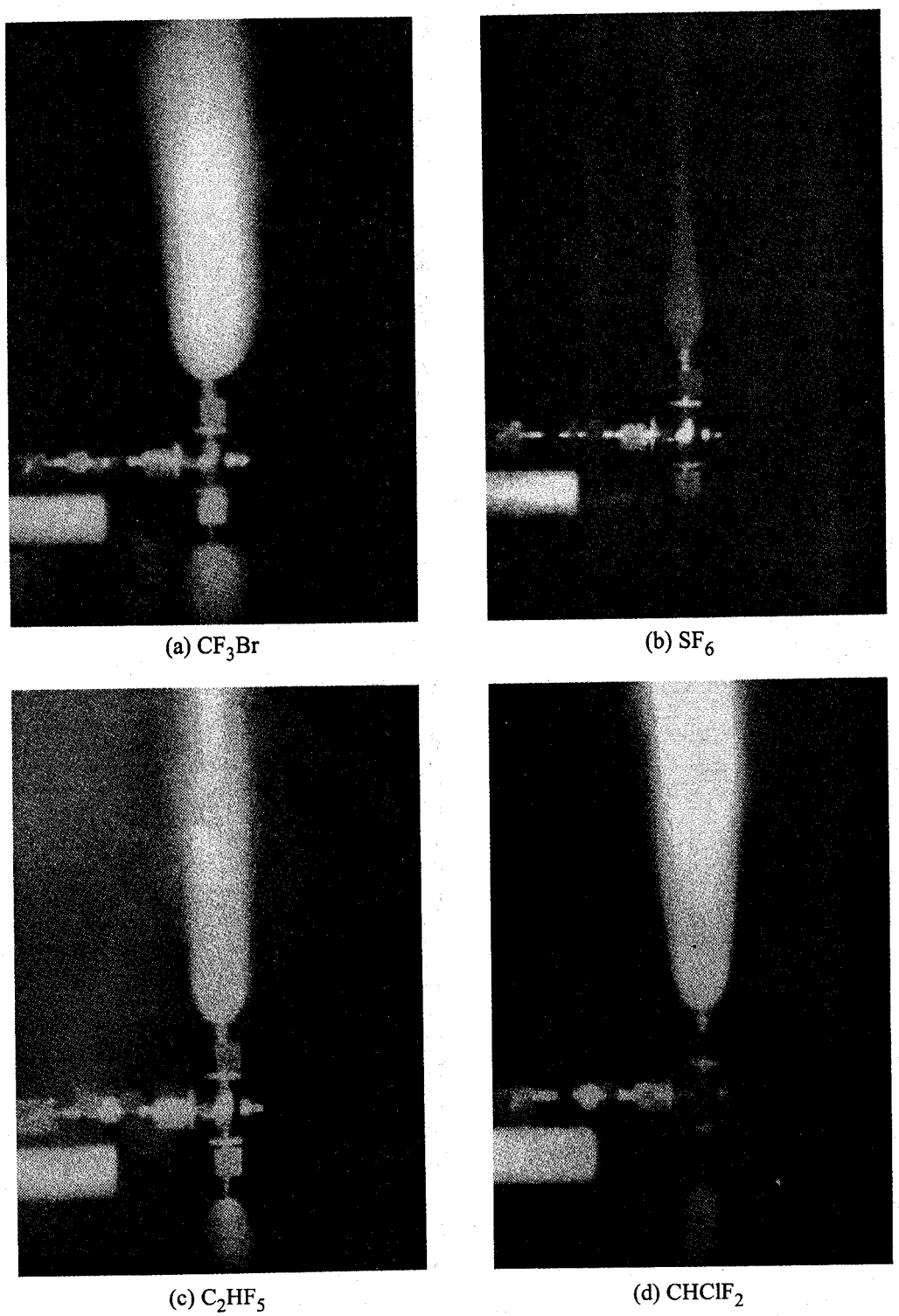


(c) C_2HF_5



(d) $CHClF_2$

Figure 17. Prints of the spray plumes discharged to atmosphere through the T-fitting after 200 ms for (a) CF_3Br, (b) SF_6, (c) C_2HF_5, and (d) $CHClF_2$.



(a) CF_3Br (b) SF_6

(c) C_2HF_5 (d) $CHClF_2$

Figure 18. Prints of the spray plumes discharged to atmosphere through the T-fitting after 900 ms for (a) CF_3Br, (b) SF_6, (c) C_2HF_5, and (d) $CHClF_2$.

12.6 Acknowledgments

This work was sponsored by the U.S. Naval Air Warfare Center at Lakehurst, New Jersey under the direction of Mr. William Leach. Concurrent work at Walter Kidde Aerospace by Mr. Mark Mitchell provided valuable insight into specifics of aircraft suppression systems and the aircraft certification process. In addition the authors are grateful to Mr. Mitchell for supplying the T-fitting that was used in the above simulant spray tests. Ms. Lois Ellis of AlliedSignal provided valuable information about the properties of SF_6. We appreciate the work of Ms. Marcia Huber of NIST in Boulder, Colorado for adding SF_6 to her software program PROFISSY. At NIST in Gaithersburg, Maryland, we would like to thank Mr. Charles Boyer who performed numerous discharge tests, and Mr. Tom Cleary and Dr. Jiann Yang who greatly facilitated the use of their experimental discharge apparatus for this work. Finally, we would like to acknowledge those who have contributed to the general knowledge in this field by an open exchange of their ongoing work: Mr. Ken Kaufmann, Mr. Gregg Wosniak, and Dr. Harendra Mehta of the Boeing Corporation and Mr. David Riordan of Short Brothers.

12.7 References

BA^{e}SEMA, *Substitutes for Halons for use in Shipboard Discharge Tests - Final Report*, BA^{e}SEMA Ltd., Report No. YD 4852, 1992.

Braun, E., Peacock, R.D., Forney, G.P., Mulholland, G.W., Levin, B.C., "Human Exposure and Environmental Impact," in *Evaluation of Alternative In-Flight Fire Suppressants for Full-Scale Testing in Simulated Aircraft Engine Nacelles And Dry Bays*; Grosshandler, W.L., Gann, R.G., Pitts, W.M., Eds.; NIST SP 861, 813-826, April 1994.

Cleary, T.G., Grosshandler, W.L., Yang, J.C., "Flow of Alternative Agents in Piping," *Proceedings of the Halon Options Technical Working Conference*, Albuquerque, NM, May 3-5, 1994.

Daubert, T.E., Danner, R.P., Eds., "DIPPR *Data Compilation of Pure Chemicals*," Version 8.0; NIST Standard Reference Database 11, Design Institute for Physical Property Data American Institute of Chemical Engineers, 1993.

Department of Transportation Federal Aviation Administration Advisory Circular Number 20-100, "General Guidelines for Measuring Fire-Extinguishing Agent Concentrations in Powerplant Compartments"; September 21, 1977.

DiNenno, P.J., Forssell, E.W., Starchville, M.D., Carhart, H.W., "Evaluation of Halon 1301 Test Gas Simulants: Enclosure Leakage," *Fire Technology* 25, No. 1, 24-40 (1989).

DiNenno, P.J., Forssell, E.W., Starchville, M.D., Carhart, H.W., Leonard, J.T., "Hydraulic Performance Test of Halon 1301 Test Gas Simulants," *Fire Technology* 26, No. 1, 121-140 (1990).

European Communities Regulation 3093/94, 22 December 1994.

Gallagher, J., McLinden, M., Morrison, G., Huber, M., "REFPROP 4.0 *NIST Thermodynamic Properties of Refrigerants and Refrigerant Mixtures,*" NIST Standard Reference Database 23, 1993.

Huber, M. L., "NIST Program PROFISSY - Version 0.03: PROperties of FIre Suppression SYstems," NIST Thermophysics Division, 1994.

Kaufmann, K. J., Miller, M.P., Woznaik, G., Mitchell, M., "Results of Halon 1301, HFC-125, and SF_6 Concentration Tests in a Large Commercial Aircraft Engine," *Proceedings of the Halon Options Technical Working Conference*, Albuquerque, NM, May 3-5, 1995.

Leach, W., Homan, J., "U.S. Navy Halon Simulant Identification Program," *Proceedings of the Halon Options Technical Working Conference*, Albuquerque, NM, May 3-5, 1995.

Material Safety Data Sheet (MSDS); Occupational Health Services, Inc., New York, NY, 1994.

Military Specification MIL-E-22285 (Wep): "Installation and Test of Extinguishing System, Fire Aircraft, High-Rate-Discharge Type," 11 December 1959, and "Amendment - 1," 27 April 1960.

Moore, D.W., "Alternate Test Agent for Halon Systems," DuPont Fluoroproducts, 1989.

Pitts, W.M., Yang, J.C., Gmurczyk, G., Cooper, L.Y., Grosshandler, W.L., Cleveland, W.G., and Presser, C., "Fluid Dynamics of Agent Discharge," in *Evaluation of Alternative In-Flight Fire Suppressants for Full-Scale Testing in Simulated Aircraft Engine Nacelles And Dry Bays*, Grosshandler, W.L., Gann, R.G., Pitts, W.M., Eds.; NIST SP 861, 291-295, April 1994.

Ravishankara, A.R., Soloman, S., Turnipseed, A.A., Warren, R.F., "Atmospheric Lifetimes of Long-Lived Halogenated Species"; *Science* 259, 194-199 (1993).

Riordan, D., correspondence to C. Womeldorf, NIST, on May 25, 1995 and conversation with C. Womeldorf, NIST, on June 16, 1995. Short Brothers Plc, Nacelle Systems Division, Belfast, Northern Ireland.

South Coast Air Quality Management District Rule 1418, Section (d)(2)(B), 10 January 1992.

Tedeschi, M. and Leach, W., "U.S. Navy Aircraft Halon 1301 Effectivity Analysis," *Proceedings of the Halon Options Technical Working Conference*, Albuquerque, NM, May 3-5, 1995.