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Flow of Alternative Agents in Piping*

T.G. Cleary, W.L. Grosshandler, and J.C. Yang
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 U.S.A

ABSTRACT

As part of the USAF, Army, Navy and FAA sponsored halon replacement project, the pipe flow characteristics of selected alternative agents for engine nacelle fire protection are being studied. Due to the remote location of the agent storage bottle, piping is required to transport the agent to various locations in an engine nacelle. The pipe flow from an agent bottle is characterized as a transient, two-phase flow. Since the selected alternative agents have thermo-physical properties different from halon 1301, the flow characteristics will be different, which may require system design changes. An experimental apparatus to study the flow characteristics of the alternative agents was designed and is described. A key feature of the experimental set-up is the ability to provide a constant head in the simulated storage bottle. This will allow quasi-steady state pressure drop data to be gathered. It may then be possible to use the quasi-steady data to estimate the transient case. The pipe flow characteristics for different initial vessel temperatures and pressures, and pipe configurations will be examined. Preliminary results on the flow characteristics of HFC-227ea and halon 1301 are presented.

INTRODUCTION

Aircraft engine nacelles currently rely on halon 1301 suppression systems for fire protection. In such applications piping carries the agent from a remotely located bottle to the nacelle. To achieve a desired concentration in the nacelle depends in part on the delivery time of the agent to the nacelle. If the flow of agent in the piping is too slow, the design concentration may not be reached and held for the required time. Typically, a pressure vessel is charged with agent to some fill condition (about 50% by volume) with nitrogen gas added to pressurize the contents to some value (normally 4.12 MPa) above the agent's saturation vapor pressure at room temperature. The outlet of the vessel is connected to a piping system for distributing the agent to the desired location(s) in the nacelle. In the event of a fire, the contents of the vessel will be released through a fast response solenoid valve or a burst disc by detonating a squib. Dispersion in the nacelle depends on the air flow, the pipe exit locations and agent delivery rate.

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While at first glance the flow of the agent from a remote location to the nacelle seems straight forward, in reality, the flow of agent in the piping is very complicated due to the highly transient nature of the process and the presence of a two-component (agent and dissolved nitrogen), two-phase flow. Ignoring the initial transient caused by the opening of the rupture disc or the valve, upon release of the agent into the piping, the pipe pressure drops due to a combination of the falling upstream pressure, flashing, and friction pressure drop. As the liquid pressure decreases, a vapor phase can form from both nitrogen degassing and flashing of the agent. If the piping is sufficiently long, the quality (mass fraction of the vapor phase) at the pipe exit could be 1. In cases where it is desired to achieve high mass flow rates there are some tradeoffs between pipe length and flow rate. This is espoused in Military Specification (Mil-E-22285) which states that the duration of discharge for halon 1301 systems (for engine aircraft nacelle protection) should be less than 1 second, that the supply tubing should be less than 3.05 m (10 ft) and, bends in the pipe (which tend to increase frictional losses) should be kept to a minimum. Current halon 1301 systems can be designed to meet the specified standards, but since halon 1301 will soon be replaced by at least one alternative agent and studies on transient two-phase flow are sparse, there is a need to examine the characteristics of the transient two-phase pipe flow of the candidate alternative agents.

The objective of this study is to investigate the flow behavior of three alternative agents in piping systems during typical pipe flow conditions, and provide information useful in the design of systems containing the ultimately selected agent. The three agents which have been selected as potential replacements of halon 1301 for engine nacelle applications are HFC-227ea, HFC-125, and CF_3I (Grosshandler *et al.*, 1994). In addition, limited experiments with halon 1301 will also be conducted to provide a reference for comparisons. The parameters to be investigated include the initial vessel temperature and pressure, the effect of dissolved nitrogen, and piping configuration (diameter, elbows etc.)

Examination of the literature on transient two-phase flow shows that most of the work performed focused on the high-pressure liquid water/steam system because of its importance in the area of nuclear reactor safety (loss-of-coolant accident, LOCA). Most information on halon 1301 discharge deals with the design of systems for total flooding applications, such as a system to protect electronic equipment located in an enclosed space. Discharge times for these applications can be an order-of-magnitude greater than for the engine nacelle system. In the total-flood case, pressure drop can be estimated by using existing empirical correlations for steady two-phase flow, yet as pointed out by DiNenno and Budnick (1988), current practice is to test each system installed individually to assure compliance with NFPA 12A, *Standard on Halon 1301 Fire Extinguishing Systems* (1993) in part because of the uncertainty in the pipe flow calculation procedures used by the various system designers. The most complete study on transient discharge of halon 1301 through piping systems reported in the literature is by Elliot *et al.* (1984). They analyzed their experimental data based on a quasi-steady flow assumption, ignoring heat transfer to the surroundings, and yet their transient predictions compared favorably with the experiments.

Our experimental approach is to examine both the transient flow and a quasi-steady flow. The quasi-steady experimental configuration will be obtained by maintaining a constant upstream condition (i.e., a constant ullage pressure during discharge) on the liquid leaving the vessel by

providing make-up nitrogen to the ullage. Under this condition, a quasi-steady mass flow can be maintained in the pipe. Therefore, a mass flow for a given pressure drop is obtained. With the mass flows at a number of pressure drops, it can be determined whether such a quasi-steady correlation can be used to estimate the transient behavior by assuming that at each instant a quasi-steady state assumption can be invoked. Pressure drop measurements from transient flow conditions will also be obtained and used to validate the applicability of the quasi-steady correlation.

EXPERIMENTAL PROCEDURE

The experimental apparatus was designed so that different configurations and conditions could be studied. A schematic diagram of the experimental apparatus is shown in Figure 1. The discharge vessel is made of a cylindrical stainless steel (SS 304) tube with an internal diameter of 0.10 m and a height of 0.50 m. Flanges are welded to the top and bottom of the tube so that a top and bottom plate can be bolted to the tube and sealed with O-rings. The vessel volume with the flanges attached is 4.06×10^{-3} m^3. The top plate has various ports for pressure, temperature, filling, and nitrogen make-up, while the bottom plate has a port for the agent release mechanism. The vessel was designed to operate at pressures up to 14 MPa (2000 psi). There is a pressure relief valve installed to protect the vessel from higher pressures. The nitrogen make-up tank is a standard high-pressure gas cylinder with an internal volume of 44×10^{-3} m^3. The valve from the cylinder was removed and replaced with brass tubing which leads to a large-orifice solenoid valve that is used to control the make-up nitrogen flow into the discharge vessel.

The agent release mechanism is a quick-opening solenoid valve (Marotta Scientific Controls Inc.**) with an exit diameter of 50 mm. Because the valve outlet is much larger than the internal diameter of the pipe, a smooth tapered section was fabricated and installed between the outlet and the pipe to minimize sudden contraction. The pipe is type 304 stainless steel tubing with 15.9 mm (0.625 in) inner diameter. It is attached to a rigid metal-framed bench to keep it fixed. A clear plastic (PMMA) sight tube 0.30 m long with a wall thickness of 3.18 mm and the same inner diameter of the piping was constructed to allow for optical access. This clear section can be placed anywhere in the piping system so that documentation of the two-phase behavior within the pipe can be provided by a high-speed movie camera (LO-CAM) operating at 500 frames per second.

The dump tanks simulate an infinite reservoir for these tests. The reservoir consists of 4 bottles with a total volume of 15×10^{-3} m^3. These bottles are chilled by dry ice in a commercial freezer. For the portions of the experiments when agent is flowing into the dump tanks, the pressure increase in the tanks is small, approximately the saturation vapor pressure of the agent

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**Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

at the dump tank temperature plus atmospheric pressure. The increase in back pressure should have a negligible effect on the flow of agent out of the bottle or in the piping. The dump tanks in the freezer also serve as an agent recovery system by condensing the agent after a test.

Measurement capabilities include temperature from thermocouples and pressure from transducers in the vessel and pipe using a high speed data acquisition system sampling at 1 kHz.

The experimental approach described above is necessary if the results are to be applicable to a generic system. Without the make-up nitrogen, the system consists of only one fixed vessel volume which for a given fill condition dictates the transient pipe pressure drop. Results for different vessel volumes can not be properly simulated by either changing the fill conditions of the vessel or changing the pipe length. If the initial conditions are changed by increasing the nitrogen pressurization, the amount of dissolved nitrogen changes and also the liquid emptying time changes. If the pipe length is shortened (for instance to fix the vessel to pipe volume ratio) the residence time of the fluid in the pipe changes and the frictional pressure drop will not be the same. Since it is desired to gather data on the fluid flow that could be used to scale to different vessel volumes, fill conditions, and pipe lengths, the rationale behind the continuous addition of nitrogen to the bottle ullage (make-up) is to provide a constant head on the liquid leaving the bottle. This will allow a quasi-steady flow condition to develop in the pipe. The pressure drop over a specific section of pipe can be evaluated for a given pressure range. Optical access will confirm the fluid state (liquid slug, bubbly two-phase, etc.) Tabulation of steady-state $\Delta P/L$ over a range of upstream pressures will allow for the estimation of the pipe pressure for an arbitrary vessel size, fill condition, and pipe length.

RESULTS AND DISCUSSION

Preliminary results from tests with HFC-227ea and halon 1301 are discussed below. Since only a limited number of experiments has been performed and the work is still in progress, only a qualitative discussion of the results is presented in this paper.

None of the cases reported here had an appreciable amount of nitrogen dissolved in the agent and all were run at ambient temperature. The vessel was first filled with an agent to a desired fill condition, then just prior to a test the vessel was pressurized with nitrogen to the desired pressure. Tests will also be performed with an equilibrium amount of nitrogen dissolved in the agent. The provision to dissolve the nitrogen in the agent includes bubbling the nitrogen through the agent slowly and waiting until the desired pressure is reached and stabilized.

HFC-227ea was tested at approximately a 50% fill condition (by volume) with nitrogen pressurization to 2.8 MPa (400 psi) with and without the addition of make-up nitrogen. Figure 2 is a time trace of the vessel pressure and the pipe pressure at a location 2 m downstream without make-up nitrogen. From the vessel pressure trace, it is obvious when the valve is actuated due to the rapid drop in the pressure. The rate of pressure drop decreases smoothly until a transition where the rate of pressure drop increases followed again by a smoothly decreasing rate until static conditions are achieved. The explanation of the pressure trace is straight forward. The initial smooth pressure decrease is due to the liquid agent leaving the vessel which takes

approximately 600 ms. Once the liquid leaves the vessel there is a slight increase in the rate of pressure drop because vapor is leaving the vessel. This follows the pressure drop behavior of the dry bay discharge experiments (Grosshandler *et al.*, 1994) where the increase in the rate of pressure drop was confirmed to occur after the liquid emptied from the vessel. The explanation of the pressure trace in the pipe is not straight forward though. For a pressure tap located 2 m downstream, the pressure starts to rise soon after the valve is open to a point which it nearly reaches the bottle pressure. The pipe pressure trace then follows the vessel pressure for some time, then it crosses over the vessel pressure curve near the point where nitrogen is presumed to be leaving the vessel. There is a change in the rate of pressure drop in the pipe similar to the rate of change in the vessel pressure drop when nitrogen starts to leave the bottle. This is presumable due to nitrogen only flowing in the pipe. A conclusion drawn from this preliminary observation is that there is not much pressure drop from the vessel to a location 2 m downstream in this configuration once the initial rise time is over. Tests run with the vessel pressurized with nitrogen only show smooth pipe pressure traces that are always below the vessel pressure.

Figure 3 is a time trace of the vessel pressure and the pipe pressure where make-up nitrogen is added to the ullage. In this run, the vessel conditions were the same as those above (50% fill and 2.8 MPa pressure). The timing sequence for the test was as follows: first, the solenoid valve for the make-up nitrogen was opened, 25 ms later the quick-opening valve was a activated, and finally, the solenoid valve was closed 1000 ms after it was opened. The vessel pressure trace shows a dip followed by a pressure recovery when the liquid out-flow and the nitrogen in-flow are essentially balanced. It is seen that at least for the vessel liquid emptying time (which for this case has to be less than the approximately 600 ms emptying time inferred from the vessel pressure trace in the case above) the vessel pressure is nearly constant. It appears that a constant pressure is maintained in the pipe 2 m downstream for a period of time. Therefore it is expected that quasi-steady-flow pressure drop data can be obtained.

High speed movies at a framing rate of 500 per second were taken from an experiment using HFC-227ea with no make-up nitrogen. In this run, the vessel pressure was fixed at 2.8 MPa and a 50% fill condition (1.5 kg of HFC-227ea) with the location of the sight tube 0.30 m downstream from the vessel exit. Figure 4 is the vessel pressure trace and the pipe pressure trace immediately upstream from the sight tube. Figure 5 shows six photographs made from progressive frames of the high speed movie. The first photograph shows that the sight tube is clear. The time here is very close to the opening of the valve. The second photograph is of the next frame (2 ms later) where the tube is now opaque, an indication of a two-phase flow. It is speculated that this is initial liquid agent that has flashed in the low pressure pipe. The third photograph is of the 12th frame where the sight tube is clearing up (24 ms from the first frame). The fourth photograph is of the 15th frame where the sight tube is entirely clear. This suggests clear liquid agent flowing in the pipe at that location. The fifth photograph shown is of frame 54 (108 ms) where the sight tube again turns opaque, and this condition persists until around the 650th frame (1300 ms) where the last wisps of clouding disappear. The sixth photograph shows frame 227 where a wavy appearance to the flow in the tube is observed. This description is not to be confused with so-called wavy two-phase flow. From the pipe pressure trace it is seen that the pipe pressure after the initial rise is never below the saturation vapor pressure for HFC-227ea at room temperature (0.45 MPa). Thus, the nature of the flow where the frames are opaque after the clear frames is unclear and requires further study. Measurements obtained from a study on

the discharge of subcooled liquid Freon-11 by Prisco *et al.* (1977) also revealed that pressures measured in various locations along the pipe were higher than the saturation vapor pressure corresponding to the inlet temperature. They attributed this behavior to the degassing of nitrogen. Since there is a finite contact time between the nitrogen and the liquid in our test, it is likely that a small amount of nitrogen dissolved in the liquid. High speed movies taken at locations farther downstream show the same sequence of events, but the duration of each event varies.

Finally to provide a qualitative comparison, tests with halon 1301 and HFC-227ea were performed with the same fill condition (50% fill and 4.1 MPa nitrogen pressurization) and pipe configuration which consisted of a straight section 3.5 m long. Two pressure taps were located in the piping, one at 1 m downstream and the other at 3 m downstream. Figures 6 and 7 show the pressure traces of the HFC-227ea and halon 1301 runs respectively. The pressure traces for the two agents are markedly different. In each figure, the pressure drop in the pipe is evident. High speed movies will be made for halon 1301 case to determine whether the sequence of events is significantly different from those of HFC-227ea.

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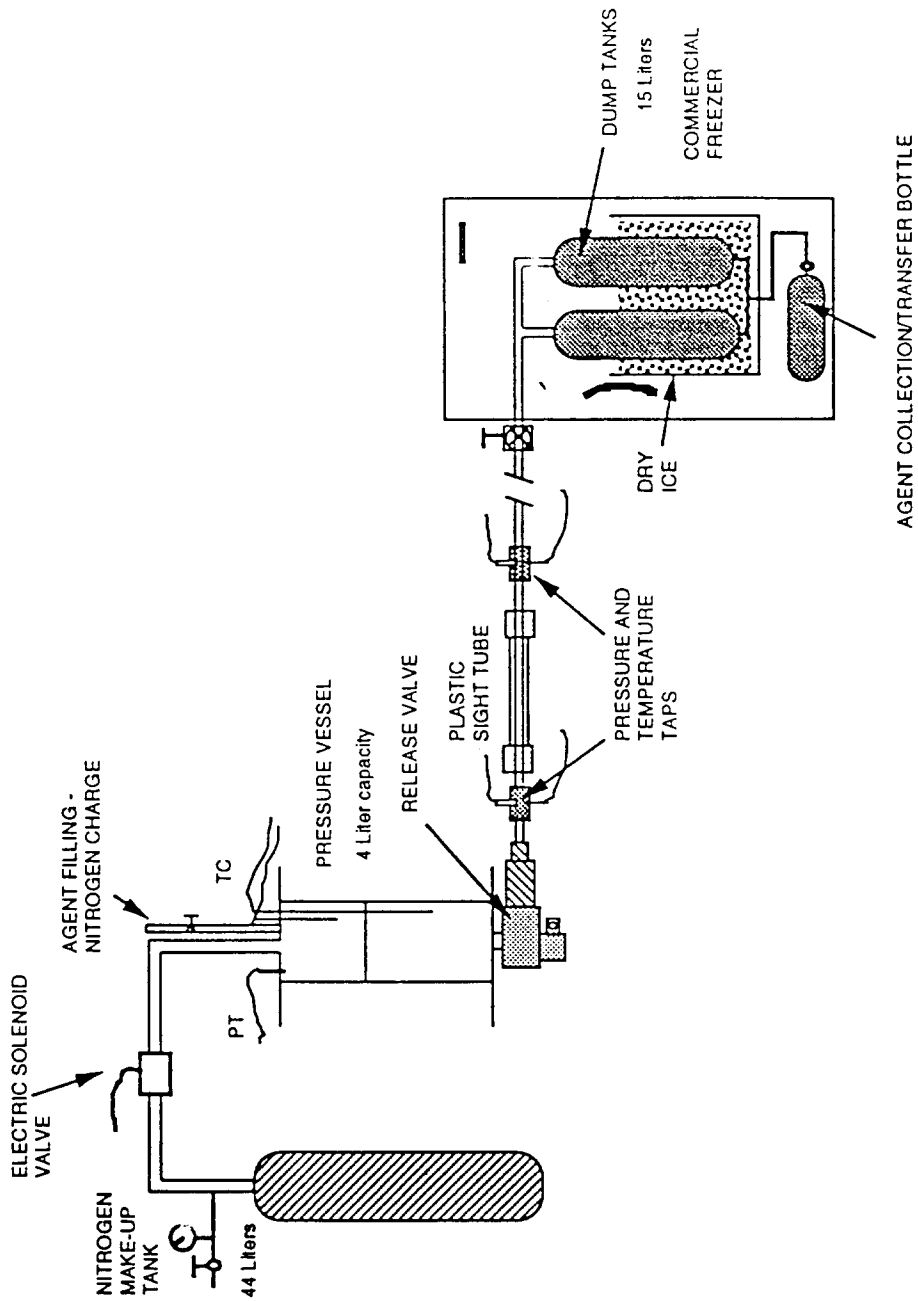

Figure 1. Schematic diagram of the experimental apparatus.

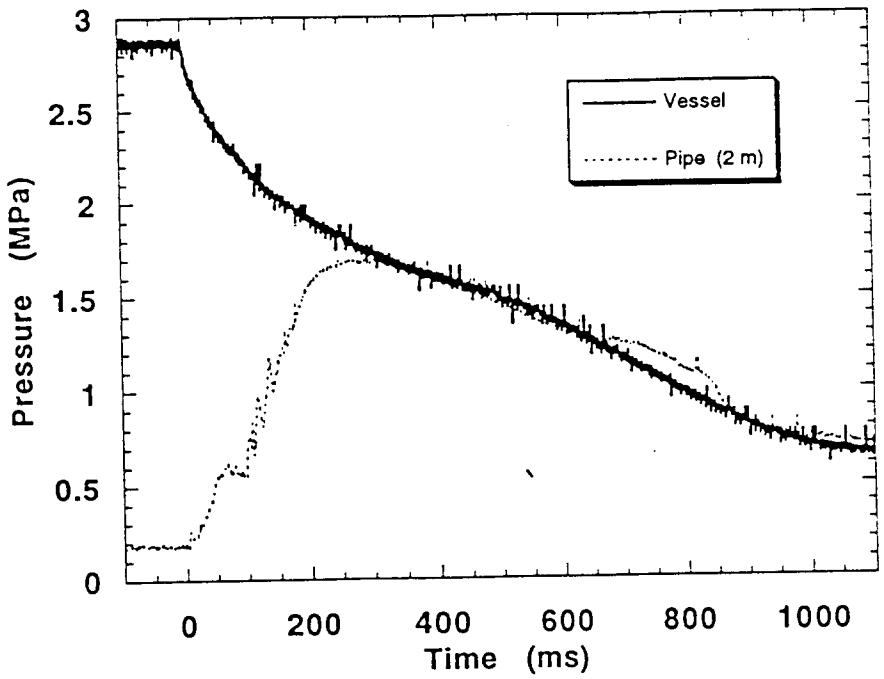

Figure 2. Pressure traces for HFC-227ea tested at a 50% fill condition, pressurized to 2.8 MPa with no make-up nitrogen addition.

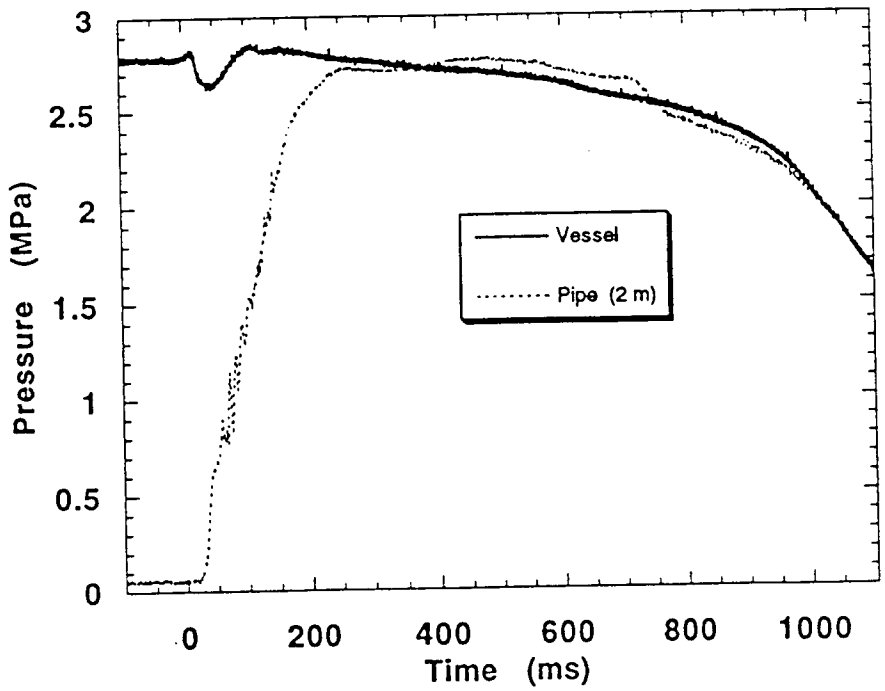

Figure 3. Pressure traces for HFC-227ea tested at a 50% fill condition, pressurized to 2.8 MPa with make-up nitrogen addition.

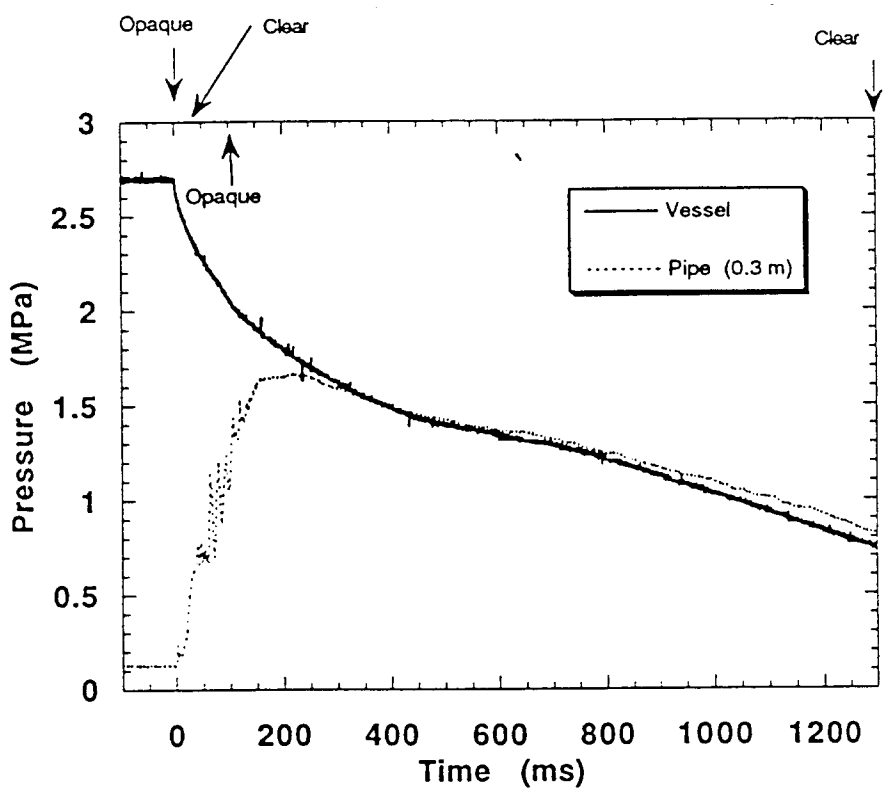

Figure 4. Pressure traces for HFC-227ea tested at a 50% fill condition, pressurized to 2.8 MPa with no make-up nitrogen addition. Arrows indicate the approximate time of the high speed movie observation.

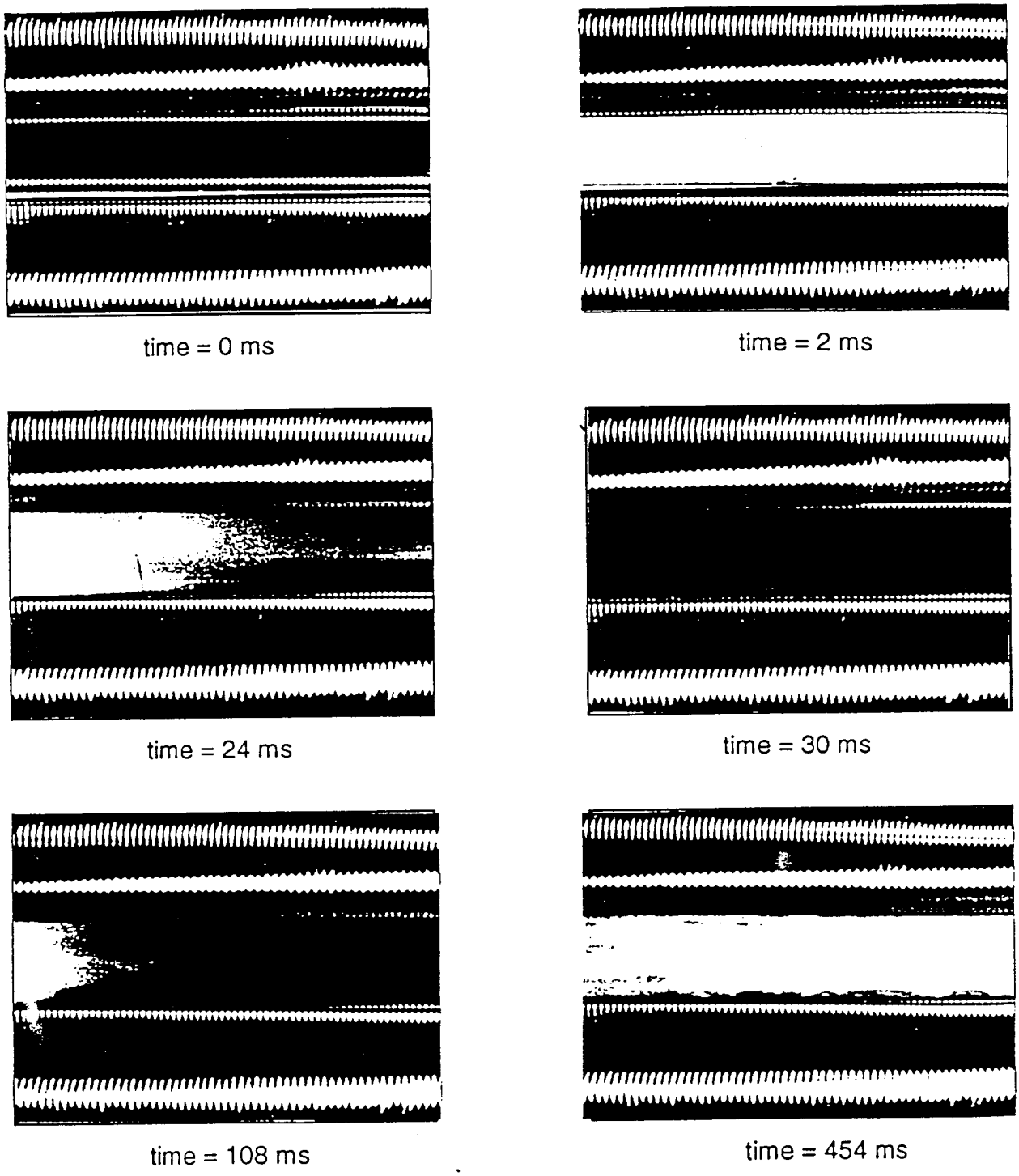

Figure 5. Photos of successive frames from a high speed movie (500 frames/s) of a clear pipe test section. The agent tested was HFC-227ea at a 50% fill condition and pressurized to 2.8 MPa. The time is arbitrarily set to zero for the first frame shown. This corresponds to a time very close to the valve actuation time.

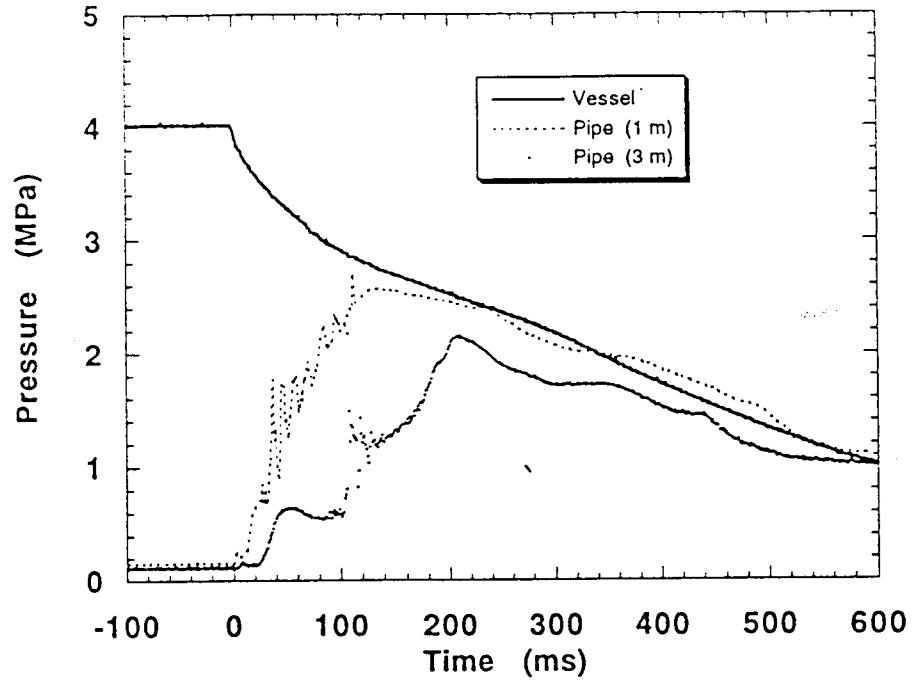

Figure 6. Pressure traces for HFC-227ea tested at a 50% fill condition, pressurized to 4.1 MPa with no make-up nitrogen addition.

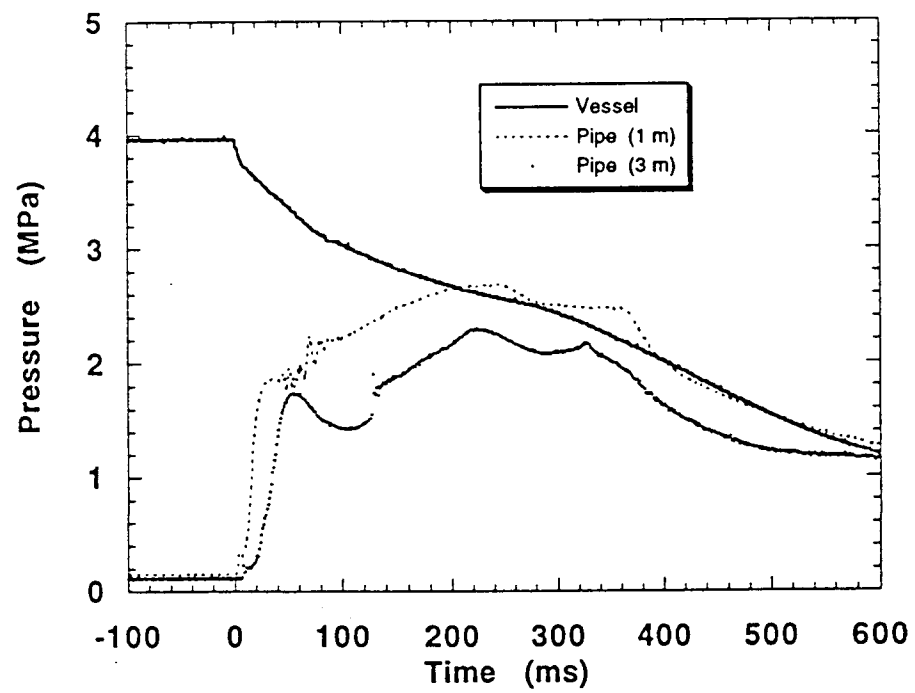

Figure 7. Pressure traces for halon 1301 tested at a 50% fill condition, pressurized to 4.1 MPa with no make-up nitrogen addition.