Dynamics of the Release of Alternate Halon Replacement Agents from Pressurized Bottles'

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1. INTRODUCTION

Halon 1301 has been widely employed on military and commercial aircraft for tire fighting purposes. Unfortunately, due to the deleterious effects of chlorine and bromine on stratospheric ozone, the manufacture of halon 1301 will be phased out by the end of 1993 under the terms of the Montreal Protocol. [1] As a result, the military **services** and the Federal Aviation Administration, with the U. S. **Air** Force coordinating the effort, have initiated a research program to identify effective halon 1301 replacements which are low ozone depleters. As part of this project, a list of eleven potential halon 1301 alternatives have been proposed. [2] The National Institute of Standards and Technology has been tasked to recommend which of the eleven compounds should be tested at full scale. The work reported in this paper is part of this task.

Two of the most critical applications of halon 1301 for military aircraft are in suppressing nacelle and dry bay fires. Nacelles surround the engines where fuel leaks or engine damage can result in dangerous fires. The pilot manually releases the agent into the nacelle following detection of a fire. Dry bays are compartments located around the outer frame of an aircraft containing a variety of equipment such as electronics and hydraulic lines. Generally, fuel tanks are located behind these volumes. If the integrity of the dry bay is compromised in some manner (e.g., battle damage or collision with an object) fire is probable when fuel and/or hydraulic fluid are released into the dry bay. Modem dry bay fire protection systems are designed to detect the presence of a fire, automatically release agent, and completely suppress the tire within thirty milliseconds.

The rate at which an agent is released from a storage vessel as well as its dispersion within the volume containing the fire are two critical factors in fire extinguishing capability. In this paper the development of an experimental system is discussed which is designed to characterize the following processes: 1) agent behavior during release from a pressurized vessel, 2) rate of agent release, 3) qualitative behavior of the agent following release, and 4) velocity of the downstream edge of the released agent. The conditions for the experiments are most appropriate for the dry bay

application for which the short period of extinction places a premium on release time and mixing behavior. Later modifications to the existing experimental system will allow characterization for conditions appropriate for the nacelle application.

2. EXPERIMENTAL

In the field, halon 1301 is stored in vessels which are pressurized with nitrogen (4.12 MPa (600 psi) is typical). Release of the agent is initiated by firing an explosive charge (squib) which ruptures a disk and allows the agent to escape. Due to safety considerations, pressure-actuated burst disks are used for the experimental system at NIST.

A schematic of the experimental system is shown in figure **1.** Two vessels having approximate volumes of *500* cm^3 have been prepared for the study. The first is constructed from stainless steel tubing with a *5.08* cm inside diameter and 24.7 cm length. One end is sealed with a welded steel disk, and the other end has a flange for mounting stainless steel plates which hold the burst disk. The second vessel is constructed from clear polymethylmethacrylate (PMMA) with a *5.08* cm inside diameter and *25.6* cm length. Aluminum plates on both ends are press fit with threaded rods and sealed with o-rings. One of these plates attaches to the burst disk assembly. The end plates holding the burst disks consist of two *0.99* cm thick stainless-steel plates with 1.90 cm holes through the centers. The rupture disk is press mounted between the two plates. Mounts have been constructed to allow the orientation of the vessels in a variety of direction (vertically upward and downward, horizontal, as well as intermediate orientations). The results discussed in this paper are limited to downward releases.

The ends of the vessels opposite the burst disks are drilled, tapped, and fitted with connections to allow agent, nitrogen, and various transducers to be introduced into the vessels. Nitrogen enters through an electronically actuated solenoid valve and a bleed valve, which controls the flowrate of nitrogen into the vessel. As shown in Fig. **1,** two 25 μm K-type thermocouples (one placed in the gas and one in the liquid) and a dynamic piezoelectric pressure transducer positioned in the gas above the liquid are located within the vessel. In addition, a second pressure transducer (not shown in Fig. 1) is located in the side of the stainless-steel vessel *6.5* cm from the burst disk end in order to measure pressure in the liquid. By backlighting the transparent vessel, it is possible to record the behavior of the liquid within the vessel using a high speed (typically 3000 frames per second) movie camera. Selected Games of the films are printed and digitized. Computer-based image analysis is used to measure the rate at which the liquid falls, and hence the release rate of the liquid from the vessel.

Instrumentation for characterizing the behavior of the released agent outside of the vessel is shown in Fig. 1. Five helium-neon lasers are aligned such that their beams pass perpendicularly through the centerline of the release. The spacing between lasers is roughly 30 cm. The beams strike silicon photodiodes which record the transmitted beam intensities. The passage of the agent

totally extinguishes each laser beam for varying periods of time. From the times of extinguishment following release, it is possible to estimate average flow velocities over the distances between the lasers.

A third dynamic pressure transducer is orientated as indicated in Fig. 1. It is located 1.3 cm downstream and 4.6 cm from the center of the burst disk. This transducer senses pressure waves generated by the release as well as direct impingement of the flow.

With back, front and side lighting, it is possible to record motion pictures of the flows generated by the released agents. High speed (3000 frames/s) and moderate speed (500 frames/s) cameras are employed. Digitization and image analysis allow a variety of parameters to be quantified including the release spread angle and rate of spread in the radial and downstream directions.

In the near future, a fourth dynamic pressure transducer and aspirated hot-film concentration probe will be positioned in the flow to provide additional characterization of the mixing behavior.

The burst disks have a nominal release pressure of 4.1 MPa (600 psig). An experiment is performed by first filling the vessel with a weighed amount of the agent and then adding a known pressure of nitrogen (typically 3.1 MPa gage (450 psig)). The line leading to the closed solenoid valve is pressurized with nitrogen to a pressure sufficient to rupture the disk. The solenoid valve is then opened allowing nitrogen to bleed slowly into the vessel, eventually rupturing the disk and releasing the agent. Pressure traces within the vessel (see ahead) are independent of the bleed rate.

A high speed data acquisition system simultaneously records the outputs of the thermocouples, pressure transducers, concentration probe, and photodiodes. Typical data rates are 25 kHz per channel. Timing is provided by triggering on the extinction of laser 1 which is located immediately downstream of the vessel exit. The data acquisition system is "pretriggered such that the conditions immediately prior to the initiation of the experiment are recorded along with the transducer responses following the release. Recorded data are stored on a hard disk for later analysis.

3. EXPERIMENTAL RESULTS

Results for downward releases of two of the eleven agents--CFC 22 (CHF_2Cl, boiling point = -41 "C) and FC 31-10 (C_4F_{10}, boiling point = -2 °C) are discussed. These two agents cover a range of physical properties typical of the full list of eleven compounds.

A. HIGH-SPEED MOTION ANALYSIS

Photographic records of the processes occurring within the PMMA vessel have demonstrated that boiling does not occur during a release. The liquid/gas interface is easily detected, and it is possible to measure its position as a function of time using image analysis. Figure 2 shows data for a downward release of *250* g of CFC *22.* The decrease in the height of the liquid with time is linear. The slope allows the constant volume flow rate for the liquid to be estimated. The result for the data of Fig. 2 is 15,300 cm^3/s, corresponding to a mass flow rate of 18.8 kg/s. Similar results have been observed for FC 31-10.

Films outside of the vessel show that the CFC **22** has a very complex behavior. Immediately following the disk bursting a very strong "flash" is evident with material spreading at very large angles. Shortly afterwards, a liquid flow develops near the exit with flashing occurring further downstream. From measurements inside the vessel, the flow velocity of the liquid near the exit is approximately **54** mh. Near the conclusion of the liquid release a second, extremely strong flashing is observed. Figures 3 and **4** show photographs of the liquid flow and the second flashing for the times indicated.

B. MEASUREMENTS WITHIN THE VESSEL

Figure **5** shows a time record of pressure within the vessel for a release of CFC 22. Zero time is when laser 1 was extinguished. Two decay behaviors are apparent. The first lasts approximately 15 ms. Based on the high speed films, this is the period during which liquid is being forced out of the vessel. As discussed subsequently, the second pressure decay is associated with the release of gaseous nitrogen and vaporized liquid which is trapped above the liquid. Pressure traces for FC 31-10 are very similar to those for CFC 22 suggesting a similar behavior during release.

Temperature measurements show that the liquid temperature remains constant during the release, while the gaseous temperature decreases due to adiabatic expansion of the gas. Temperatures lower than -100 °C have been measured.

C. MEASUREMENTS OUTSIDE OF THE VESSEL

Figure 6 shows an example of the external pressure traces observed during releases of CFC 22 and FC 31-10. The *two* "flashes" observed in motion pictures of the release are evident for the CFC 22. Interestingly, only one much weaker flash is detected for the FC 31-10.

Tune records for the lasers are shown in Figure **7** for a release of FC 31-10. Sharp extinctions are observed when the released agent reaches a laser beam. The extinction measurements allow an estimate of the period required for the laser beam transmission to recover which is associated with the passage of the two-phase flow and the evaporation of agent or condensed water vapor. Average velocities determined from laser extinction times for the downstream edge of the two-phase flow are shown in Figs. 8 and 9 for a number of releases of CFC **22** and FC **31-10.** Different behaviors for the *two* liquids are apparent.

4. DISCUSSION

Observed behaviors for all of the releases are consistent with nonboiling liquid being forced from the vessel by the high pressure gas above it. The observed linear dependence of the liquid height on time is surprising since it is expected that the liquid flow through the **orifice** decreases as the gas pressure decreases. At the present time the origin of the linear dependence is unknown.

By assuming a constant time rate of volume change for the liquid and an adiabatic reversible expansion of the gas, it is possible to derive a simple expression for the pressure of the gas within the vessel as a function of time during the period of liquid release. The result is

$$P = P_o\left(1+\frac{kt}{V_o}\right)^{-\gamma}$$

(1)

where t is the time, P is the pressure in the gas, P_o and V, are the pressure and volume at t = 0, **7** is the ratio of constant pressure and volume heat capacities, C_p/C_v (the value for nitrogen, **y = 1.4,** is assumed), and k is the constant rate of volume change, $\partial V/\partial t$. **A** computer program is used to fit the experimental data to this expression. **A** fit to the experimental data for 0 to **15** ms is included in Fig. *5*. The corresponding value of k is **13,600** cm^3/s.

Once the liquid is completely expelled from the vessel, the remaining pressure drop is due to the constant volume, adiabatic release of **gas** through the orifice. For high **pressures** the exit flow is choked. This is a classic textbook problem. Kim-E provides an excellent discussion of this problem and the solution. [3] The result is

$$P = \left[1-\frac{CA}{V_o}\left(\frac{RT_o\gamma^3}{M}\right)^{1/2}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left(\frac{1-\gamma}{2\gamma}\right)t\right]^{\frac{2\gamma}{1-\gamma}}P_o$$

(2)

where C is the orifice discharge coefficient, **A** is the orifice area, R is the universal gas constant, T, is the initial temperature, and M is the molecular weight of the gas. Figure *5* shows a fit of the experimental data to this expression for 25 to **40 ms.** The fit is quite good over this time range. For lower **pressures** the fit is not as good due to a breakdown in the assumption of critical flow.

The mixing behavior outside of the vessel is quite complicated. When the agents exit the pressurized vessel **as** liquids they become superheated (i.e, the vapor pressure of the liquid is greater than atmospheric pressure). Superheated liquids can boil very rapidly leading to rapid volume expansion. This **process,** known as flashing, has been investigated by Brown and **York** [4] and Lienhard and Day [5]. Flashing results in a rapidly expanding two-phase flow. The period required for a superheated fluid to flash decreases with increasing superheating.

Liquid velocities at the exit of the vessel are on the order of 50 m/s for CFC *22* while average velocities of the two-phase flow are on the order of 70 m/s (see Fig. 8). This large increase in flow velocity is attributed to flashing of the liquid near the nozzle. Interestingly, for positions further downstream, the measured average velocities are more characteristic of the liquid flow velocity. The velocity behavior for FC **31-10** is very different. Near the vessel exit, velocities are on the order ($\approx$ 57 m/s) of the liquid release velocity. Further downstream the velocities increase to values approaching 70 m/s. The increase in velocity is attributed to a flashing behavior which occurs well downstream of the vessel exit. The delay in flashing behavior for the FC **31-10** as compared to the CFC **22** is a result of the considerably higher boiling point of the FC 31-10.

The finding suggest that at room temperature release rates of the various agents will not vary greatly. However, the vaporization and mixing behaviors of the released agents outside of the vessels do depend dramatically on the agent's properties. Such variations in vaporization and mixing behavior will affect the ability of an agent to suppress a tire. Criteria need to be developed to characterize such effects.

Future work will provide more careful quantification of the mixing behavior of these flows. Measurements will be made for each of the eleven agents. Studies will also be carried out to characterize the effects of release direction on the release and mixing behavior. Preliminary results for upward releases of CFC 22, FC 31-10, and HCF 227 indicate dramatic differences depending on whether the release is upwards or downwards. The effects of cooling and heating the liquids in the vessels on the release and mixing behavior are also to be investigated.

5. REFERENCES

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[3]   M. E. Kim-E, *The Possible Consequences of Rapidly Depressurizing a Fluid*, Master's Thesis, Massachusetts Institute of Technology, January, 1981.
[4]   R. Brown and J. L York, *A.I.Ch.E. Journal* **8 (1962) 149.**
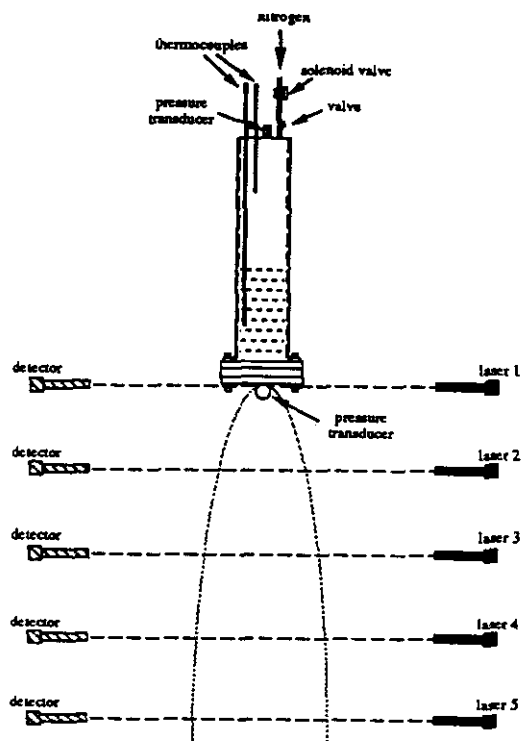[5]   J. H. Lienhard and J. B. Day, I. Basic Engineering **92 (1970) 515.**

Figure 1. Experimental apparatus for investigation of downward releases of halon alternatives.
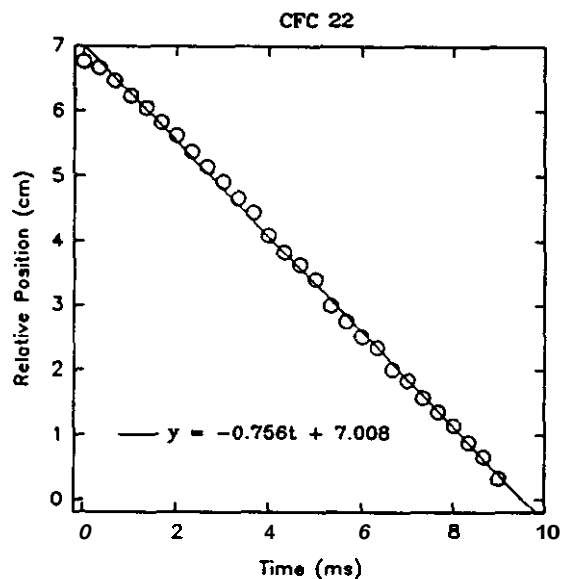

Figure 2. Plot of liquid-gas interface as a function of time determined from high-speed film of CFC 22 release.
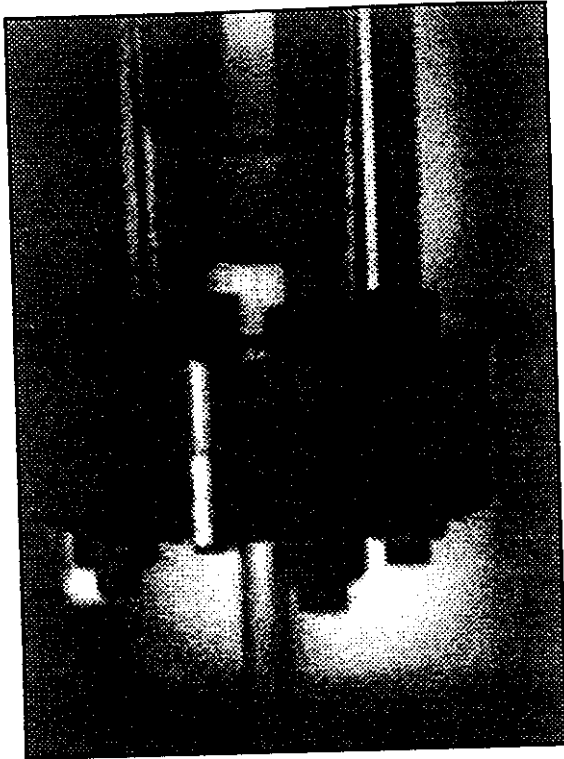
Figure 3. Digitized image of a frame of high-speed film showing liquid level and exit flow at 6.0 ms following release of CFC 22.
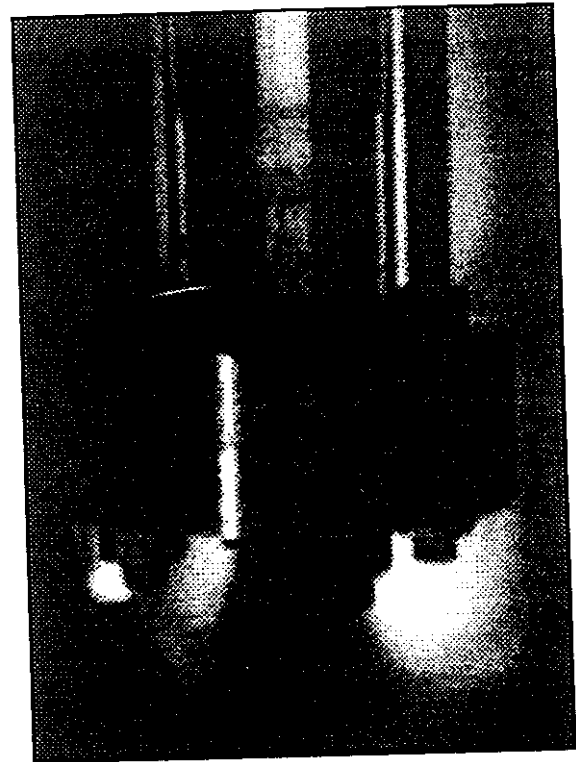

Figure 4. Digitized image of a frame of high-speed film showing exit flow and flashing at 11.1 ms following release of CFC 22.
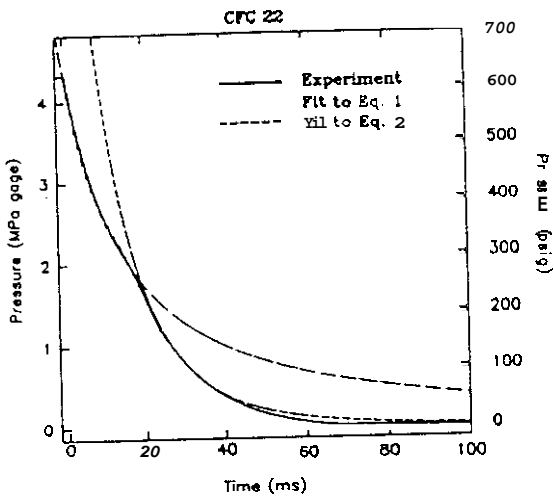

Figure 5. Pressure recorded in the upper region of the vessel during a release of CFC 22.
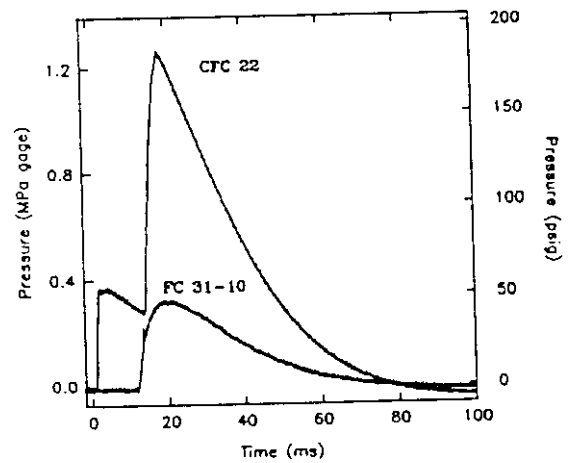

Figure 6. Pressure traces detected near vessel exit for releases of CFC 22 and FC 31-10.
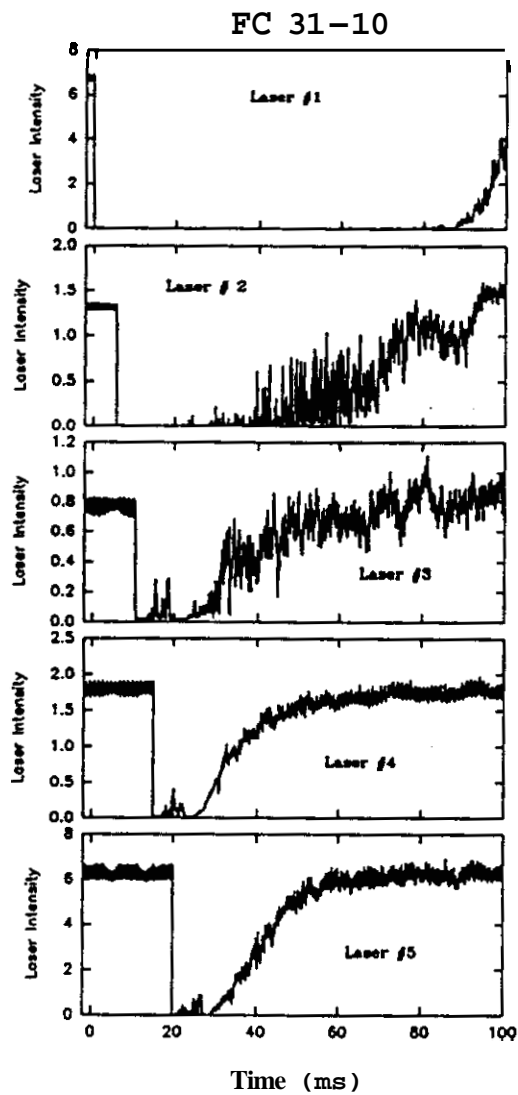
FC 31-10

Time (ms)

Figure 7. Extinction of laser beams located 0, 320, 65.5, 96.0, and 130.0 cm from vessel exit by a release of FC 31-10.
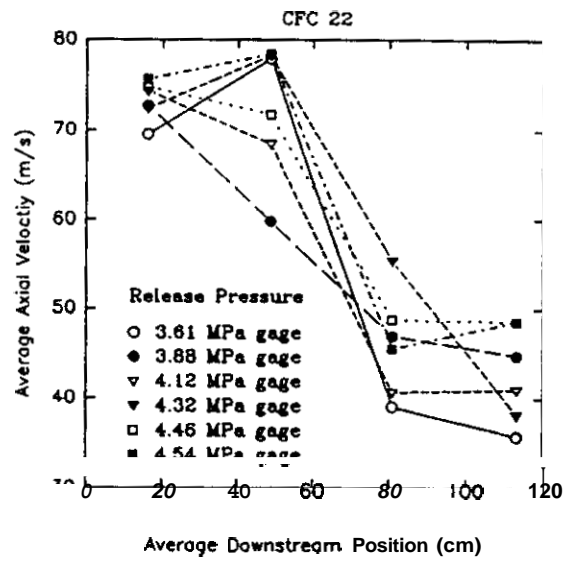

Figure 8. Average velocity of the downstream edge of the flow at indicated positions for a release of CFC 22.
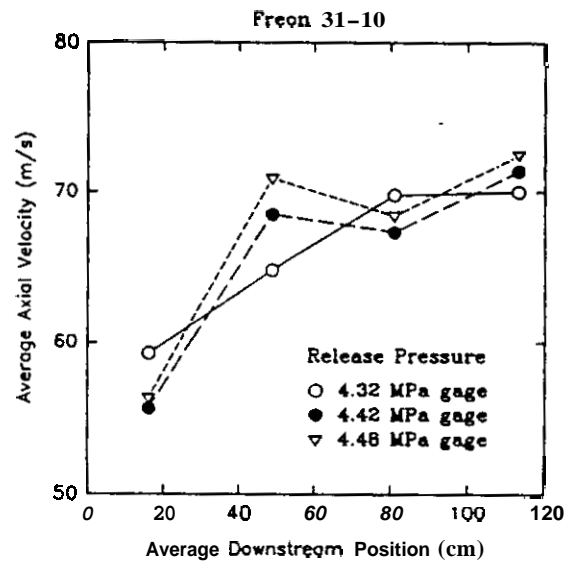

Figure 9. Average velocity of the downstream edge of the flow at indicated positions for a release of FC 31-10.

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