Cold Discharge of CF$_3$I in a Simulated Aircraft Engine Nacelle

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INTRODUCTION

One of the potential candidates for halon 1301 replacement in aircraft engine nacelle and dry bay fire protection applications and fuel tank ullage inerting is trifluoroiodomethane (CF$_3$I). Before CF$_3$I can be considered as a potential drop-in replacement, several operational and technical issues must be addressed or re-examined. CF$_3$I has a normal boiling point of –22   e dispersion of CF$_3$I into air at temperatures down to –40   C may not be as effective as halon 1301, which has a normal boiling point of
          C. Although tests have been conducted at room temperature [1], no information on the discharge of cold CF$_3$I into a cold ambient can be found in open literature. This research program, which is a continuation of the work that we have reported at HOTWC 2000 [2], is to examine this important aspect to assure that there is no deterioration in dispersion performance of CF$_3$I under such conditions.
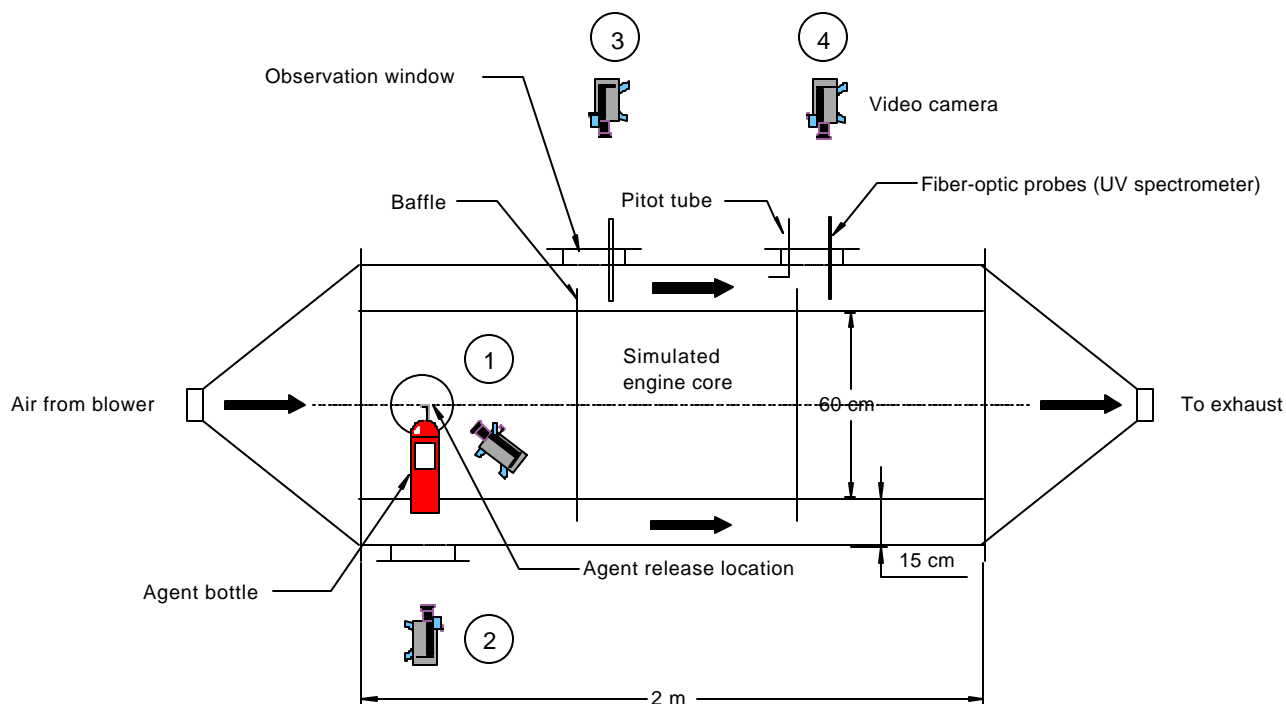
EXPERIMENTAL APPARATUS

The experimental apparatus consisted of a simulated engine nacelle with baffles, an agent release port, four observation windows, and two measurement ports. The simulator had dimensions commensurate with a typical small engine nacelle. Figure 1 is a schematic of the simulator. The annulus of the simulator had an inside diameter of 0.6 m and an outside diameter of 0.9 m, resulting in a cross-sectional area of 0.35 m^2. The length (2 m) of the simulator was comparable to the distance between the agent injection port and the downstream end of a typical small engine nacelle. The simulator was fabricated of stainless-steel sheet metal. A receiver bottle (Pacific Scientific [2], P/N 36200122) with an internal volume of 2.36 L was used to store CF$_3$I for discharge. A fast-response static pressure transducer (uncertainty $\pm$ 10 kPa) was mounted on the bottle to monitor the pressure inside the bottle during filling and discharge. A K-type thermocouple (uncertainty $\pm$ 1 °C) was inserted into the bottle to record the temperature of the liquid agent before discharge. A quick-acting solenoid valve (Pacific Scientific, P/N 36400036) was used to release the agent. To tailor the agent discharge time ($\approx$ 0.5 s), a reducer was placed at the valve exit. The agent was released through a vertical tee at the end of a short stainless-steel tubing (i.d. = 15.9 mm, o.d. = 19.1 mm) connected to the reducer. Four CCD cameras (30 frames/s) were used to observe the agent discharge behavior at the release port (Camera 1), at a location in the bottom of the simulator to observe any pooling of agent (Camera 2), and at the two concentration measurement locations (Cameras 3 and 4), respectively. A frequency-controlled variable-speed blower provided airflow through the nacelle simulator. The maximum air speed in the annulus, measured using a pitot tube, can reach 9.2 m/s. Figure 2 is a photograph of the simulator.


Figure 1. Schematic of the apparatus.

To achieve an operating temperature of –40 °C, the entire facility will be housed inside the NIST large environmental chamber, and the discharge experiments will be conducted inside the chamber. The lowest temperature attainable in the environmental chamber is –40 °C. Several airflow rates through the simulator will be used in the tests. Discharge experiments in room temperature will also be conducted to establish baselines for comparisons.

The dispersion effectiveness of CF_3I was assessed based upon concentration measurements inside the engine nacelle simulator (see Figure 1). Figure 3 is a photograph showing the mounting of one set of the fiber-optics probes which was placed inside the nacelle simulator. The spectroscopic measurements were made using an Ocean Optics S2000 UV/VIS fiber optic spectrometer. The optical components consisted of deuterium/tungsten source, four (UV grade quartz) collimating lenses, and 300 mm diameter optical fibers. These were arranged to provide two measurement locations (coincident with Cameras 3 and 4) approximately 0.75 m apart along the direction of the airflow in the engine nacelle testing apparatus. A bifurcated fiber (1 m in length) was used to connect the source to a pair of collimating lenses secured by brackets to plexiglas viewing windows located on the top of the apparatus (Figure 3). The source radiation emanating from each lens was transmitted over a 0.038 m optical path (perpendicular to the airflow) to an opposing set of collimating lenses connected by independent optical fibers (2 m in length) to the master and slave spectrometers. Although the manual indicated that these optical components should have a spectral range from 200 nm to 850 nm, we found that there was very little throughput at wavelengths shorter than 250 nm. This was a concern, since the agent of interest, CF_3I, absorbs in the UV from about 225 nm to about 325 nm (Figure 4).

Figure 2. A photograph of the nacelle simulator.
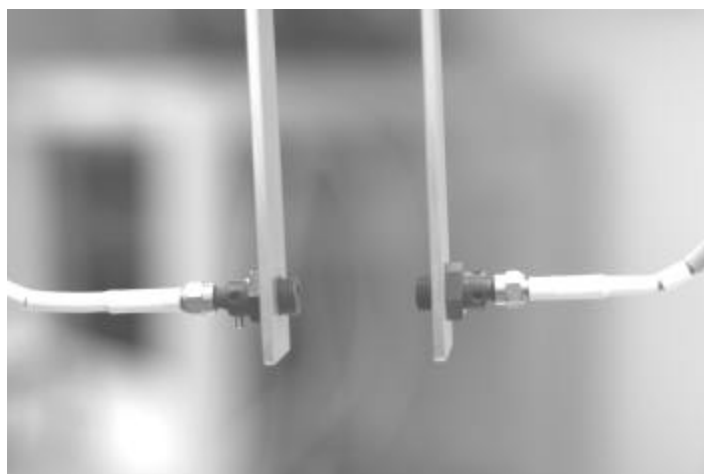
Figure 3. Fiber-optic probe.

The spectrometer settings used for the measurements in the nacelle testing apparatus were as follows. The integration time (analogous to the shutter speed) was set at 30 ms and the pixel resolution of the analogue to digital converter (ADC) was set at 100, which amounts to a spectral resolution of only about 30 nm. With this configuration, we were able to achieve a data acquisition rate of 14 single scan spectra (7 at each location) per second. Although this high data acquisition rate had an adverse effect on the quality of our measurements, it was thought to be necessary to capture the time dependent details of the agent discharge. An estimate of the uncertainty of our measurements was obtained by comparing results obtained with these settings to more accurate values obtained after signal averaging 100 scans at the full resolution of the spectrometer (≈ 0.3 nm). Based on this analysis, the CF_3I partial pressures reported in this paper are accurate to ± 15 %.
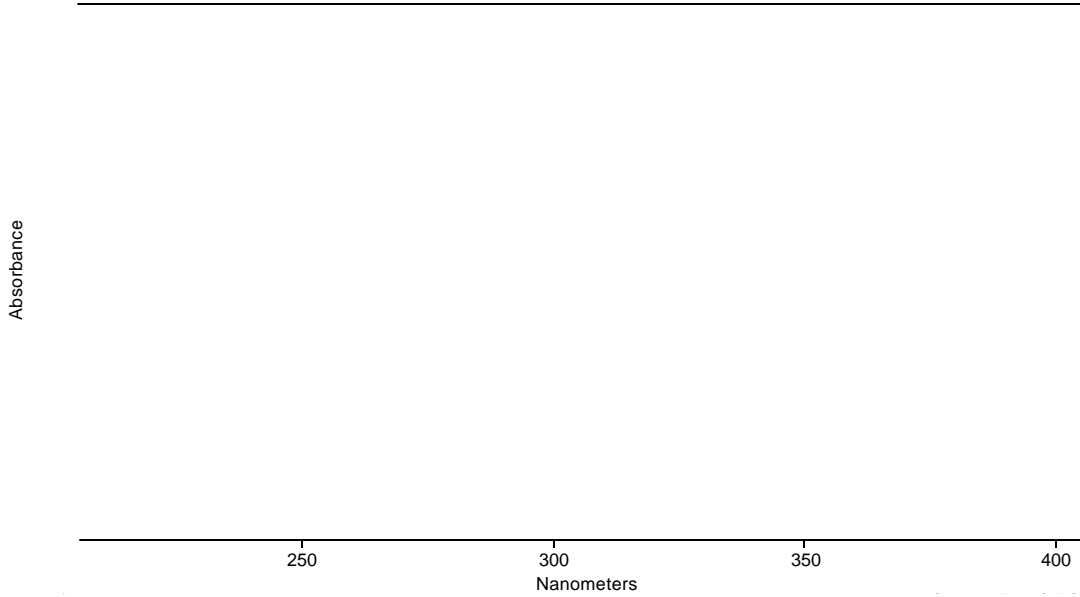
Figure 4. UV/VIS spectrum of CF₃I.

The CF$_3$I partial pressures (p) were obtained from absorbance (A) measurements, made in the nacelle testing apparatus, using Eq. (1)

$$p = \left(\frac{A\ell_r}{A_r\ell} \right) p_r,$$

(1)

where the subscript, r, is used to denote the reference quantities measured in a 0.075 m quartz cell containing 10.1 kPa of CF$_3$I at room temperature. The absorbance was defined by the Bouguer-Beer-Lambert law (commonly known as Beer's law) in accordance with Eq. (2).

$$A(\boldsymbol{\lambda}_i) = -\log\left[\frac{I(\boldsymbol{\lambda}_i)}{I_0(\boldsymbol{\lambda}_i)} \right] = a(\boldsymbol{\lambda}_i) p\ell$$

(2)

Here ℓ is the optical path length, $a(\lambda_i)$ is the absorption coefficient and $I(\lambda_i)/I_0(\lambda_i)$ is the fraction of the incident radiation with wavelength, λ_i, transmitted through the cell containing the absorbing molecules (in this case, CF$_3$I).

Given the simulated nacelle volume, the amount of agent required for a fixed injection period ($\approx$ 0.5 s for typical nacelle applications) was estimated using the generic nacelle modeling results discussed in Gann [3]. The preparation of CF$_3$I/dissolved nitrogen mixtures followed the procedure described in Gann [3]; the agent bottle was charged with $\approx$ 1 kg of CF$_3$I and then pressurized with nitrogen to the desired pressure (4.21 MPa or 2.75 MPa) at room temperature. Table 1 lists the proposed experimental matrix.

Table 1 Experimental matrix for cold temperature agent dispersion

Initial conditions of vessel	Conditions of vessel before discharge	Conditions in simulated fire compartment
22 ℃ and 4.12 MPa	–40 ℃ at prevailing $P^{\P}$	22 ℃
22 ℃ and 4.12 MPa	–40 ℃ at prevailing $P^{\S}$	–40 ℃ [§]
22 ℃ and 4.12 MPa	22 ℃ and 4.12 MPa	22 ℃ (baseline)
22 ℃ and 2.75 MPa	–40 ℃ at prevailing $P^{\P}$	22 ℃
22 ℃ and 2.75 MPa	–40 ℃ at prevailing $P^{\S}$	–40 ℃ [§]
22 ℃ and 2.75 MPa	22 ℃ and 2.75 MPa	22 ℃ (baseline)

¶ Dry ice will be used to chill the vessel.
§ Tests will be performed in an environmental chamber.

RESULTS AND DISCUSSION

The present discussion will focus on results that we have obtained thus far. The experimental conditions (see the shaded areas in Table 1) that we have examined include discharge of CF_3I at room temperature and –40 ℃ (nominal) into the simulator. The airflow and temperature within the simulated fire compartment were maintained at 1.69 kg/s ± 0.04 kg/s and 22 ℃ ± 1 ℃, respectively.

Figure 5 shows the temporal variation of pressure inside the bottle during discharge. In the figure, the prevailing bottle pressure before discharge at –45 ℃ was much lower than that at 23
reduction in the initial bottle pressure, the discharge time (≈ 0.24 s) of the cold *liquid* agent was much longer than that (≈ 0.16 s) of the baseline case; the liquid discharge time corresponds to the transition point in the pressure *vs*. time curve [4].

When CF_3I was discharged at room temperature, the observations obtained from Camera 2 showed that a small amount of CF_3I pooled in the bottom of the simulator upon release. However, the liquid CF_3I boiled off within 66 ms. On the contrary, when CF_3I was discharged at –45 ℃, a significant amount of liquid CF_3I pooled at the bottom of the nacelle upon release. The liquid CF_3I evaporated slowly and remained for several seconds before complete evaporation.

The observations from Cameras 3 and 4 showed that a cloud of CF_3I passed through the field of view of the cameras after agent discharge. The observations from Cameras 3 and 4 were similar for discharge of CF_3I at room temperature and –45 ℃.

The concentrations of CF_3I, obtained from absorbance measurements at 300 nm, are shown for both the warm and cold releases in Figures 6 and 7. These values are based on the assumption that there is no contribution to the extinction at this wavelength due to scattering or absorption of the incident radiation by droplets. While the validity of this assumption is questionable at the onset of the release, the off-resonance extinction at 500 nm for the cold temperature discharge, presented in Figure 8, indicated that droplets are present for only a short period of time (< 2 s) immediately following the discharge. A similar observation was made for the room temperature discharge as well. Thus, the assumption that the absorbance at 300 nm was due solely to the absorption of CF_3I gas would appear to be valid; at least for measurements made more than 2 s after the discharge.
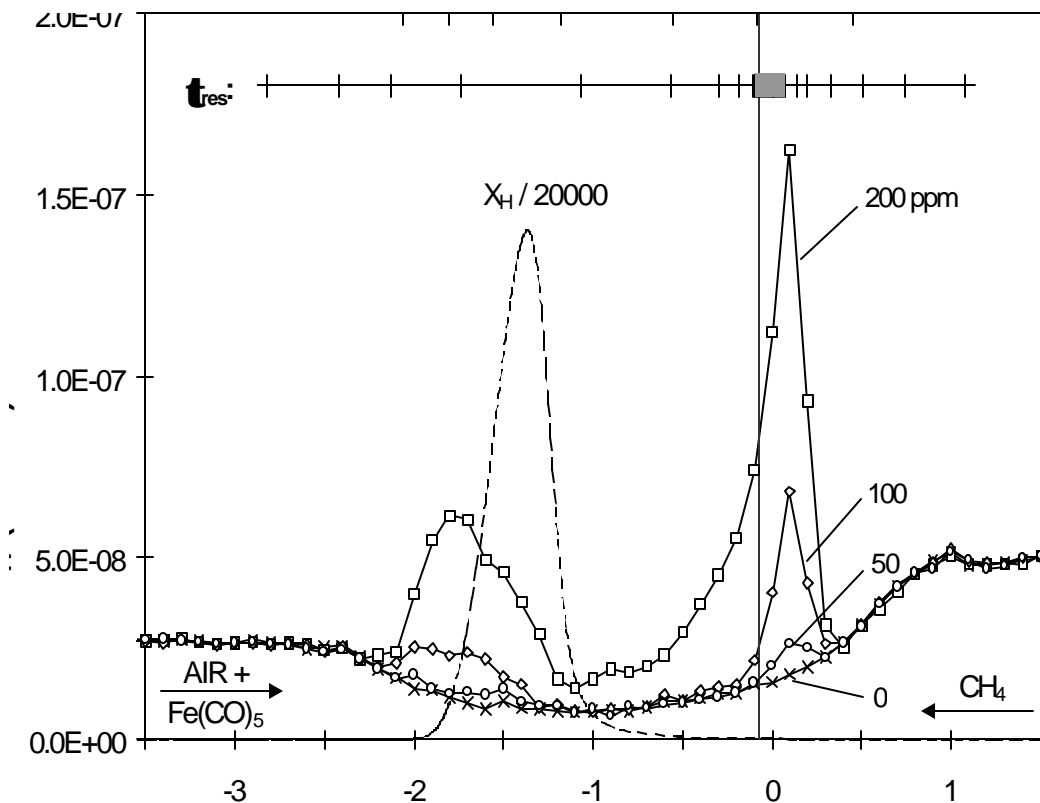
**Figure 5. Pressure *vs*. time curves during release.**

According to Military Specification (MIL-E22285), the volume fraction of Halon 1301 must remain at 0.06 with 0.5 s minimum duration for all locations within the protected area [3]. Heptane cup burner experiments have demonstrated that the extinction concentrations of Halon 1301 and CF_3I are similar (0.032 volume fraction) [5]. If it is assumed that the Military Specification for Halon 1301 can be extended to CF_3I, the preliminary measurements in Figures 6 and 7 suggest that a volume fraction of 0.06, which corresponds to 6.06 kPa in Figures 6 and 7, can be attained over a duration of 0.5 s in both the cold and room temperature discharge.

FUTURE WORK

Although the preliminary results are encouraging, more experiments are still required to delineate the dispersion of cold and room temperature CF_3I in room air. In addition, we need to perform experiments in the NIST cold environmental chamber to complete the experimental matrix.
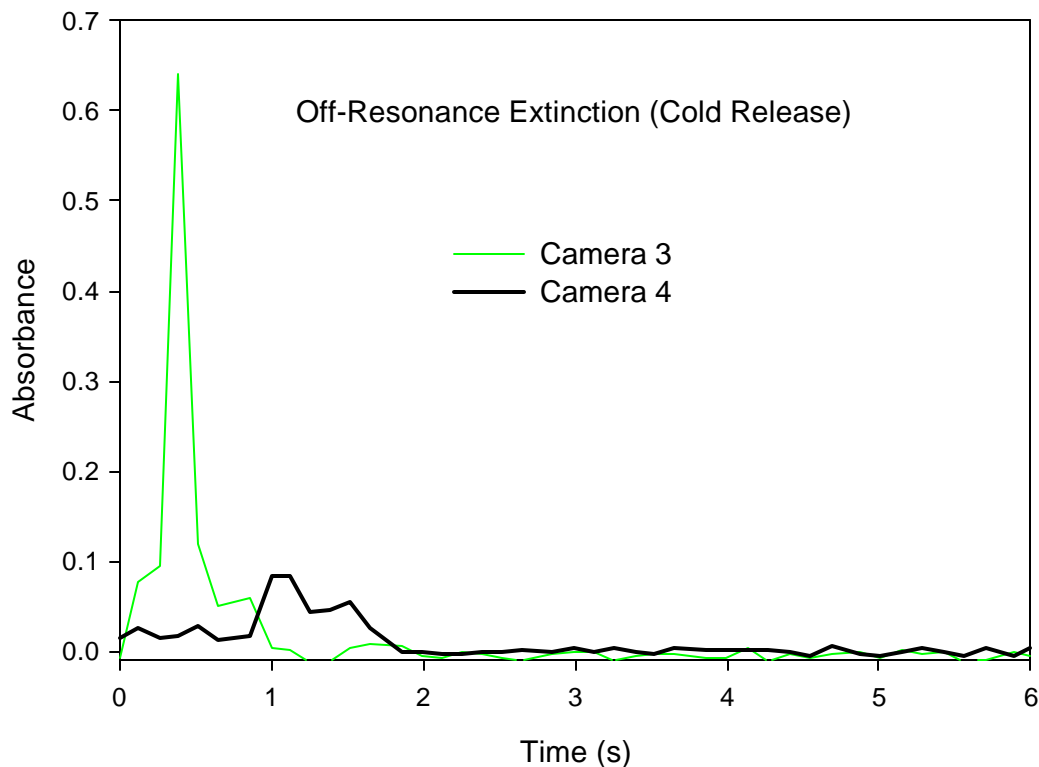
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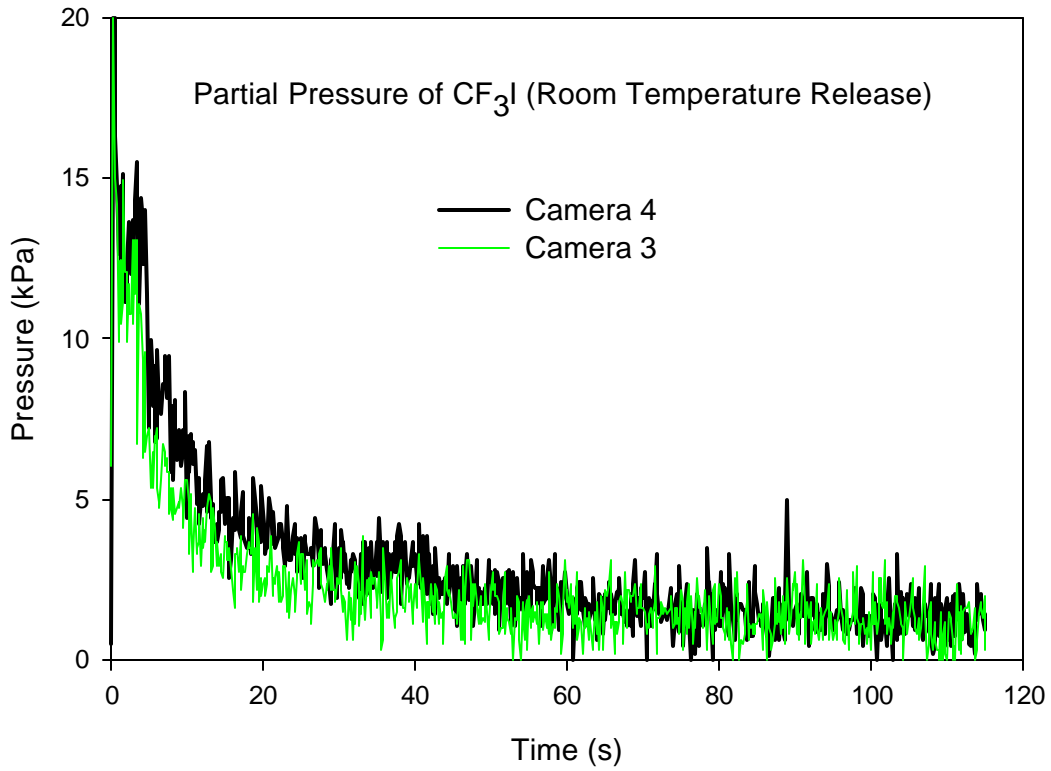
Figure 6. Partial pressure of CF$_3$I as a function of time.
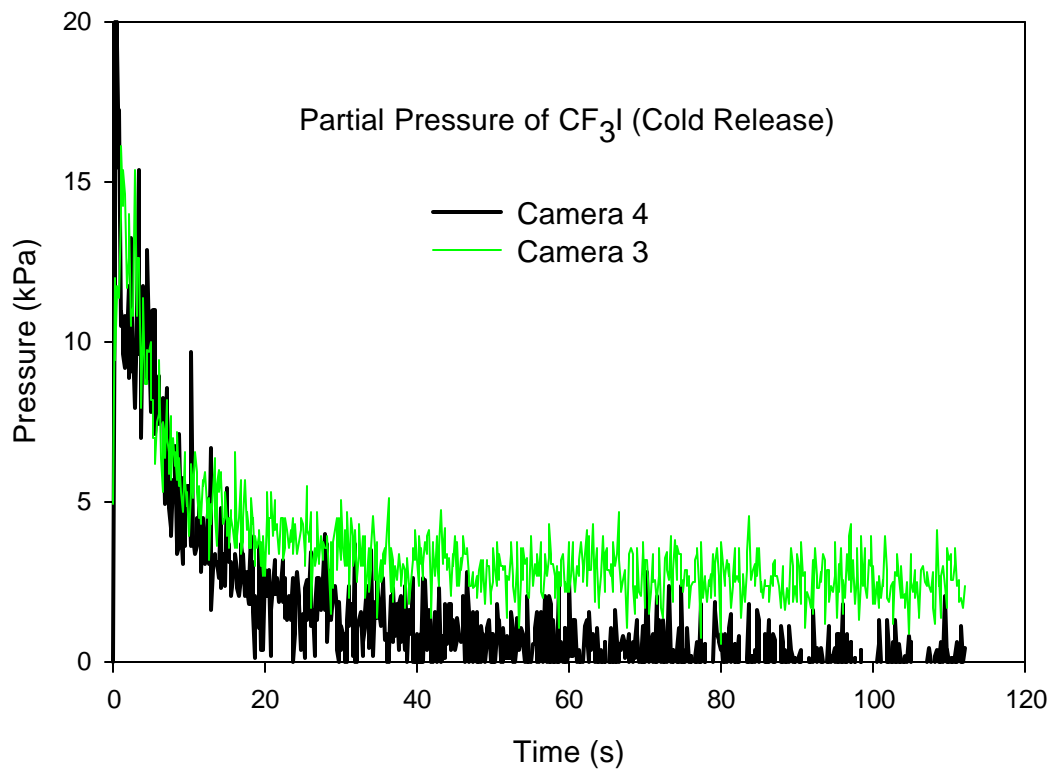
Figure 7. Partial pressure of CF$_3$I as a function of time.

Figure 8. Off-resonance extinction at 500 nm during the cold temperature release.

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