PERFORMANCE OF A FAST RESPONSE AGENT CONCENTRATION METER

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INTRODUCTION

MOTIVATION

There is a need for monitoring the concentration of potential halon replacement chemicals with millisecond response time [1]. One scenario of great concern to the Air Force is the penetration of an enemy shell into the fuel tank of an aircraft. To prevent structural damage to the aircraft wing or fuselage to the point where the plane would crash, the Air Force considers it crucial that the fire extinguishing agent be distributed throughout the interior region surrounding the fuel tank, the so-called dry-bay, in less than 30 ms. Other applications of interest include evaluation of extinguishment of fires within military tanks penetrated by shells and in ship compartments.

The instruments currently used for monitoring the concentration of Halon 1301 are the Statham analyzer and the Halonyzer [2].* Each has a time response on the order of 200 ms or longer. Clearly, they are not capable of monitoring the distribution of the agent in a dry-bay type environment. There is a need for a much faster time response instrument for monitoring the potential halon replacement chemicals. The design goal is an instrument with a response time of *3* ms that could be used with a variety of fire suppression agents over a concentration range from 1 to 20 % with an expanded uncertainty of ±10 % of the nominal value.

ORIGINAL INSTRUMENT DESIGN

An overall schematic of the original Differential Infrared Rapid Agent Concentration Sensor (DIRRACS) is shown in Figure 1. A detailed description of the instrument design and theory of operation is given by Pitts et al. [1]. The earliest and most recent versions of the DIRRACS will be referred to as DIRRACS I and II, respectively. The DIRRACS is basically a non-dispersive IR absorption instrument. The IR radiation from a coil heater source heated to 500 °C is directed through a 2.8-cm long sample volume. The transmitted beam passes through a long-wavelength cut-off filter to remove IR radiation with λ longer than 14 pm, through a chopper operating at 500 Hz, a narrow-band-pass filter transmitting from 8.4–8.9 µm, to a $LiTaO_3$ pyroelectric sensor. Figure 2 shows a schematic of the optical design used in the DIRRACS. As illustrated in Figure *3*, a narrow-band-pass filter overlaps with a strong absorption feature for HFC-125 (C_2HF_5). There is also strong IR absorption, resulting from the C-F stretch vibrational modes, in the same spectral region for other agents with C-F bonds including HFC-227 (C_3HF_7), FC-218 (C_3F_8), Halon 1301 (CF_3Br), and CF_3I. The pyroelectric sensor has a built-in FET amplifier. The output signal was increased with a 100x low-noise amplifier and frequencies below about 300 Hz

* Certain commercial equipment or instruments are identified in this paper in order to specify adequately the experimental procedure. This in no way implies endorsement or recommendation by NIST.

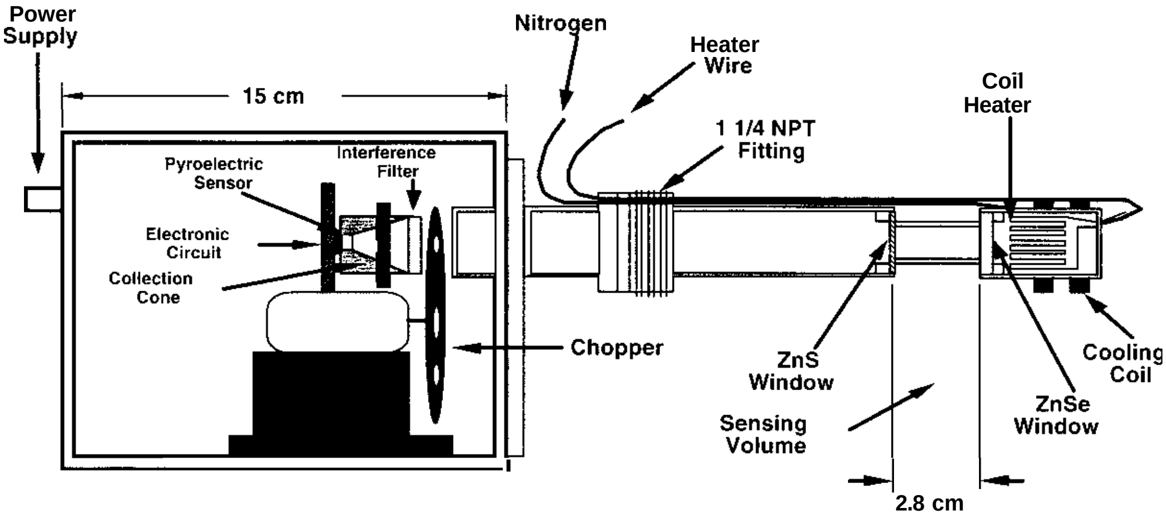

Figure 1. A schematic of the overall design of DIRRACS I.

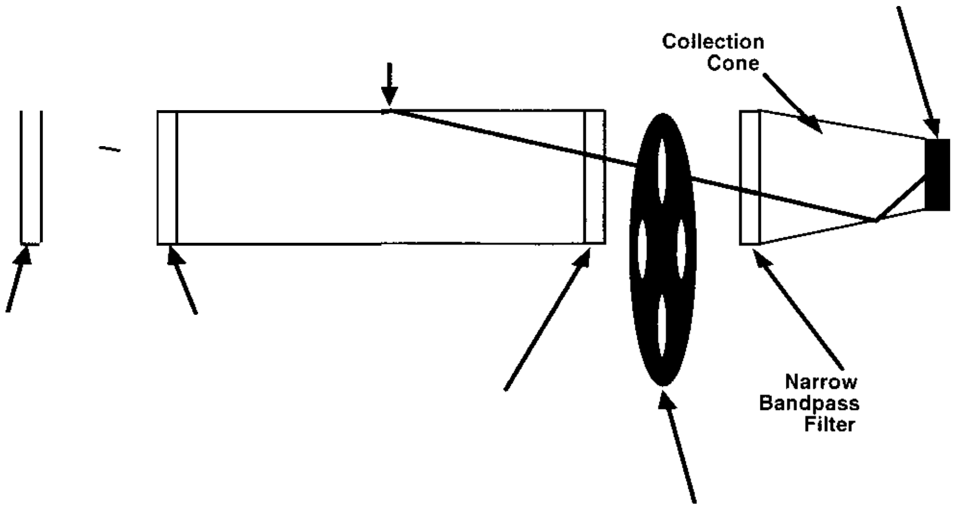

Figure 2. A schematic of the optical design used in DIRRACS I.

were filtered. The detector output was collected at 20 kHz using a digitizing card mounted in a PC and analyzed to determine the peak-to-valley (Pk-Vy) voltage difference. A computer controlled calibration system (to be described later) utilizing three mass flow controllers was used for calibrating the Pk-Vy signal versus HFC-125 concentration. For the 2.8 cm path length, the instrument is sensitive over a mole fraction range from 0.01 to 0.25.

While the calibration measurements indicated a nominal ±10 % uncertainty (coverage factor k=2), actual tests using a transient agent release facility indicated a systematic difference between

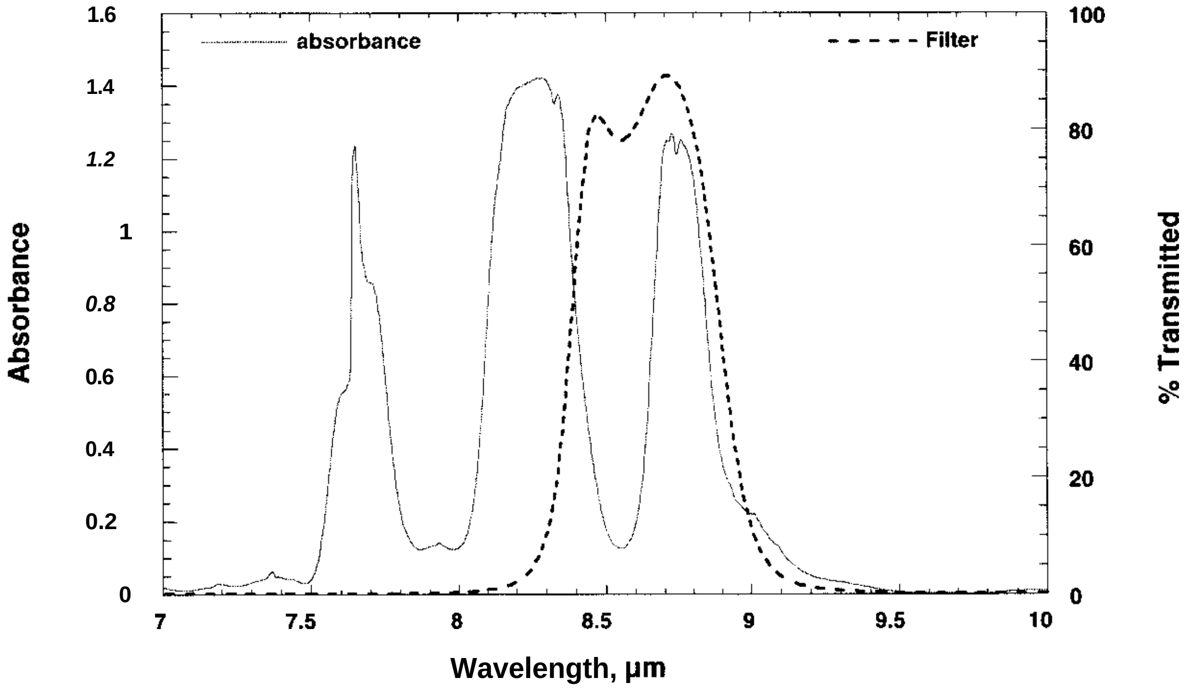

Figure 3. The absorption spectrum of HFC-125 superimposed with the transmittance spectrum for the band-pass filter,

the measured and expected values and a much larger noise as compared to the calibration measurements. Subsequent study indicated that the high flow velocity in the facility caused a change in the instrument response by affecting the source temperature and inducing vibrations in the instrument. An additional limitation of the method was the high background signal from the IR radiation from the walls. Two approaches were used to correct the problems. The first approach was to surround the IR source with a cooling coil to minimize the effect of the flow on the source temperature. The second method was to use a second narrow-band-pass filter at a nearby, non-absorbing wavelength. In this case, it was expected that both signals would be affected in the same way by a change in the source temperature so that the ratio would be constant. Neither method solved the flow effect problem, though the cooling coil approach provided some improvement, and neither method addressed the problems with vibration or background radiation from the walls.

However, even with these limitations, useful data have been obtained using the DIRRACS I. Two models of the DIRRACS I were used in the first measurements of the dispersal time of an agent in the dry-bay facility at Wright-Patterson [1]. The preliminary measurements indicate a relatively long time, on the order of a few seconds, for dispersal of the agent throughout the dry bay. This information has important implications about the mechanism of extinguishment when the fire is far from the release point of the agent. If the fire is extinguished under these conditions, the mechanism must not involve a direct interaction of the agent on the fire if one assumes the presence of the fire does not affect the distribution of the agent. These results show the value of a fast response agent measurement. The next section describes major design changes leading to DIRRACS II.

DEVELOPMENT OF DIRRACS II

IMPROVED HARDWARE DESIGN

The drawbacks of the DIRRACS I necessitated major modifications to the original design for the improved version. The goals were to eliminate the temperature and flow sensitivity of the source, detector, and other components, increase the signal-to-noise ratio, and increase the frequency response. Figure 4 is a schematic of the DIRRACS-2 design; Figure S is a photograph of the breadboarded instrument as set up to measure a transient agent release. The key design features of the DIRRACS-2 are summarized below.

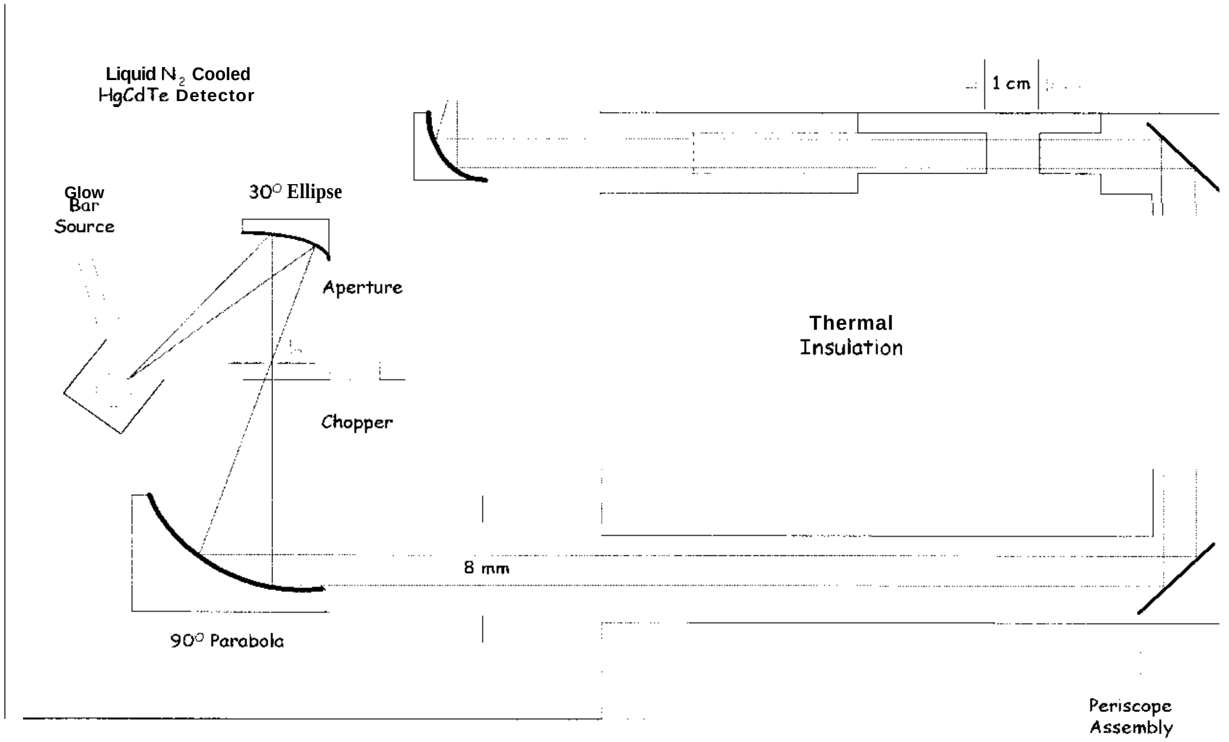

Figure 4. Schematic of DIRRACS II.

The addition of a periscope was a critical design element for reducing the high noise level of the DIRRACS I at velocity conditions of 10 to 20 m/s. The vibrations were greatly reduced by constructing the periscope assembly from standard stainless steel vacuum components. This structure is much more rigid than the previous optical housing. The decrease in sample path length by about a factor of two increased the practical maximum mole fraction measured by the instrument from about 0.2 to about 0.5. The periscope allows the sampling volume to be coni-pletely isolated from the rest of the instrument so convective flow, and temperature variations at the measurement location cannot affect the source or detector.

High frequency operation was an important feature to improve in the new design. The beam was focussed through an aperture just before the chopper, and a faster IR detector was used to allow operation of the chopper at frequencies as high as 4000 **Hz,** while the previous design with a large, unfocussed beam and slow detector was limited to about 400 Hz. The performance of the HgCdTe detector improves with frequency up to 4000 **Hz,** while the pyroelectric detector response falls off for frequencies above about SO Hz. The IO-fold increase in frequency

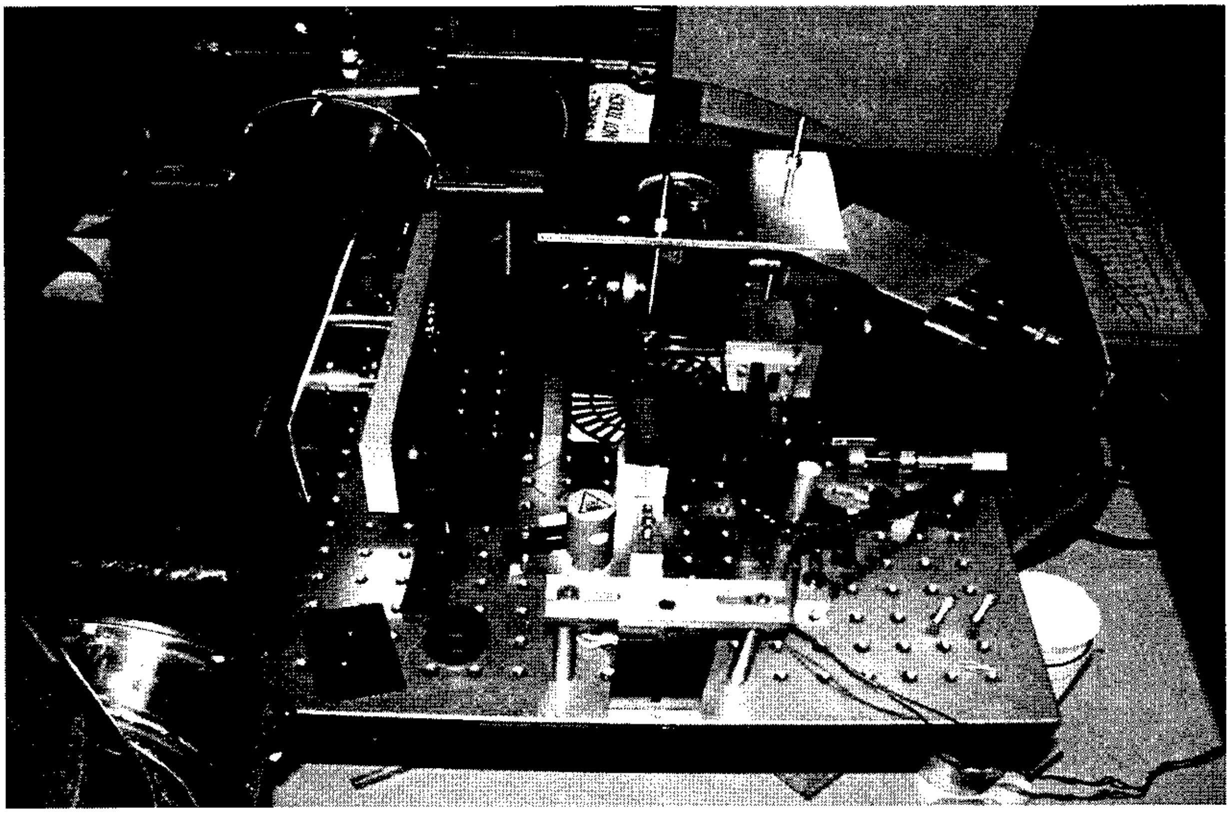

Figure 5. Photograph of the DIRRACS II with the periscope assembly mounted within the flow channel of the TARPF (Transient Application Recirculating Pool Fire) facility. IR radiation is emitted by the source (cylinder with triangle on top at bottom central) toward an elliptical mirror, reflected through the chopper and pinhole, collimated by a parabolic mirror (behind chopper), through the periscope (attached to the duct at left), reflected by a 90-deg mirror and a focussing mirror, through a narrow-band-pass filter, and finally detected by a HgCdTe detector (under the plate with the hole).

corresponds to about a 10-fold improvement in time response. The new HgCdTe detector also produces a distinct, nearly square-wave output well above any background signal from extraneous radiation sources. The detector does require liquid N_2 cooling, but one filling provides at least *2* h of stable operation.

The two major optical design changes were to isolate the IR light source from the flow/agent and to use a collimated IR beam instead of an uncollimated beam. By placing the IR source within the instrument housing, the problems of the high flow affecting the temperature of the source and the movement of the source were eliminated. Also, the use of a commercial IR source assured a more stable output with a higher intensity at the wavelength range of interest. The elliptical and parabolic mirrors were used to produce an 8 mm collimated beam, which was ultimately focussed on the detector. The background IR radiation contributed little (<1 %) to the IR radiation reaching the detector, while in the previous design as much as 50% of the IR radiation originated from blackbody radiation from the walls.

DATA ACQUISITION AND ANALYSIS

In addition to the hardware design improvements, improvements to data acquisition and analysis were also made. The old DAQ hoard was limited to about 20 kHz sampling frequency. The new DAQ board allows variable data collection rates up to 250,000 samples/s. Most often, a setting of 128,000 samples/s is used to allow data to be collected over a longer time period for a given level of data storage. Either an internal or external trigger can initiate data collection. The previous method of analysis involved post processing of the data, which required at least an hour. The current software combines the functions of acquisition and analysis. In conjunction with a faster computer and new data acquisition board, the software reduces the data and displays it within 20 s after acquisition. The software performs preliminary filtering using Fast Fourier Transform analysis to remove DC offset, drift. and 60 Hz noise. The software performs the filtering using digital lock-in amplification with the frequency determined by the chopper output and averages over a discreet and selectable number of cycles.

The data analysis can be displayed in two formats. The first display (Figure 6) consists of a plot of the raw voltage signal versus time and a plot below it of the chopper output versus time. The second display is the peak-to-valley voltage signal versus time. The user can toggle back and forth between the two displays. The software also allows zooming in on specific time periods and changing scales on the plots. The software allows both the raw data and the analyzed data to be exported for use with various standard software packages for additional plotting and statistical analysis. Currently. the calibration curve relating the peak-to-valley voltage and the agent concentration is not automatically applied using the DAQ/analysis software.

EXPERIMENTS

CALIBRATION

Calibrations of the DIRRACS II were conducted with a facility fully described in Pitts et al. [I]. Only a summary of the apparatus and procedure are presented here. The calibration facility consists of three mass flow controllers and various solenoid and pneumatic valves controlled with a computer, data acquisition board, and analog/digital output hoard. A 2-L/min mass flow controller and a 10-L/min model are used to meter the agent through the system. The programming prescribes at what point the fraction of agent in the mixture is best supplied through the higher capacity controller. The third controller is a 10-L/min model, which is dedicated to air flow.

The program uses equations based on calibrations of each flow controller for agent or air to set the mass flows through each controller to match the user input mass fraction of agent. The system output changes the mixture at the calibration cell within seconds. The sealed cell with an inlet and outlet for agent/air mixture flow was attached to the DIRRACS II periscope around the sampling volume. Because leakage of agent into the periscope through the window seals was suspected, 120 kPa (17 psi) pressure air was blown into the two periscope ends to prevent accumulation of agent that would impact the calibration. Since the cell was not particularly designed for the DIRRACS II, it had a relatively large interior volume and required about 1 min for a mixture to completely change to a new mixture input by the operator.

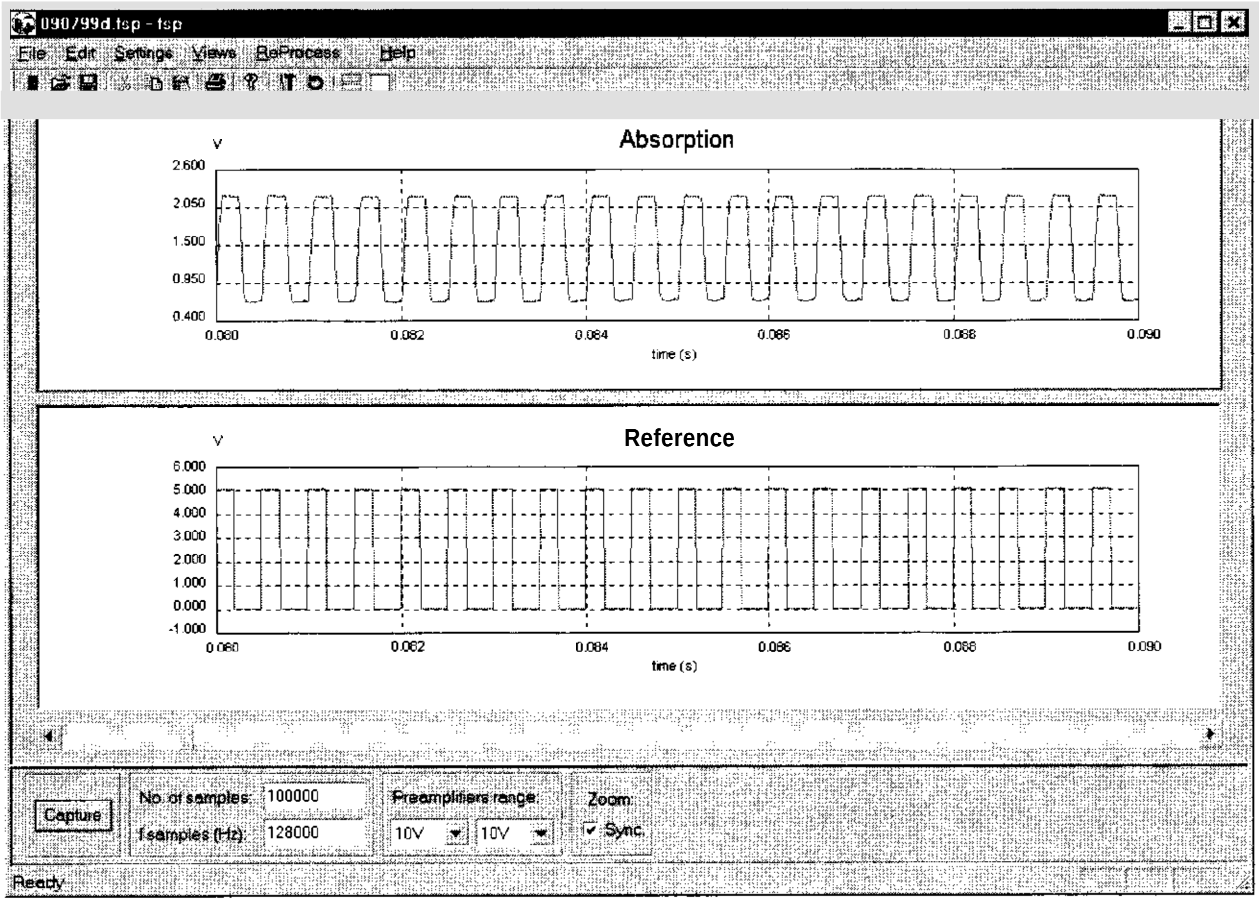

Figure *6*. Screen display for the data acquisition and processing software, showing a plot of the raw signal generated by the DIRRACS II, and is zoomed to a time range of 10 ms. The lower plot is the reference signal generated by the chopper.

Only a preliminary calibration of the DIRRACS II was conducted because plans are to continue with the next stage of development of a more compact version, which will also be refined to improve performance (Conclusions/Future Work). The new version will be calibrated more rigorously as an actual prototype for field use. This initial calibration of the DIRRACS 11 for HFC-125 is shown in Figure 7. The normalized average peak-to-valley voltages are plotted versus agent volume fraction. Each data point represents an average of data collected over 1 s. The standard deviations for 1 s samples of data generated with particular calibration mixtures ranged between 0.1 and 0.25 % of the averages.

The expanded combined standard uncertainty (2 standard deviations) among the average peak-to-valley data points shown in Figure 7 is about ±2 % of nominal for the calibrations that were conducted, which translates into a ±0.005 mole fraction uncertainty. An investigation of the potential sources for this variation will be conducted in the next series of modifications.

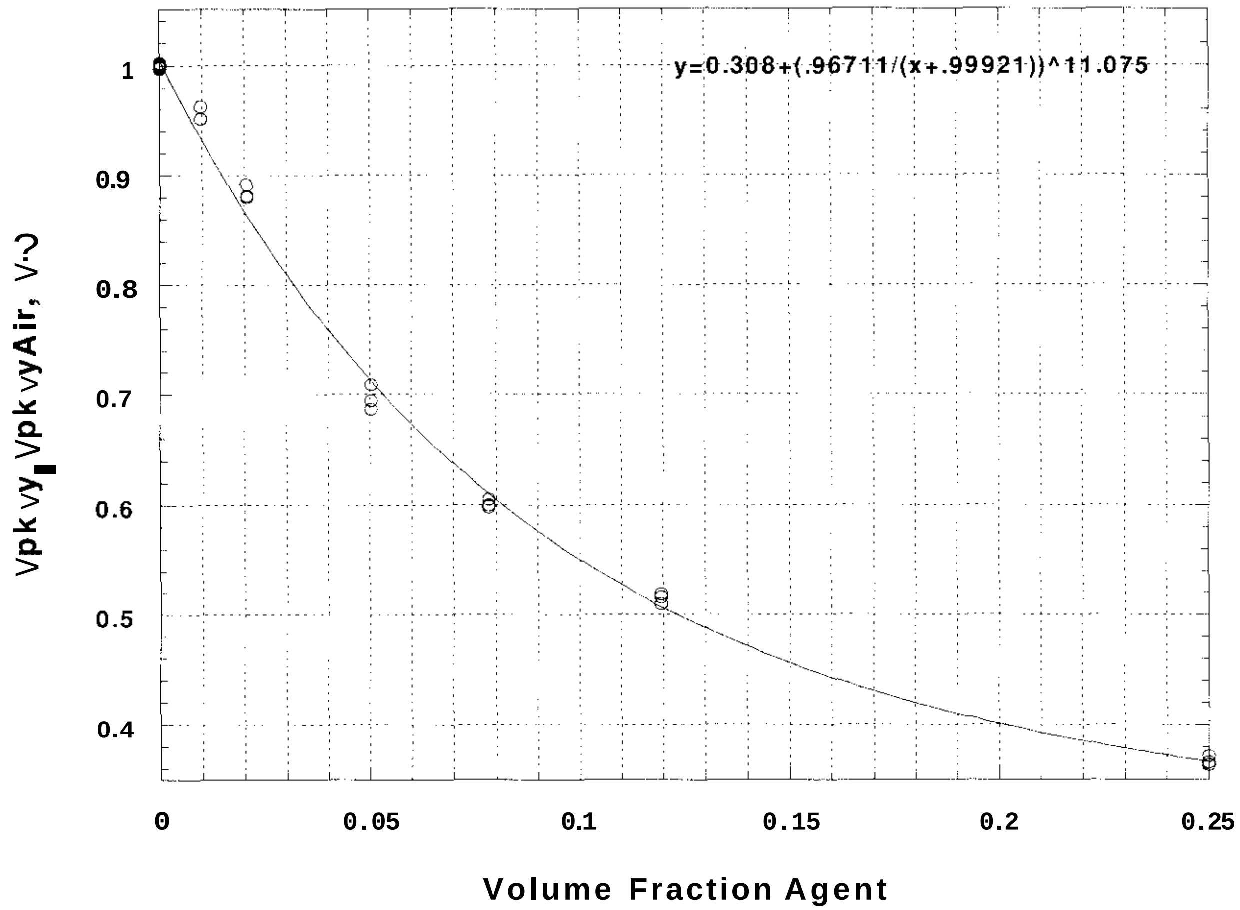

Figure 7. A calibration plot of average normalized peak-to-valley signals versus the volume fraction of HFC-125. Error bars for the averages are smaller than the symbols.

AGENT RELEASE TESTS

Releases of HFC-I 25 were conducted in the Transient Application Recirculating Pool Fire (TARPF) Facility at NIST. The facility is more completely described in Grosshandler et al. [3]. **A** schematic is shown in Figure 8. The facility consists of a 2.5 m long duct of 9.2 x 9.2 cm square cross section, which is connected to a high capacity air compressor. Variable orifice plates allow the compressor to generate air velocities up to 20 m/s in the duct. Various agents can be stored in 1 L and 2 L cylinders. Before a test, a cylinder is filled to a prescribed pressure. which is measured with a pressure transducer inside the cylinder. A release is controlled with a timer that determines the length of time the cylinder solenoid valve is opened. The normal operation of the TARPF facility consists of igniting a flame in a test section and releasing various amounts of agent upstream to observe the extinguishment behavior. For the DIRRACS testing, no flame was ignited, but the air flow and agent release capabilities of the system were utilized. The periscope assembly was mounted 0.5 m downstream of the pool fire zone and about 2 m downstream of the region where the agent is mixed into the air stream.

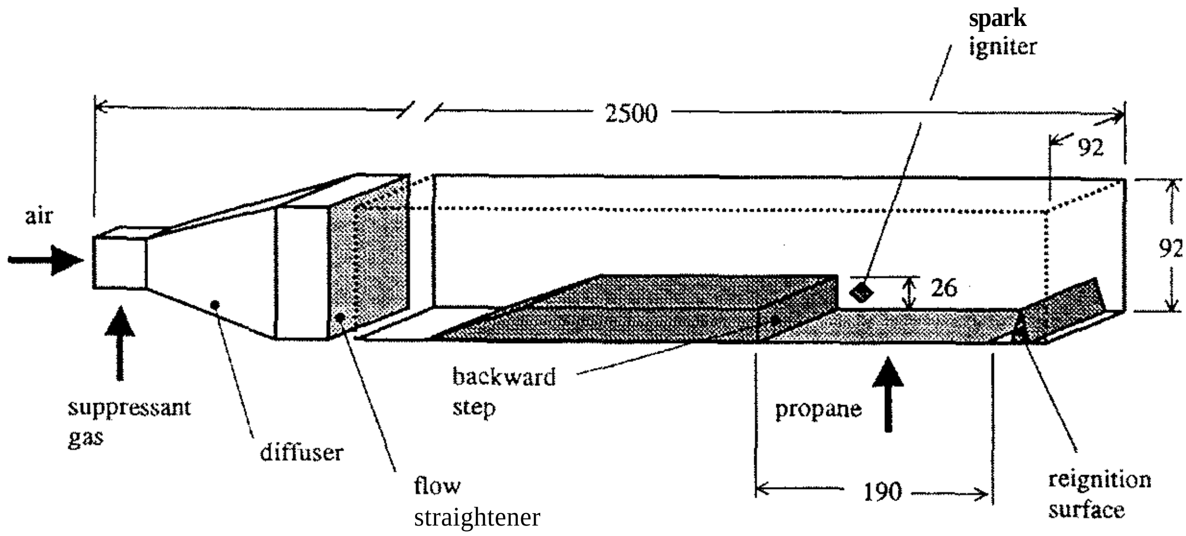

Figure 8. A schematic of the TARPF facility at NIST used to conduct release experiments monitored by the DIRRACS II.

Over **40** release tests were conducted in the TARPF facility. Each test was conducted with specified settings of air flow, agent vessel pressure, and agent vessel valve opening period. In order to capture events of less than 1 s with the data acquisition system, varying combinations of total points collected and sampling frequency were used. The series of tests with the DIRRACS II was used to help characterize the distortion of pulses of agent as they moved downstream after each release. Only two tests are described here as typical of those in the series.

RESULTS/DISCUSSION

Figure 9 shows the results obtained from two releases of the HFC-I **25** agent in the TARPF facility. The first was a **100** ms pulse with a **30** kPa initial agent pressure, and the second was a 150 ms pulse with a **330** kPa pressure. The air velocity through the duct was 11 m/s. The ordinate is the peak-to-valley voltage normalized by the background value, which is proportional to the IR intensity incident on the detector. The abrupt decrease in the voltage is a result of the IR absorption by the HFC-125. The width in the dip in the voltage is slightly larger than the release time because of downstream mixing effects.

The plot of volume fraction versus time for the same experiments as Figure 9 is shown in Figure 10. The different pulse durations are apparent, although the step releases become significantly spread out. These two tests represent the conditions near the extremes that were tested. The test data indicate that a **0.005** volume fraction of HFC-**I25** can easily be detected and differentiated from background noise. Also, turbulent fluctuations on the order of 5 to 10 ms are clearly resolved due to a combination of the 2-kHz chopping frequency and the Fourier Transform high frequency filtering, For just air flowing past the periscope in the TARPF facility, the standard deviation normalized by the average of a 1 s sample of data was typically about **0.2%.** This is a substantial improvement over the DIRRACS I, which had a standard deviation of **23%** under the same conditions.

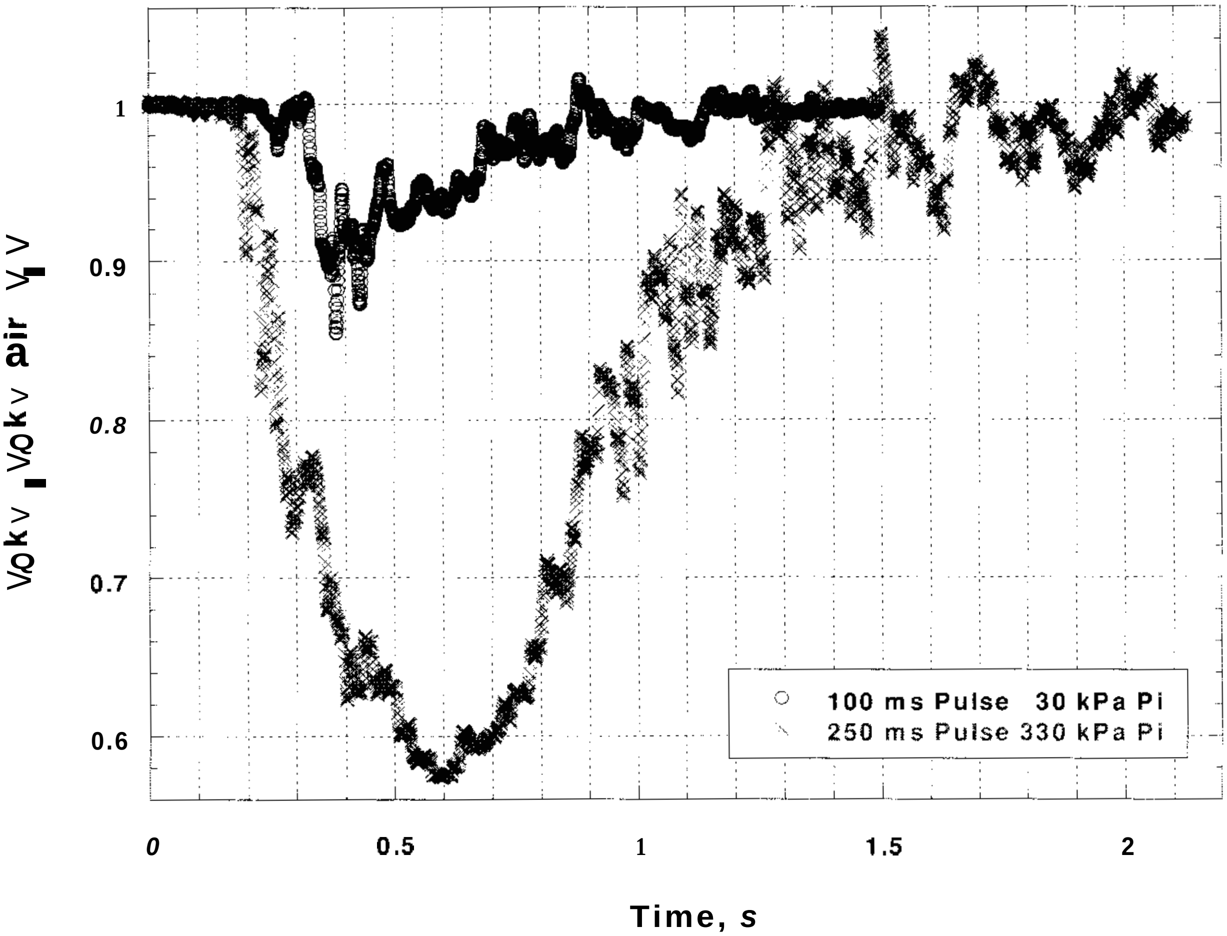

Figure 9. **A** plot of normalized peak-to-valley signals resulting from processing the raw signal from the DIRRACS II generated from two HFC125 releases with chopping frequency of 2 kHz and sampling frequency of 128 kHz.

CONCLUSIONS/FUTURE WORK

Preliminary testing of the DIRRACS II has generated results with significantly higher signal-to-noise ratio and faster time response than the previous model. The sensitivity and dynamic range have been increased as well. The success of the design changes has proven the concept and leads to the need for further improvements, which will enable the instrument to be used in full-scale agent release testing applications.

The next stage of development of the DIRRACS II is the assembly of a portable version to be deployed for field experiments. The current plan is to shrink the spaces between the optical components and, as possible, obtain more compact versions of the components. A housing will also be constructed to provide better electronic isolation as well as to protect the instrument from dust and debris generated in release tests. It is estimated that the footprint (excluding the periscope) of the new version will decrease from 48 x 58 cm to about 30 x 30 cm.

Concern was raised about the intrusiveness of the DIRRACS II due to the size of the periscope relative to practical test volumes and flows. The behavior of flows around the periscope geometry will be modeled, and a decision will be made as to whether the periscope needs to be

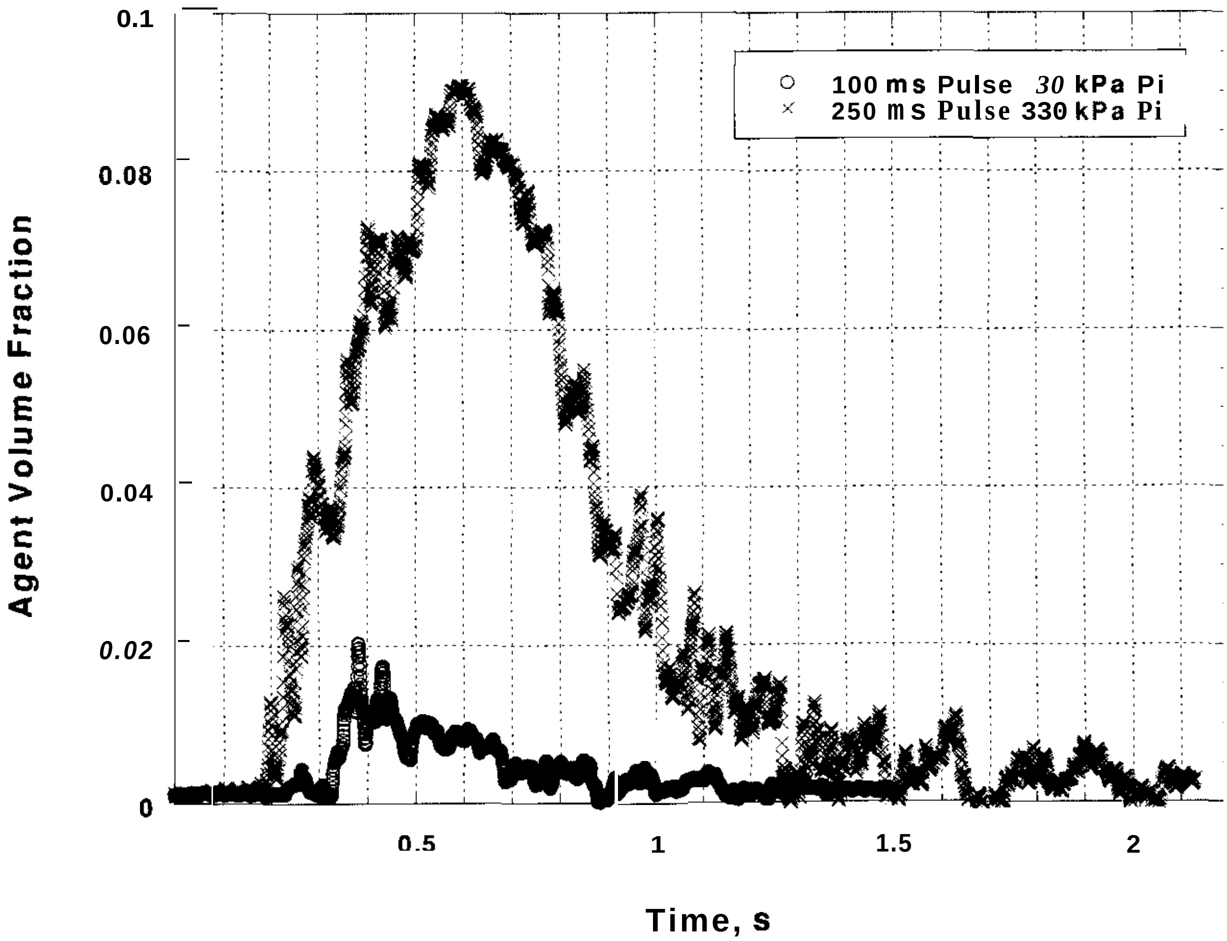

Figure 10. **A** plot of HFC 125 agent volume fraction versus time for two releases of HFC-125 in the TARPF facility.

redesigned to have a smaller profile that produces less obstruction. Another option to be considered is the use of fiber optics to access sampling locations more distant from the main body of the instrument.

The question of leakage of agent through the windows will be addressed in two ways. First, the window seals will be checked and, if necessary, improved. Second, the periscope will be fitted with plumbing for a low flow of air or nitrogen, which will create a slight, positive, internal pressure to prevent leakage of agent into the periscope.

The issue of variation of the calibrations from day to day will be investigated. The calibration facility will be checked carefully. Also, the flow-through calibration cell will be redesigned to minimize volume and thus the time response to a step change in concentration. An effort will be made to ensure that the final version of the DIRRACS will be used in conjunction with an HFC-125 calibration that is consistent and for which any variations are understood.

The performance of this instrument will be assessed based on tests planned for later this year at Aberdeen Proving Ground. The modified DIRRACS II technology has potential to be useful for transient agent concentration measurements due to its much improved signal quality and the elimination of temperature and flow effects.

ACKNOWLEDGMENTS

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