Development of a Portable Micro-environmental Cell for the Testing of Neutron Bubble Detectors in a Simulated Jet-Aircraft Environment

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Abstract

Neutron-sensitive bubble detectors were chosen as the primary detection tool to survey the dose equivalent received by aircrew exposed to natural radiation. As part of the qualification criterion, a novel micro-environmental cell was designed, assembled and tested. This apparatus is capable of simulating the climate, i.e., pressure, temperature and relative humidity, inside a jet aircraft while irradiating bubble detectors in-situ. The cell environment was manipulated using an on-line control and data acquisition system developed using LabView software.

Keywords: neutrons, bubble detectors, aircrew, data acquisition

1. Introduction

In 1990, the International Commission on Radiological Protection recommended that aircrew be considered occupationally exposed to natural background radiation [1]. In response to this recommendation, the Royal Military College of Canada - Collège militaire royal du Canada (RMC-CMR) and the Defence Research Establishment Ottawa - Centre de Recherche pour la Defence, Ottawa (DREO-CRDO) initiated a research program to investigate the natural radiation exposure to Canadian Forces (CF) pilots [2]. Since neutrons are a significant contributor to the total dose equivalent received by aircrew flying above 6 km (~ 20 000 ft) [3,4,5], the neutron-sensitive Bubble Detector (BD) was employed for the CF Pilot Survey (CFPS). This type of detector is particularly suitable since it is also portable (i.e., non-powered) and reusable.

A BD is a small test-tube sized instrument that records neutron events by the production of small bubbles that can be read with the naked eye and then manually reset (Figure 1). It is an ideal instrument for this application since it has a good response to neutrons in the 1-100 Mev region where a significant contribution of the neutron dose equivalent is received by aircrew [4,5].

Models of the BD response function have been developed by others [6,7]. In general, bubble formation is initiated by a liquid-gas phase transition that is thought to occur when sufficient energy is deposited (e.g., by charged particle recoil) in a nucleation site. The models indicate that for bubble nucleation compounds such as Freon, the minimum energy required to expand the bubble beyond the critical radius is a function of liquid vaporization, the temperature-dependent bubble surface formation and expansion against the pressure of the site liquid. Furthermore, the manufacturer, Bubble Technology Industries, acknowledges that the elasticity of the bubble's host medium and, therefore, detector lifetime is affected by water loss from the unit [8].

Based on the available bubble formation models, it was suggested that the BD response could be affected by normal aircraft cabin depressurization, temperature fluctuations and changes in the relative humidity. Consequently, a micro-environmental cell was developed to allow in-situ irradiation of three BDs with real-time variations in temperature, pressure and relative humidity as controlled by an on-line data acquisition system. This paper describes the micro-environmental cell, on-line data acquisition system and test results indicating that the chosen model of detector (BD-PND) is suitable for measurement of the in-flight neutron dose equivalent received by aircrew.

2. Micro-environmental Cell Design

The environmental cell is shown in Figure 2 along and with its associated hardware connections in Figure 3. The cell differs from conventional environmental chambers which typically vary temperature in a large refrigerator-sized room. Furthermore, no chamber exists which allows detector irradiation while simultaneously controlling the temperature, pressure and relative humidity in real-time. Control of the environmental parameters was facilitated with an on-line data acquisition system based upon the LabView software platform [9]. The cell and software are designed to operate from 4°C to 35°C, at a pressure between 1 to 0.5 atmospheres, over a wide range of relative humidity (20% to 90% RH).

To accommodate simultaneous neutron irradiation, part of the acrylic side-wall of the cell was cut away to allow for the insertion of three Aluminum tube holders for the BDs. Since Aluminum has a smaller neutron scattering cross-section at high energy (~ 1 MeV) than that of hydrogenated plastics, such as acrylic, use of aluminum in a portion of the cell wall will therefore minimize neutron scattering effects in the line-of-sight between the neutron source and the detectors (Figure 2) [5,10].

For these tests, an AmBe source was chosen for the energetic neutron field (~ 5 MeV) to allow the examination of trends in BD behaviour with respect to changes to these parameters in the cabin air. Furthermore, if desired, these trends could be scaled by a conversion factor to provide comparable in-flight measurements [5]. In all cases, BDs were calibrated by the manufacturer, Bubble Technology Industries (BTI), using an AmBe neutron source, NCRP-38 neutron dose equivalent conversion units and at one atmosphere of pressure [8]. This calibration is generally suitable for most terrestrial applications, such as for personnel working at nuclear power plants. Before conducting these experiments, the RMC-CMR AmBe source strength was verified. The neutron fluence spectrum is shown in Figure 4. Note that this source has a higher fluence in the lower energy bins which may be associated with neutron scattering from the room surroundings. However, the overall measured spectral shape is in good agreement with an internationally recognized standard spectrum [11].

The temperature (T) and percent relative humidity (%RH) were controlled using the input signals from a Digital Thermo-Hygrometer probe at the cell base. Thermocouples were placed at the top of the cell and a thermocouple was inserted in the gel of a de-capitated BD. The de-capitated BD was kept in close proximity to the other BDs under test. The probe temperature measurement was considered accurate to 1°C and its calibration is traceable to the National Institute of Standards and Technology. The thermocouples were separately calibrated in both an ice-water and a boiling water bath. Both the thermocouple and probe readings were typically within 1°C to 2°C of each other.

Temperature stability was maintained in the cell through air recirculating supported by a small whisper fan at the base of the cell. Active temperature control was maintained using an on-line resistive heater and a manually controlled water cooling jacket. The water cooling jacket is a plastic cylinder fitted to the outside of the cell where a 0.125" space is created to allow cooling water to flow around the outside cylinder wall.

The percent relative humidity (% RH) was adjusted using moistened air (i.e., ambient air bubbled though a water vessel) and by passing "ultra zero gas" (air at approximately 1% moisture) through the cell (Figure 2). The relative humidity measurement by the probe was quoted by the manufacturer to be within 3% at 25°C over the range of interest of 20% to 90% RH.

Cell pressure was maintained by balancing the negative pressure from a vacuum-belt (and baffle) assembly against the positive pressure generated through fine adjustments in the %RH and small leaks in the pressure vessel. A millivolt output transducer, located at the air in-take to the cell base, monitored the absolute pressure in the cell that was input to the software controller. Prior to use, the pressure was calibrated using an absolute pressure gauge that was attached to the air in-take line.

3. Climate Control Software

The cell climate was controlled through an Apple Macintosh IIfx computer fitted with various National Instruments boards and components (Table 1). The computer control algorithm was written using the object-oriented programming language LabView 3 [9]. Since LabView is based upon a graphic-user-interface (GUI) technology, the virtual control and feedback instruments (and underlying subroutines) are represented as icons that the code developer can link together in order to pass information through the software. The subroutines generate a digital output signal which opens or closes the solenoids that, in-turn, affect the cell parameters (T, % RH and P). Feedback sensors (e.g., probes, thermocouples) are used to determine the parameter state which is compared to pre-set values as defined by the user and to within the code developers specified tolerance for those parameters.

3.1 Main Software Program

The user interface for the main software controller (i.e., the virtual instrument for the cell) is shown in Figure 5. As depicted, the display of the virtual instruments for temperature, % RH and pressure have user pre-set values that can be input either graphically or digitally. For instance, a computer mouse can be used to choose the level of "mercury" in a thermometer graphic or a value can be typed via the keyboard into the digital display . The two chart recorders display the real-time output of the measured temperature from the thermocouples, the pressure from the pressure transducer and % RH as registered by the probe. For quick reference, a simulated Light Emitting Diode (LED) cluster (i.e., a series of coloured circles on the screen) provides a visual reference that gives the open or close status of the various solenoids. Previous testing verified that it was sufficient to scan input (I) signals at 1 scan s^{-1} (from external probes) to maintain the appropriate environmental conditions in the cell. The device number and channel range indicator are specific to the type of boards being used. The "STOP ACQUISITION" button was added to terminate the program on user demand without having to resort to disabling the software internally.

Figure 6 shows the main software diagram. All routines beginning with the letters AI are pre-packaged subroutines that are available within the LabView platform. The "AI CONFIG" and "AI START" virtual instruments (VIs) (or subroutines) are used by the computer to initiate the data acquisition (e.g., scan rate, continuous acquisition). The "AI READ" VI forwards the feedback signals to the "Volts to Units" VI and the "Volts to T/F" VI, which were written specifically for the environment cell (Section 3.2). The output of the "Volts to Units" VI is displayed on chart recorders (on the user interface) and is also written to a data spread sheet using the "WRITE FILE" VI. The latter is initiated by the "OPEN/CREATE/REPLACE FILE" VI and terminated by the "CLOSE FILE" VI. The file utilities are also pre-written subroutines for use in LABVIEW. The LED cluster (on the user interface) is fed via a digital word output from the "Volts to T/F" VI that is configured, written and read by the various "PORT" VIs from LabView.

3.2 Input Signal Conversion and Output Control Software

The two application specific subroutines within the main program were written utilizing LabView functions. They are the "Volts to Units" and "Volts to T/F" (or "Volts to Boolean Logic") VIs (Figures 7 and 8, respectively). The function of the "Volts to Units" VI is to bring the input signal from the acquisition board and to parcel the data into temperature readings from the thermocouples (elements 0,1,2) and the temperature probe. The relative humidity signal (element 4) and the pressure signal (element 5) are also converted. Elements 0 through 5 are then passed to a vertical array routine which is transposed and fed out as processed data. If the input signal is absent, the array is set to TRUE, and this information is forwarded through the software to the user.

The output of the "Volts to T/F" VI is designed to control the solid state relays that open and close the solenoids which, in turn, produce changes within the environment of the cell. This action is accomplished by passing the processed data, from the "Volts to Units" VI, as a voltage signal that is parcelled by element-number to data-manipulation subroutines. For instance, temperature measurements from thermocouple elements 0 and 1 are averaged and passed to a comparator circuit along with the user pre-set temperature setting (i.e., ± 5%). The comparator circuit then decides if the temperature input is greater or less than the pre-set value and outputs the last two digits of the digital word which is used to control the solenoids. The relative humidity and pressure signals are handled in a similar fashion. The output of the "Volts to T/F" VI is, in turn, displayed as changes from red to green coloured dots located on the LED cluster as shown on the user interface. As with all VIs, there is an attached error handler to indicate when/if a logic, or programming, error has occurred.

4. Written Software Output

Since our experiments were designed to test the effect of an aircraft climate on the BD response, it was important that a real-time record of the variations in T, P and % RH (as displayed on the charts in Section 3) was maintained. This record also serves as a means to judge the ability of the software to control the system parameters within the specified tolerances. From our experience, the only time limitation in running the software controller arose when the written file exceeded the available hard disk storage space. For instance, a typical 5-hour conditioning period for the BD produced a text file of 630 kB.

An example of the trace produced by the T, P and % RH control is given in Figures 9 and 10 for a pre-set user condition of 28°C, 65% atmospheric pressure (i.e., 10 000 ft equivalent aircraft altitude) and 60% RH. As shown in Figure 9, the Digital Probe (which is located near the resistive heater at the cell base) typically recorded a slightly higher temperature than the temperature sampled using a thermocouple located at the top of the cell. The measured temperature of the BD gel (of the de-capitated detector) was maintained within 1°C over 500 s. As seen in Figure 10, the time taken for the P and % RH to stabilize is much less than that for temperature. The fluctuation in pressure is on the order of 70 s which could be further reduced if the tolerance was reduced from ± 5%. However, this reduction would mean that the vacuum pump system would have to operate over a longer period of time. Unfortunately, this action would also result in a premature draining of the dry air tank which, in turn, would increase the experimental costs.

5. BD Experiment

5.1 BD In-cell test Procedure

Tests were conducted to determine how the sensitivity of the BD-PND detector would be affected by a different climate. The BD-PND is unique in that it is a temperature-compensated device where its stated sensitivity is averaged from 20 to 37 °C, with a ± 20% standard deviation. For completeness, however, the testing also included the BD-100R model which is not temperature-compensated. The latter detector has a long history of use and was used in earlier aircrew studies [12].

The test parameter chosen for this investigation is the BD sensitivity which is calculated by:

$$Sensitivity = \frac{N_B}{DE} \qquad (1)$$

where N_B is the number of bubbles and DE is the dose equivalent. In the present environmental cell work, the DE was derived from an AmBe source with strength, S_n, such that

$$DE = \frac{S_n * t * C_F}{4\pi r^2} \qquad (2)$$

where t is time, C_F is a constant (= 3.7 x 10^{-4} μSv cm^2) for an AmBe spectrum and the NCRP-38 recommendation (as used by the manufacturer), and r is the distance from the source to the detector. Since the uncertainties in N_B and DE are independent and random, the total uncertainty for a measurement was calculated by summing in quadrature the original fractional uncertainties of the variables used in the analysis [13].

The environment cell experimental procedure was carried out in three steps:

1. The temperatures of the BDs were stabilised by equilibrating them in a temperature controlled (± 5%) water bath.

II. The BDs were then conditioned in a simulated aircraft-cabin environment for five hours.

III. Finally, the BDs were irradiated with neutrons from an AmBe source.

The range in the cabin air temperature (T), pressure (P) and percent relative humidity (% RH) was varied to provide similar conditions as experienced in-flight. These parameters were varied as 21, 28 or 36 °C in temperature, either 1000 ft or 10 000 ft in equivalent aircraft altitude (i.e., cabin air pressure) and 25 or 60% percent relative humidity. The conditioning time was chosen so as to simulate a typical domestic flight in Canada from Toronto to Vancouver.

Once conditioned, the third step involved the irradiation of BDs inside the cell in a 10 μSv free-field neutron dose equivalent from a (2.1 ± 0.2) x 10^{11} Bq AmBe neutron source (in NCRP-38 dose equivalent units). Neutrons from this source result from the radioactive decay of ^{241}Am, where alpha particles (~ 5.48 MeV) interact with a beryllium target such that

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + {}^{1}n + 5.708Me \quad (3)$$

This process generates both gamma rays and neutrons. The gamma rays have energies of 4.4 MeV and/or 7.7 MeV and originate from the decay of the carbon nucleus as in Eq (3), and from capture neutron interactions (n,γ) in the shielding material. The neutron spectrum from this source has three groups, around 1, 4 and 8 MeV, with an fluence-weighted energy at 4.73 MeV [11].

5.2. Analysis and Discussion of Environmental Cell Study on BDs

For the BD-PND detector, the analysis of the effect of aircraft climate on BDs was extended to include statistical inference techniques (e.g., Analysis of Variance (ANOVA)) [14]. The latter approach was used to understand the systematic effect of an independent factor, or the combined (i.e., overall) effect of multiple factors, on the outcome of an experiment. In this case, temperature and pressure are independent factors, but there may also be a cross-interaction between temperature and pressure which could affect the detector sensitivity. Furthermore, since the % RH did not affect the detector sensitivity (for the allotted conditioning time), the analysis was confined to an examination of only the effect of temperature and pressure on detector sensitivity.

As shown in Figure 11, the temperature-compensated detector (BD-PND) exhibits scatter with temperature which is within the ± 20% uncertainty as stated by the manufacturer. In comparison, the reported trend for the un-compensated BD-100R [6] shows a monotonically increasing function with temperature at ground level (i.e., 1 atm pressure). Furthermore, the data for a 3 km (10 000 ft) equivalent altitude are within the spread of the ground level data (i.e., within the ± 20% uncertainty for the BD-PND detector).

To indicate the effect of pressure, the ratio of the response at ground level to that at 3 km (10 000 ft) is shown as a function of temperature in Figure 12. The uncertainty in the data again reflects the spread due to temperature compensation effects. A ratio of unity represents the situation where pressure and temperature would have no effect on the detector response. From Figure 12, the data set is seen to be more or less equally distributed about the unity line, suggesting that pressure does not systematically bias the in-flight measurements.

Since the BD-PND is the primary survey tool for the Canadian Forces study [5], a two-way ANOVA study was also conducted. For this analysis, the two-way ANOVA was designed to examine repeated environment cell measurements with variations in both temperature and pressure. As in the case of a one-way ANOVA, the sum of squares and mean squares were calculated from which the F-statistics and associated p-values could be determined. The details of this calculation are given in reference 5. As shown in Table 2, the F-statistic for temperature exceeded the critical F value; therefore, the hypothesis that temperature is insignificant must be rejected. In comparison, the F-statistics for the effect of pressure alone and for the interaction of temperature with pressure are less than the critical F value. Therefore, pressure alone and the cross-interaction between temperature and pressure are insignificant. In other words, the effect of pressure on the BD-PND sensitivity can be neglected while temperature is an important parameter which must be considered. In-flight studies also confirmed the results from the environmental cell work [15].

6. Conclusions

A micro-environmental cell has been assembled for use in the long-term conditioning of neutron-sensitive bubble detectors for a simulation of the environmental conditions in a jet aircraft. The climate (i.e., pressure, temperature and percent relative humidity) experienced by the detectors was controlled using an on-line data acquisition system that could be varied by the user in real-time. Variations in the cell parameters were examined and the cell climate has been shown to stabilize within a few minutes. The experimental results of this study confirmed that routine passenger cabin depressurisation does not affect the sensitivity of the BD-PND model of bubble detector (to within experimental uncertainty). As expected, long term conditioning tests indicated that temperature does affect the BD sensitivity; however, the temperature compensation mechanism of the BD-PND model is sufficient to provide reliable data (within ± 20%) over the temperature range of interest.

7. Acknowledgements

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8. References

[1] International Commission on Radiological Protection, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publications 60, Pergamon Press, Oxford (1991).

[2] P. Tume, B.J. Lewis, L.G.I. Bennett, T. Cousins, T.A. Jones, B.E. Hoffarth, J.R. Brisson, P. Goldhagen, A. Cavallo, A.Van Steveninck, M. Reginatto, P. Shebell, F. Hajnal, T.J. Jamieson and F.J. LeMay, "Assessment of the Cosmic Radiation Field at Jet Altitudes," Proceedings of the American Nuclear Society Topical Meeting on Radiation Protection and Shielding, April 21-25, No. Falmouth, Massachusetts, (1996).

[3] D. Regulla and J. David, "Measurements of Cosmic Radiation on board Luftansa Aircraft on the Major Intercontinental Flight Routes," Radiat. Prot. Dosim. 48 (1993) 65.

[4] G. Reitz, K. Schnuer and K. Shaw eds., Radiation Exposure of Civil Aircrew, Radiat. Prot. Dosim. 48 (1993) 1.

[5] P. Tume, "The Use and Characterization of Bubble Detectors for the Assessment of the Occupational Exposure of Canadian Forces Pilots," Ph.D. Thesis, Department of Chemistry and Chemical Engineering, Royal Military College of Canada-Collège militaire royal du Canada, May (1996).

[6] M.J. Harper, "Calculation of the Recoil Ion Effective Track Length in Neutron-Radiation-Induced Nucleation," Nucl. Sci. Eng. 114 (1993) 118.

[7] M.A. Buckner, "Improving Neutron Dosimetry Using Bubble Detector Technology," Oak Ridge National Laboratory, TM-11916, February. (1993).

[8] R. Noulty, personal communication, Bubble Technology Industries, Chalk River, On. Canada, (1994).

[9] National Instruments Corporation, LabVIEW™ for Macintosh, Users Guide Part Number 320590-01, August (1993).

[10] S. Glasstone and A. Sesonske, Nuclear Reactor Engineering, Van Nostrand Reinhold Company, New York (1981).

[11] G. Burger and R.B. Schwartz eds., Guidelines on Calibration of Neutron Measuring Devices. International Atomic Energy Agency Publications, Tech. Rep. No. 285, Austria, August (1988).

[12] B.J. Lewis, R. Kosierb, T. Cousins, D.F. Hudson and G. Guéry, "Measurements of Neutron Radiation Exposure of Commercial Airline Pilots Using Bubble Detectors," Nucl. Technol. 106, (1994) 373.

[13] J.R. Taylor, An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, University Science Books, Mill Valley, California (1982).

[14] G.E.P. Box, W.G. Hunter and J.S. Hunter, Statistics for Experimenters, Wiley, New York (1978).

[15] P. Tume, B.J. Lewis, L.G.I. Bennett, "Characterisation of Neutron-Sensitive Bubble Detectors for Application in the Measurement of Jet Aircrew Exposure to Natural Background Radiation," Nucl. Instr. Meth. Phys. Res.A. 406 (1998) 153.

Table 1: **Various Boards and Peripherals Required for the Environmental Cell**

Component	Remark
NB-MIO-16L-9	Multifunction analogue and digital input/output board used for analogue input.
NB-DIO-24 (24 bit)	Parallel digital input/output board; used for output control.
24 Channel SSR Backplane	Solid state relay series backplane which was connected to the DIO-24 board.
SSR-OAC-5 Output Modules	Used to control output solenoid switching.
5B Series 16-Channel Backplane	Connected to MIO-16L board.
5B Series Type T Linearized Thermocouple Modules	Used to linearize temperature signals from Type T Thermocouples and an adjusted signal (using a variable resistor) from the pressure transducer.

Table 2: **ANOVA for Computing the Effect of Temperature and Pressure on BD-PND Sensitivity**

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*F*	*p-value*	*Critical F*
Temperature	3325.969	2	1662.985	9.469625	0.00093	3.402832
Pressure	257.4085	1	257.4085	1.465776	0.237802	4.259675
Temperature*Pressure	182.3282	2	91.16408	0.519121	0.601574	3.402832
Within	4214.7	24	175.6125			
Total	7980.406	29				

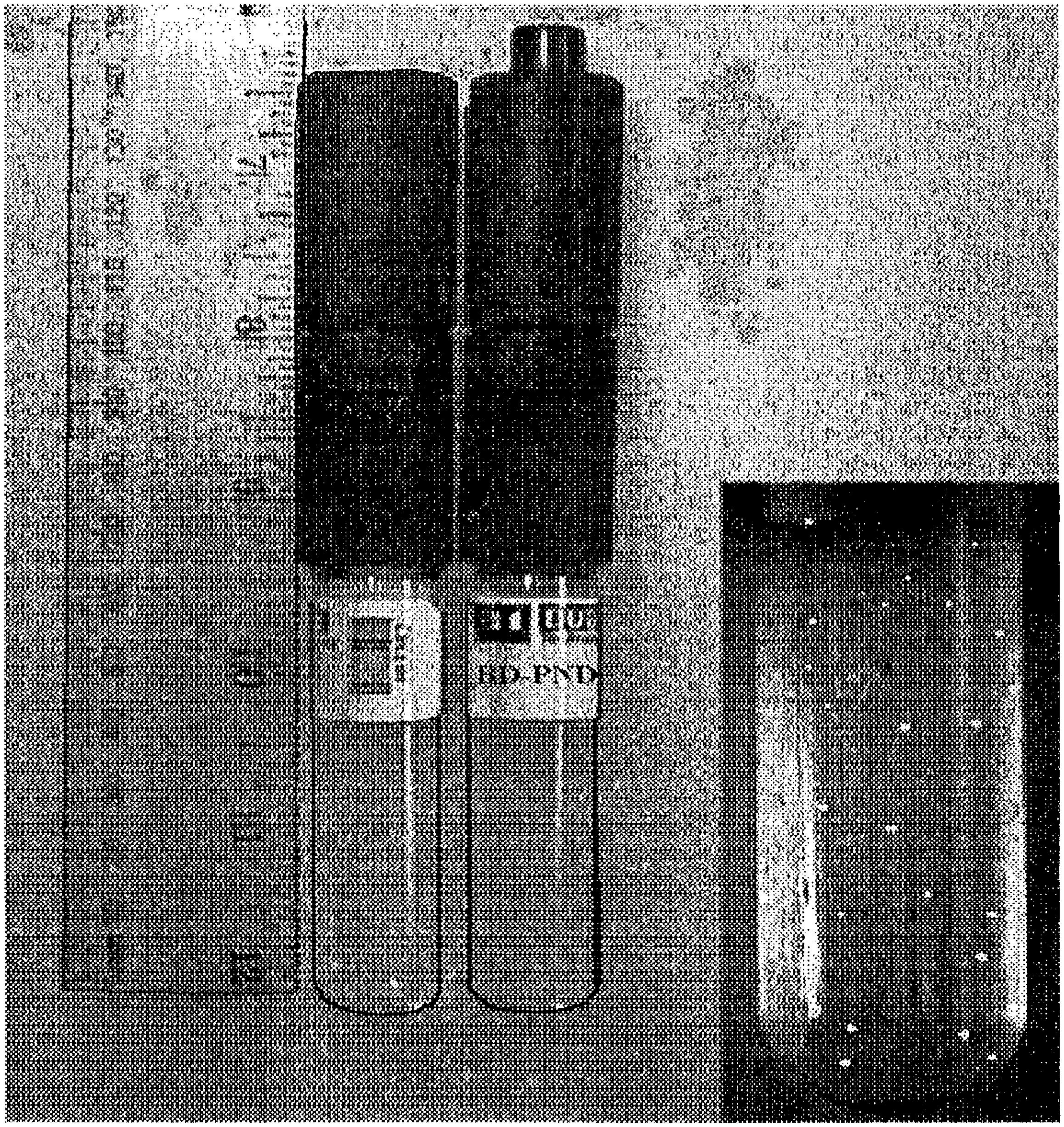

Figure 1. BD-PND model of a neutron-sensitive bubble detector.

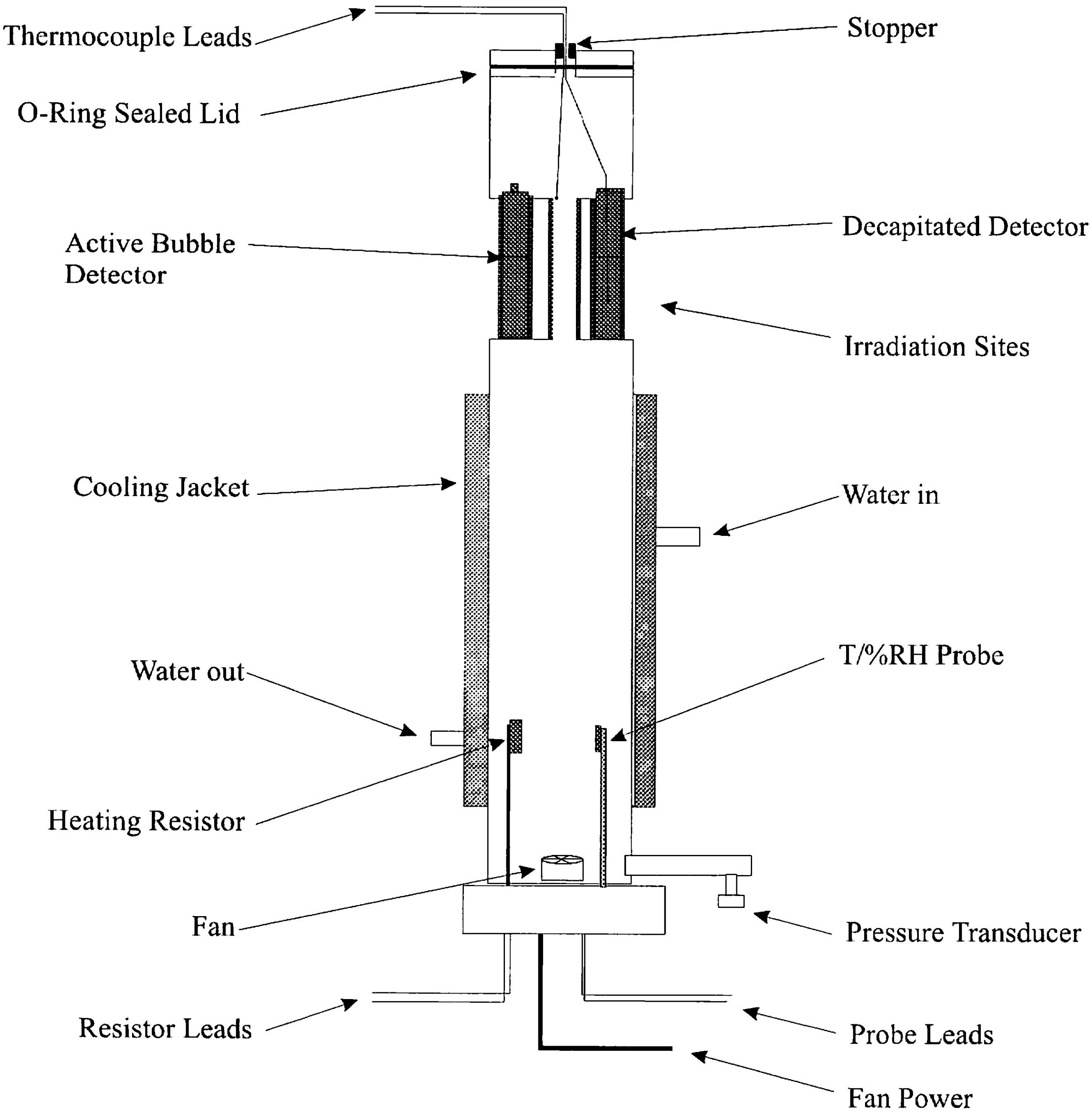

Figure 2. Schematic diagram of the environmental cell.

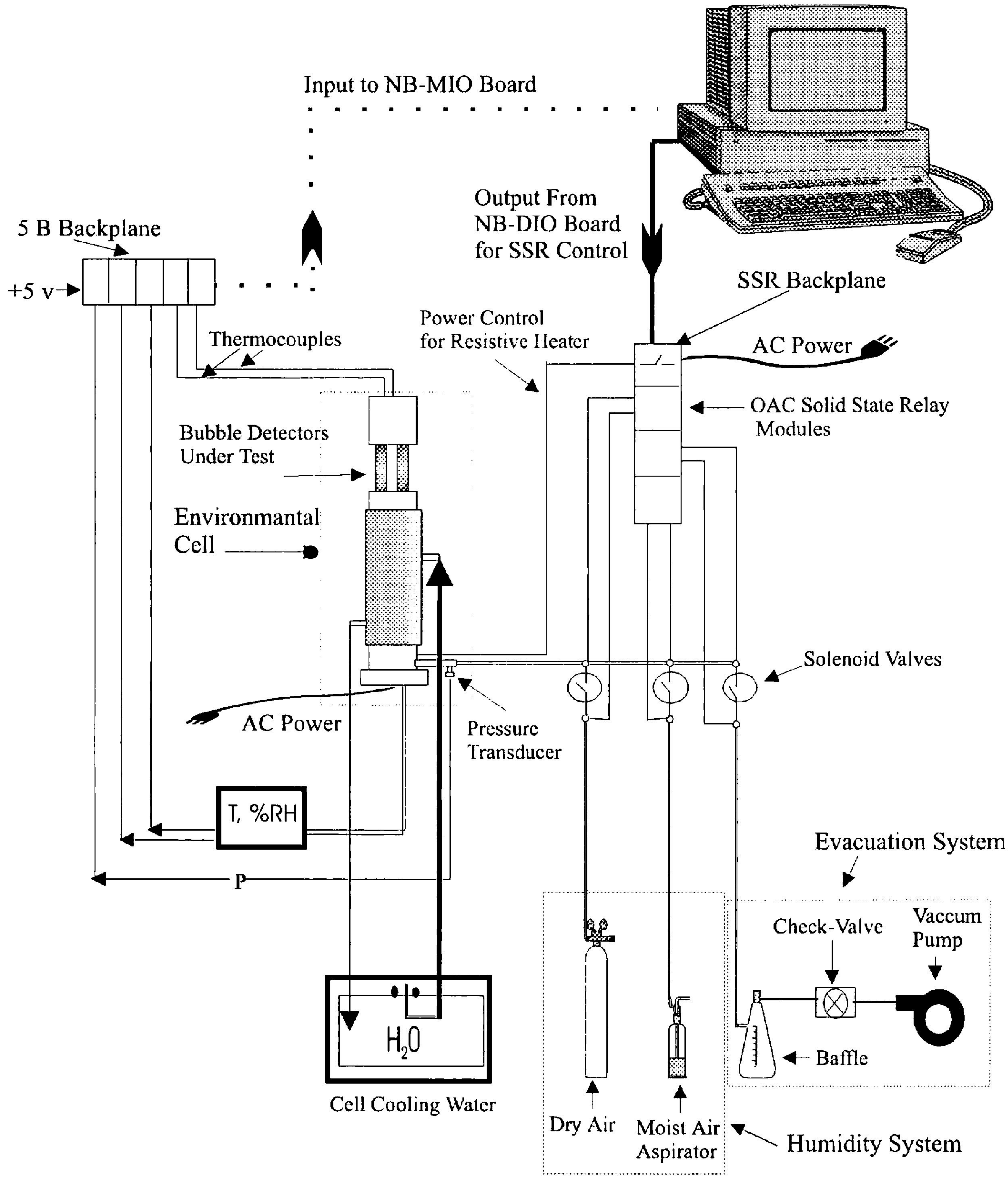

Figure 3. Schematic diagram of the environmental cell showing its associated hardware connections.

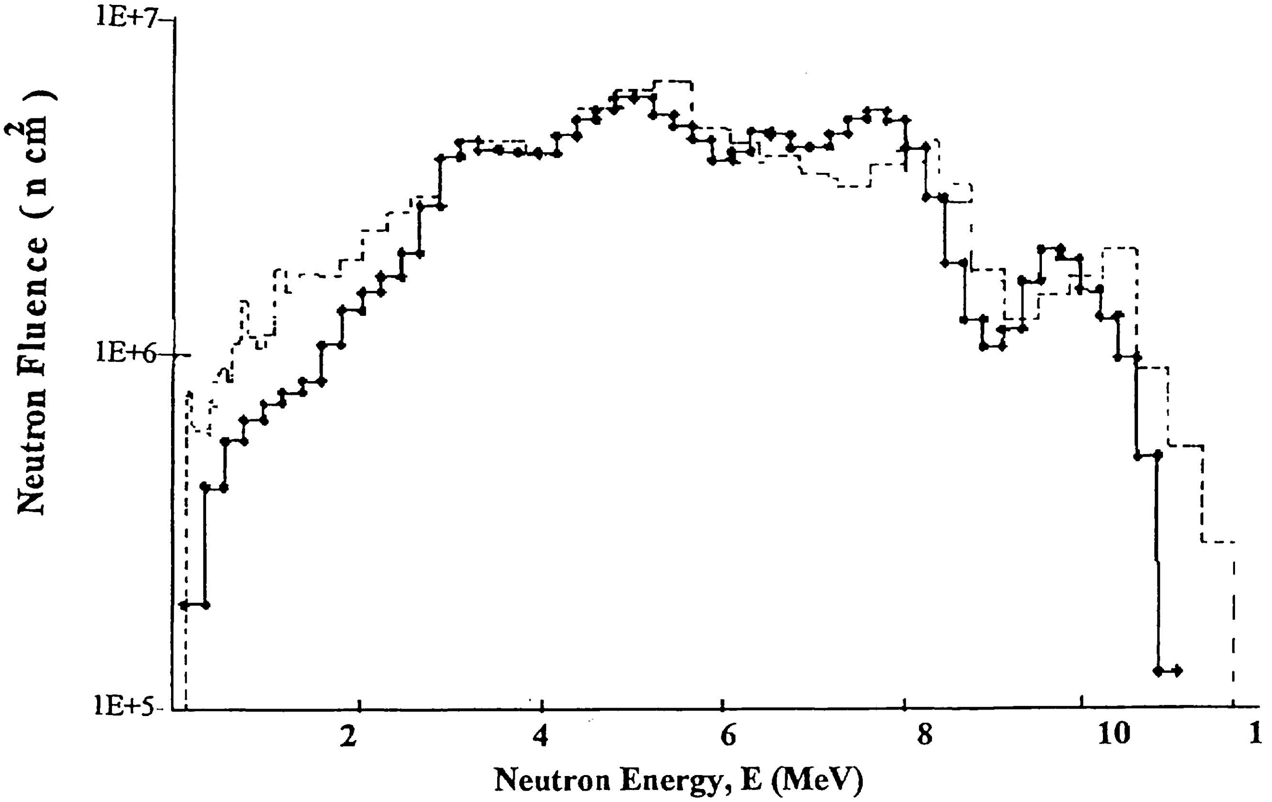

Figure 4. Neutron spectral measurements for the RMC-CMR AmBe source. The lines represent the following data sets: (---) = RMC-CMR AmBe source spectrum and (-•-)= 6 Ci AmBe reference source spectrum [1].

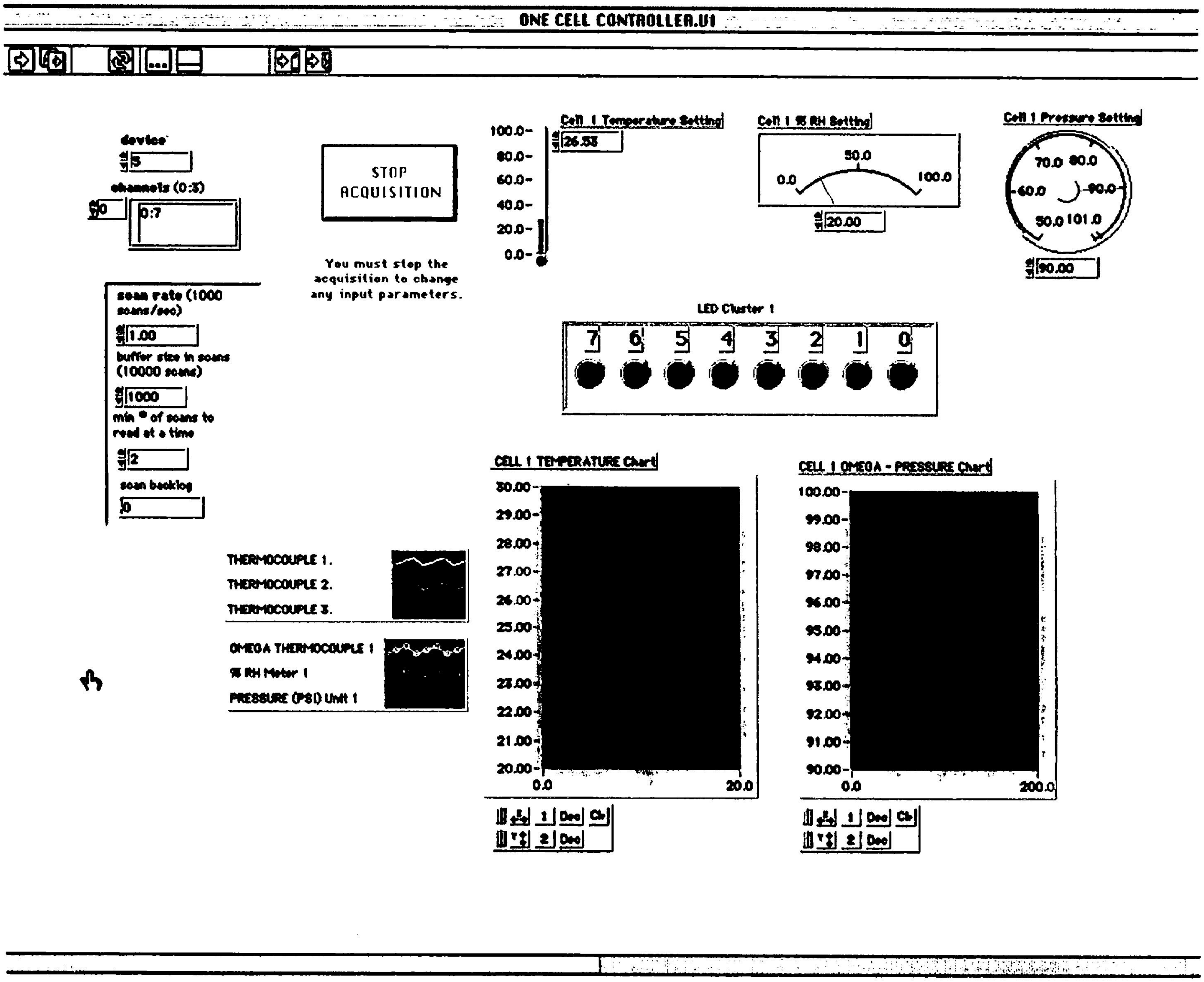

Figure 5. User interface for the main control software for the environment cell.

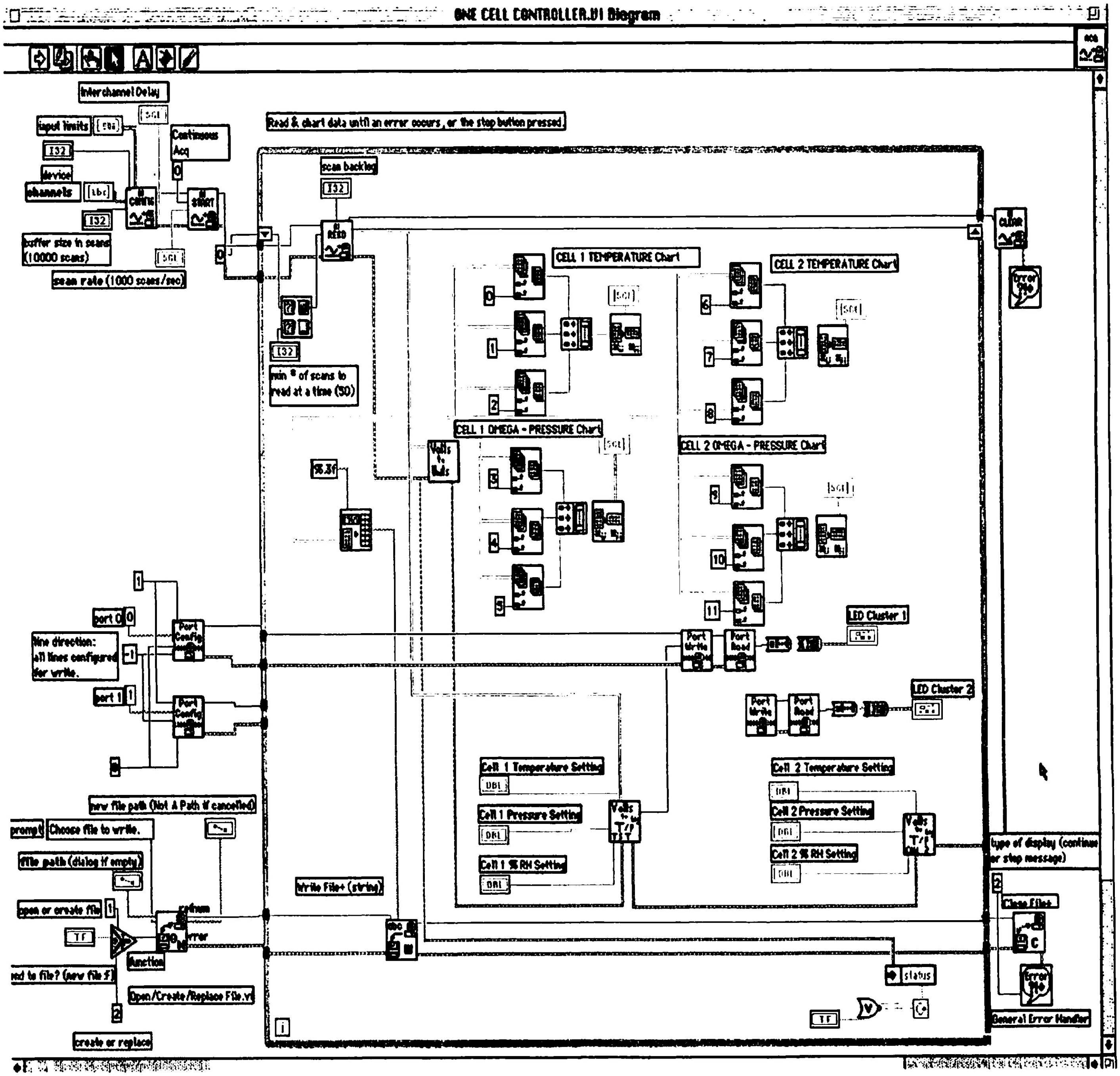

Figure 6. Diagram of the main control softrware as developed using LabView.

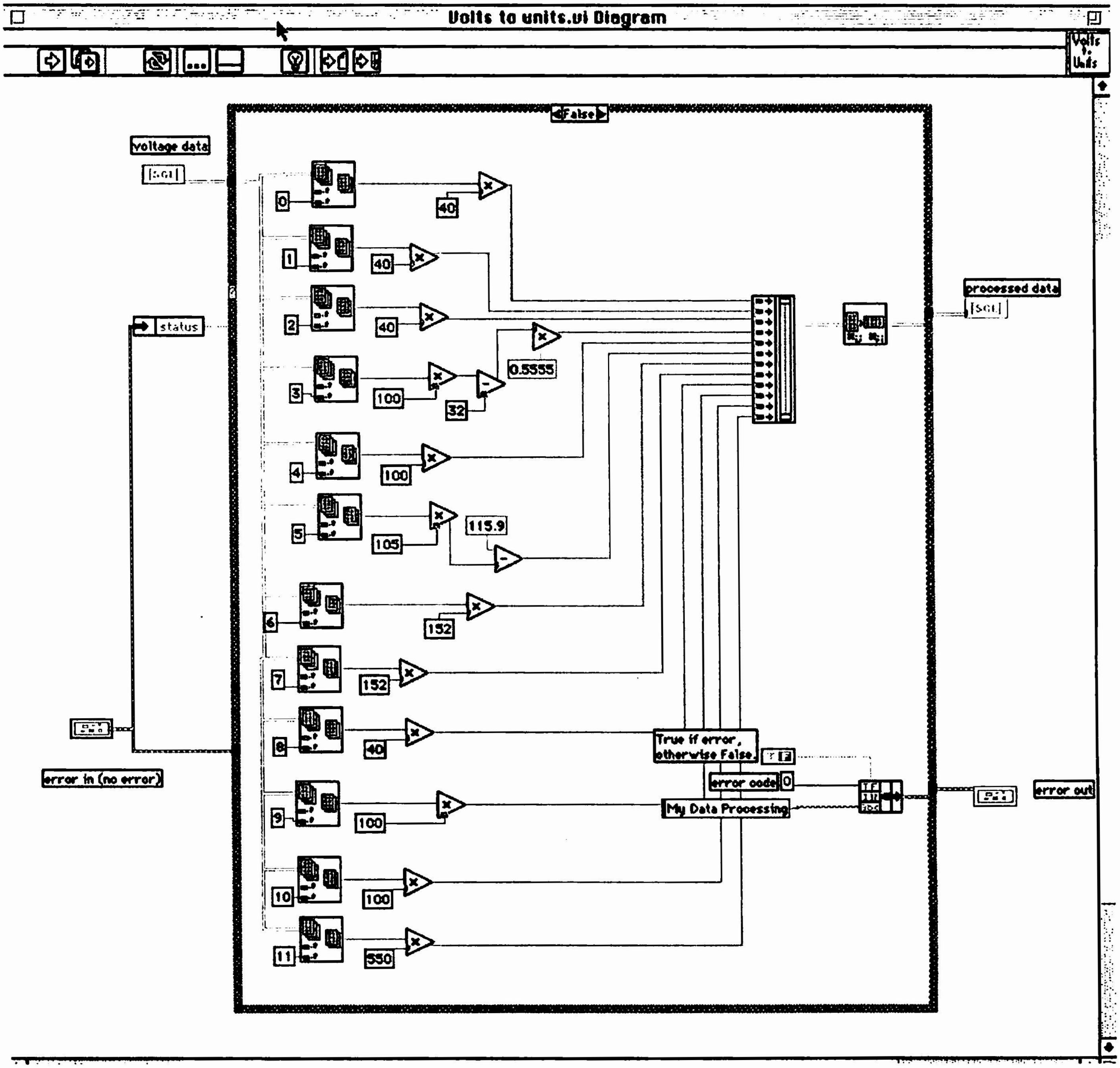

Figure 7. Labview software diagram for the "Volts to Units" instrument.

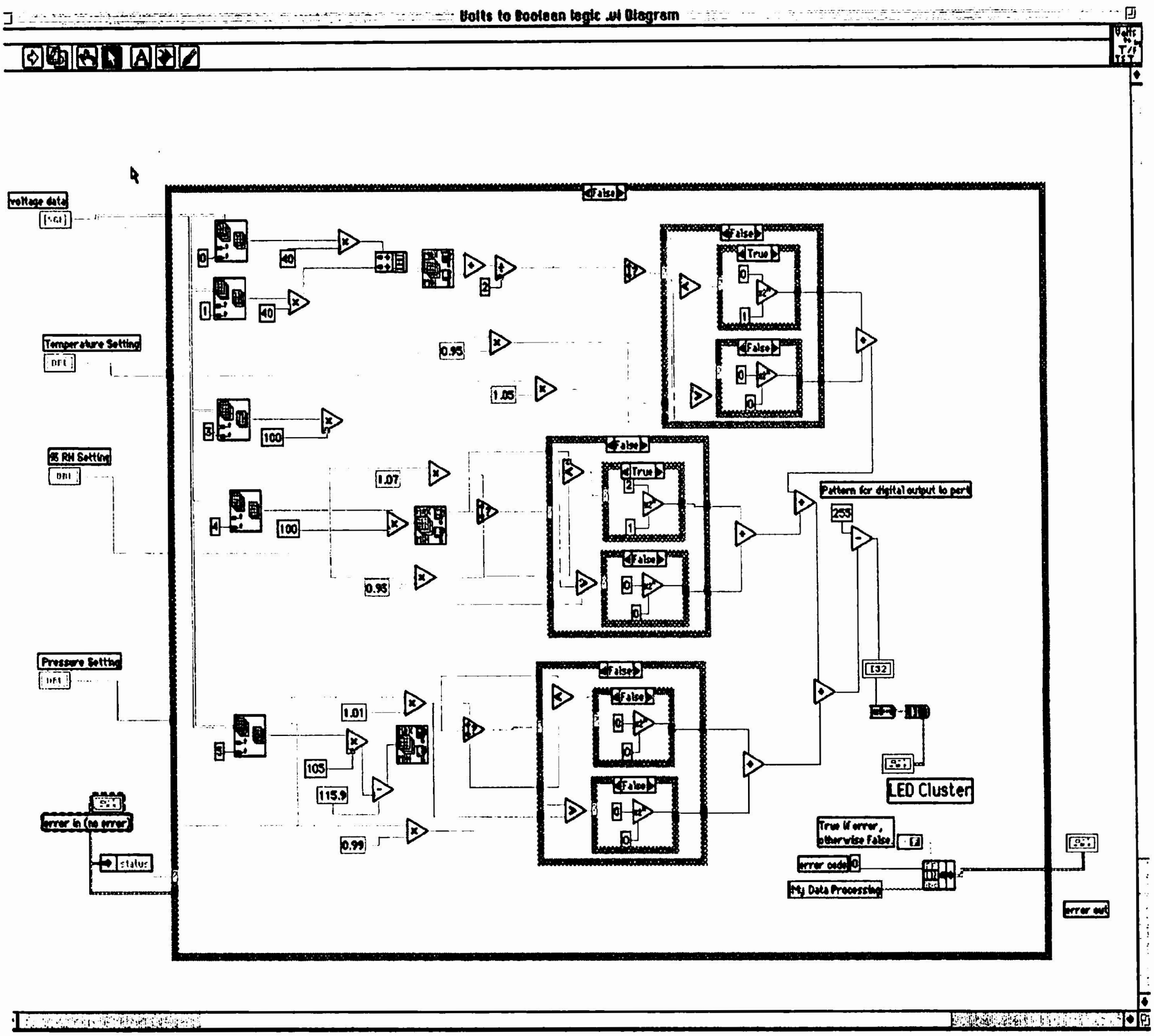

Figure 8. LabView software diagram for the Volts to T/F (or Volts to Boolean Logic) virtual instrument.

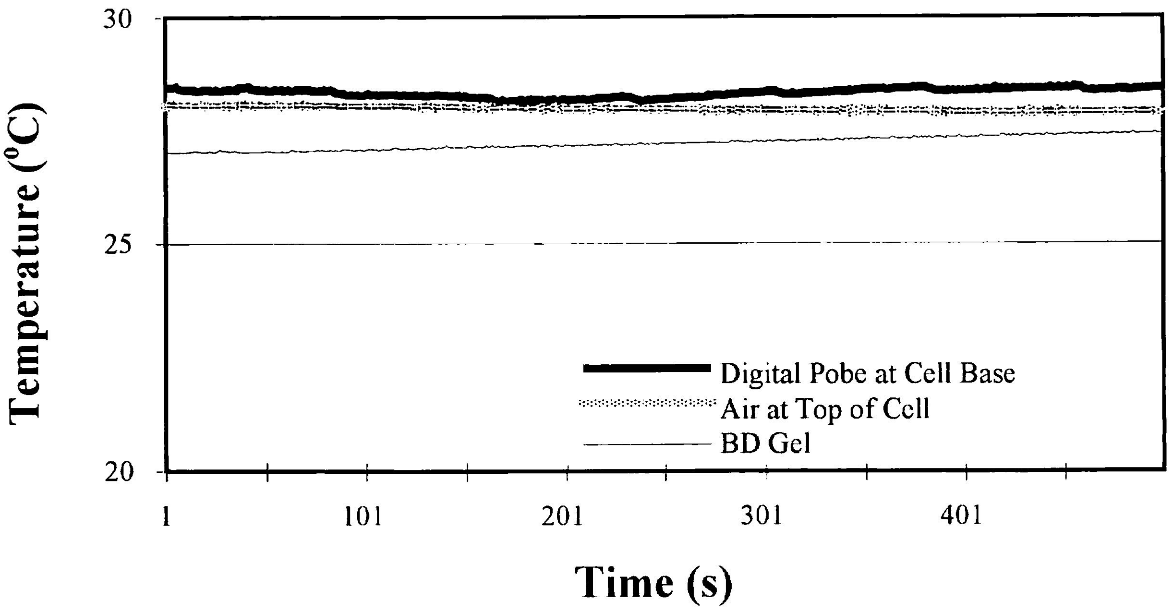

Figure 9. Real-time temperature measurements at different cell locations and inside the BD gel during conditioning.

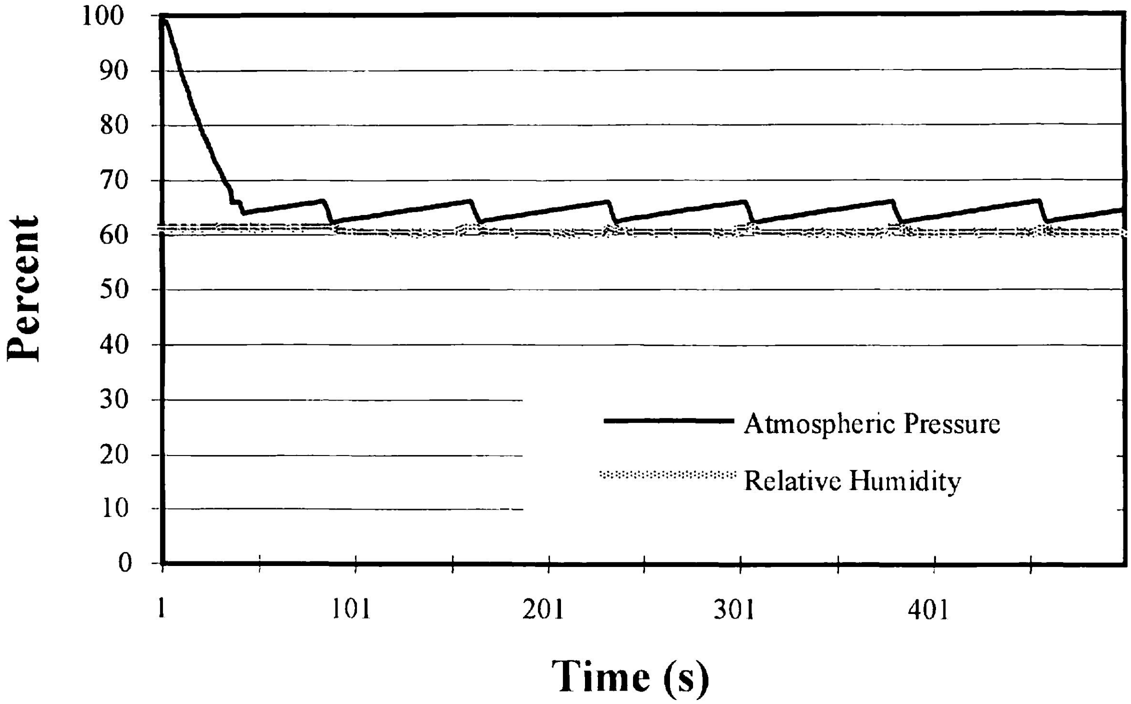

Figure 10. Real-time percent variation in cell pressure (as referenced to one atmosphere) and relative humidity.

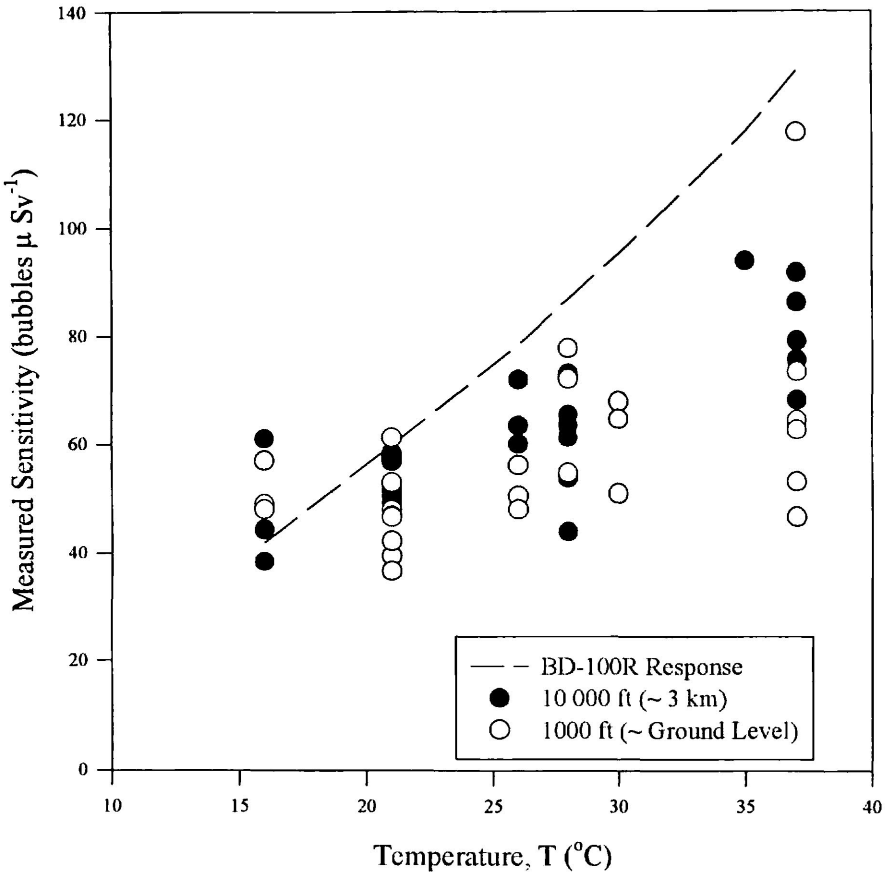

Figure 11. Measured sensitivity of BD-PNDs at ground level and 10 000 ft (~ 3km) equivalent cabin pressure for a range in temperature.

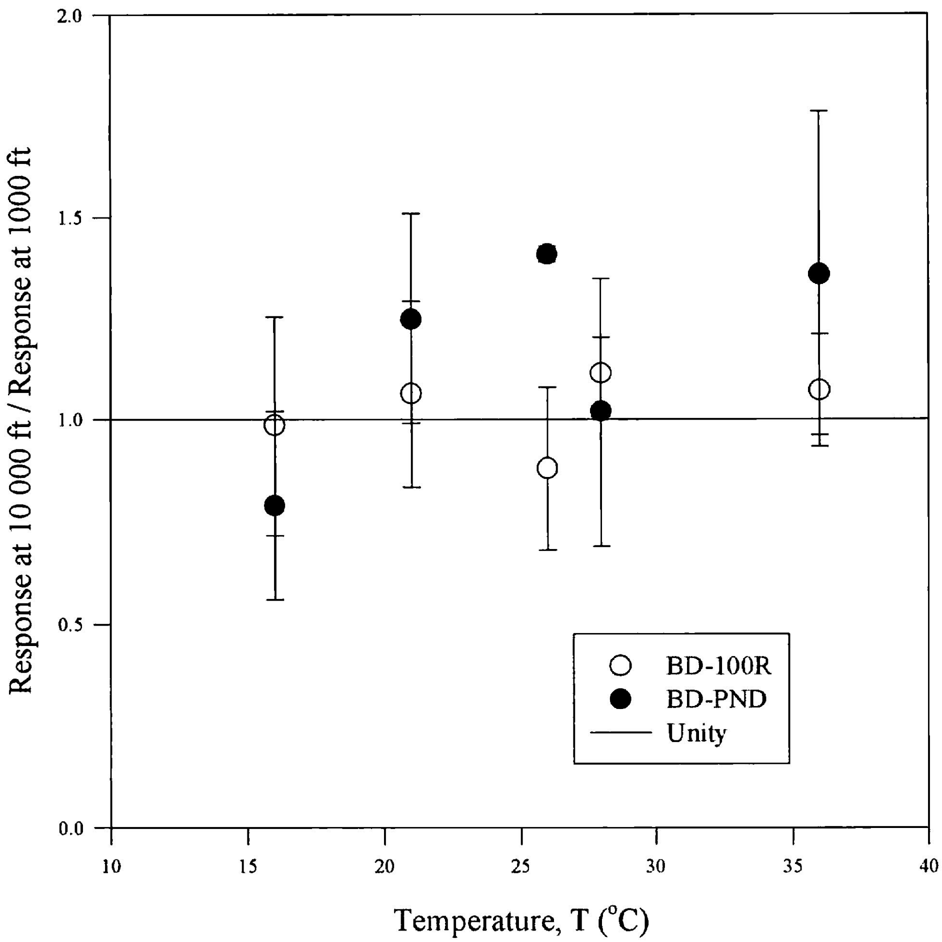

Figure 12. Ratio of the responses of the BD-PND and BD-100R at 10 000 ft (~ 3km) equivalent cabin pressure to the responses at ground level as a function of temperature.