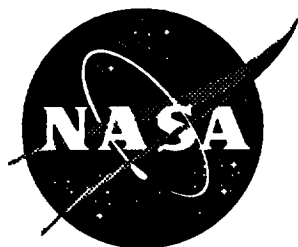


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A HYBRID ELECTRONICALLY SCANNED PRESSURE MODULE FOR CRYOGENIC ENVIRONMENTS

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SUMMARY

A miniature multichannel pressure measurement module measuring 5.5 cm in length by 2.5 cm in width by 3 cm in height was developed with accuracy to $\pm 0.1\%$ F.S., independent of the tunnel operating temperature. This instrumentation has been designed for use in the NASA 0.3 Cryogenic Tunnel and in the National Transonic Facility (NTF) operational environments. The prototype module, intended for installation in cryogenic wind tunnel models, consists of 16 silicon pressure sensing microsensors, each with an onboard temperature sensor, arranged in two parallel rows, with two CMOS multiplexing dice, and an instrumentation amplifier in a DIP package. The selection of custom circuitry designed for cold performance and the careful choice of packaging materials with low thermal expansion coefficients and materials properties favorable for cryogenic applications have contributed to reliability and repeatability. The experimental module has been thermally cycled dozens of times during cryogenic pressure calibrations and tunnel runs. Subsequent pressure calibrations performed at 90-day intervals over the past year all fall within a $\pm 0.1\%$ overall error window for the combined errors of thermally induced offset drift and sensitivity.

INTRODUCTION

There are currently 17 cryogenic wind tunnels (ref. 1) (see Appendix A) in operation worldwide. Most operate in a temperature range of -190 C to $+70\text{ C}$. The coldest temperature falls approximately 140 deg. C below the lowest mil-spec temperature for the performance rating of electronic components. Most electronic integrated circuits will cease to function at cryogenic temperatures due to limitations in materials properties. The failure mechanism may be due to mechanical contraction of conductors such as a track separation on the substrate or the sensor chip interconnect metallization. At some temperature below -55 C , many integrated circuits cease to function due to the effects of charge carrier freezeout which results from insufficient dopant levels which in the case of sensors, will manifest as a severe drift and nonrepeatability in calibration. Another limiting factor may be due to the use of elastomeric materials for die or substrate attachment that tend to become rigid and brittle at cryogenic temperatures.

CRYOGENIC PRESSURE SENSING DICE

Each of the silicon pressure sensors employed in the present instrument has a square profile 2.54 millimeter on each side and is 0.3 millimeter high (see fig. 1). There are four diffused (boron) resistance bridge elements, two acting in compression and two acting in tension, integral to the etched membrane used for sensing pressure. There is also one additional bridge element on the die rim, insensitive to pressure, which provides a temperature measurement of each sensor die used for temperature compensation. In order for the silicon pressure sensing dice to operate properly below -100 C , it is necessary that the dopant impurity level be on the order of $1\text{E}20$ atoms of boron per cubic centimeter (see fig. 2) (ref. 2). This dopant level ensures that the sensors do not suffer from charge carrier freezeout due to low charge carrier mobility. The piezoresistive pressure sensors are influenced by the thermal offset and sensitivity shifts

(see fig. 3) (ref. 3) in the bridge resistors, and heavily influenced by mechanical mounting effects between the die and substrate due to temperature-dependent differences in coefficient of thermal expansion between the die and substrate materials, all of which contribute to the sensor overall thermal offset drift. Plots of individual sensors mounted by the preferred method of field-assisted bonding (ref. 4) to a Pyrex 7740 substrate yield smoothly varying, repeatable offset (see fig. 4) and sensitivity curves (see fig. 5).

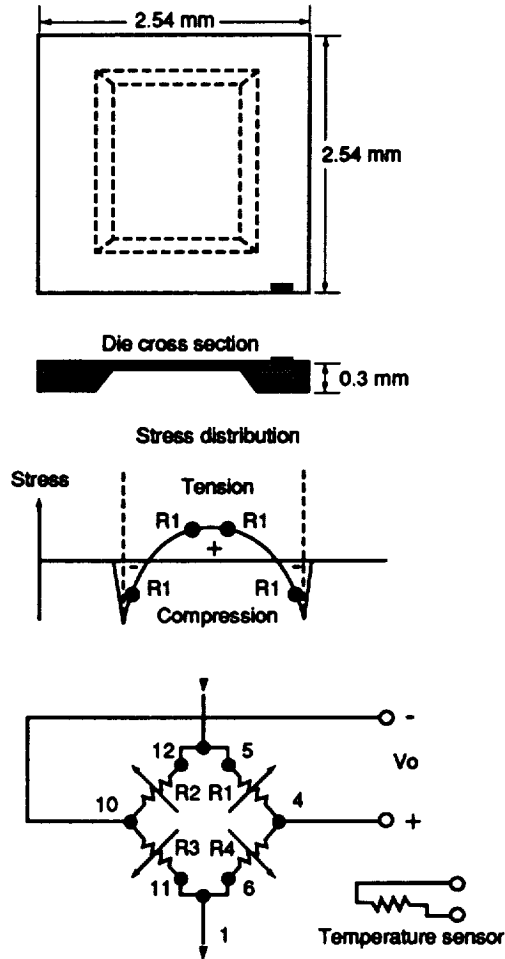


Fig. 1. The top view of the die shows the location of the port and the placement of the resistors. The effective circuit is the typical wheatstone bridge configuration.

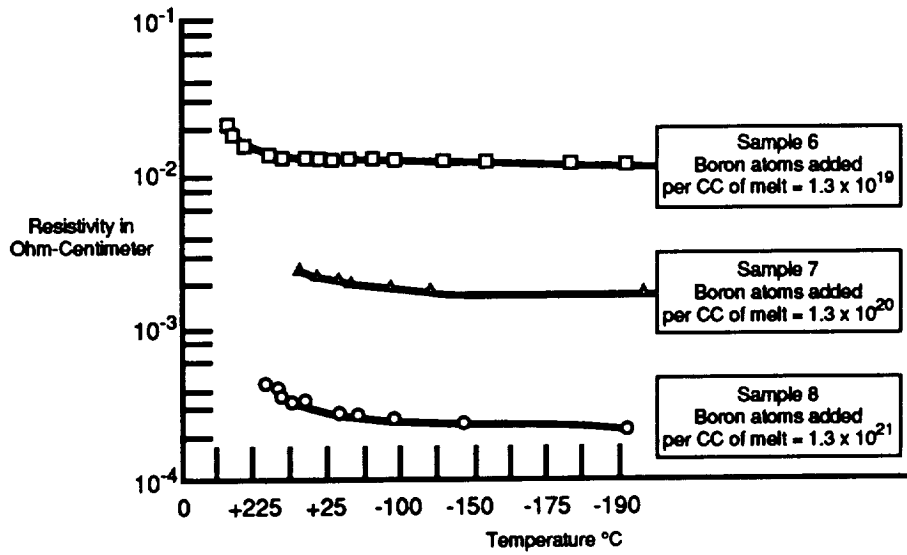


Fig. 2. Charge carrier density vs. temperature.

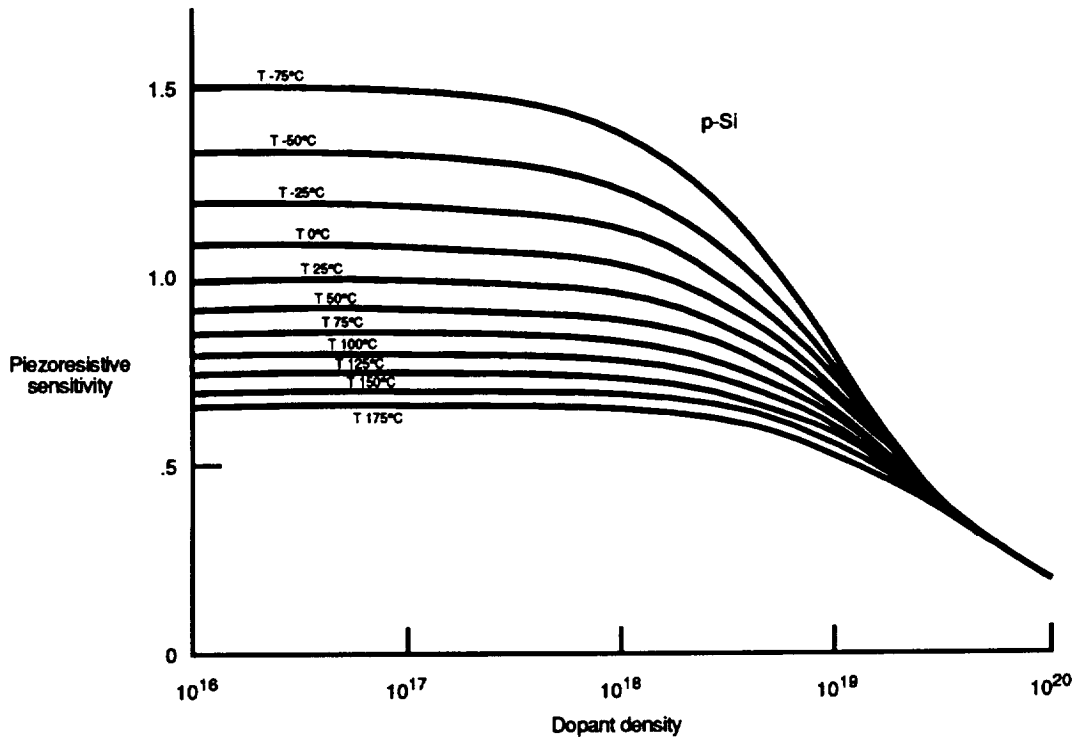


Fig. 3. Piezoresistance coefficient vs. temperature.

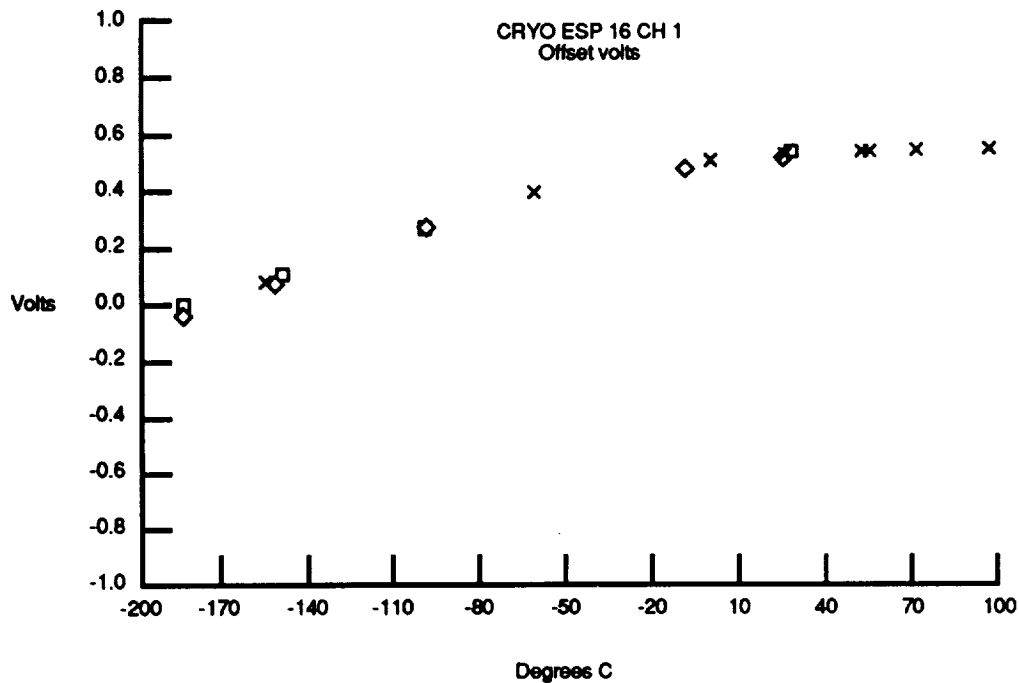


Fig. 4. Channel 1 offset hysteresis plot, each symbol is a different thermal cycle.

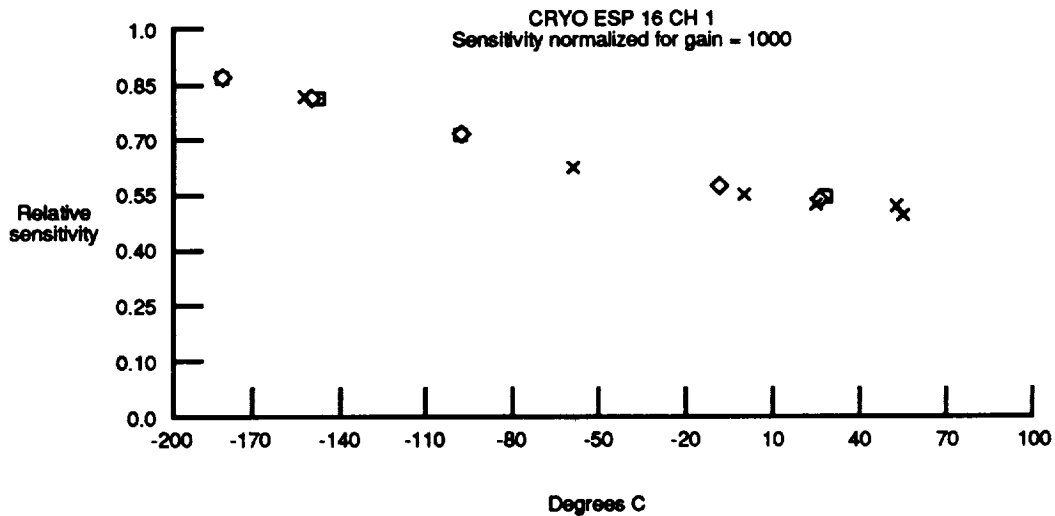


Fig. 5. Channel 1 sensitivity hysteresis plot, each symbol is a different thermal cycle.

CIRCUITRY FOR CRYOGENICS APPLICATIONS

The ideal pressure sensing geometry for model pressure instrumentation would consist of a custom VLSI array of sensors with onboard multiplexing, amplification, and the means for laser trimmed thermal compensation delivered from the silicon foundry, ready for integration in a module. Excellent single-channel sensors are currently available, and these same dice can be assembled in a hybrid package in such a way as to achieve essentially the same results. The

method of joining the sensor dice rigidly to the substrate without using epoxy die attach materials has resulted in an improvement in the thermal repeatability of these sensors at room temperature and particularly at cryogenic temperatures. First, the important step was development of annealed, metallized, and drilled Pyrex substrates in the precise geometry and the development of precise fixturing to hold the sensors and substrate together so joining could be accomplished by field-assisted bonding. Cryogenic tests were conducted to determine multiplexer switching and instrumentation amplifier gain performance (see figs. 6 and 7). The tests indicated amplifier linearity and repeatability without thermal distortion by the signal conditioning system.

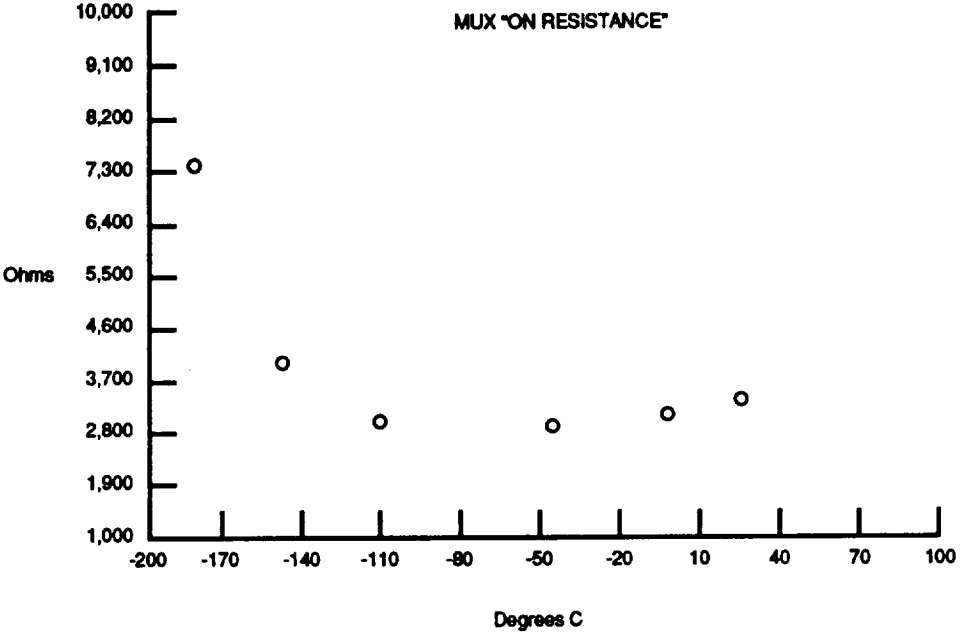


Fig. 6. Multiplexer "on" resistance vs. temperature.

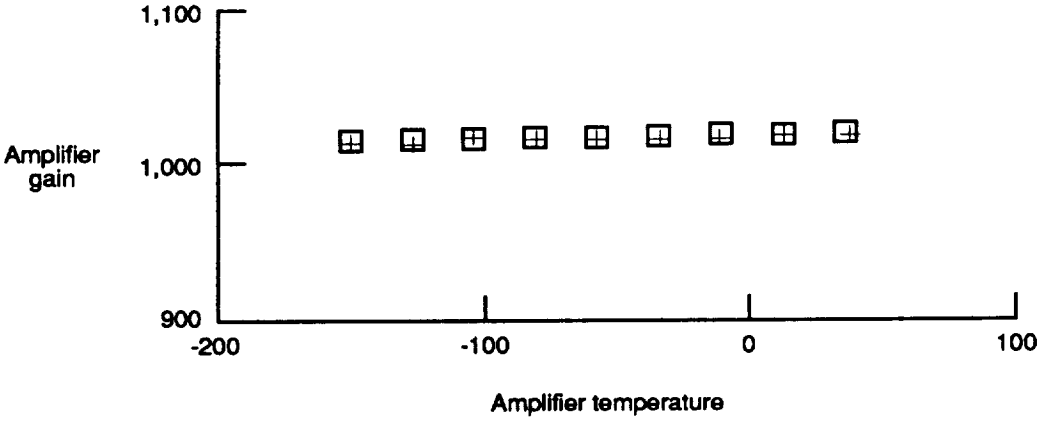


Fig. 7. Instrumentation amplifier gain vs. temperature.

MATERIALS AND PROCESSES FOR CRYOGENIC TEMPERATURES

The requirement for structural integrity in electronic packaging is met by the use of metallic materials with low coefficients of thermal expansion such as Kovar. The coefficient of thermal expansion of Pyrex 7740 glass matches that of silicon well enough to tolerate thermal cycling in properly annealed substrates (ref. 6). The Pyrex substrate is first metallized with Titanium/Tungsten for the adhesion layer, and then a 1.5-micrometer layer of gold is deposited for good conductivity. The circuitry pattern is then etched to produce low-resistance, high-quality tracks. The silicon pressure sensors are bonded to the metallized substrate by field-assisted thermal bonding. This process, otherwise referred to as Mallory bonding by the electronics industry, takes place at 375 C. It is performed under high vacuum with an applied field strength of 1E6 volts per meter on the silicon sensors Pyrex interface. After bonding, the sensor substrate is then attached to the tubing plate using a thin sheet of thermosetting polyamide film (see fig. 8). The modified polyamide material remains flexible at - 196 C and provides a compliant bond between these two surfaces. The electrical interconnection of the sensor circuitry to the substrate is made using a thermo-ultrasonic wedge-ball bonding machine with substrate heating applied.

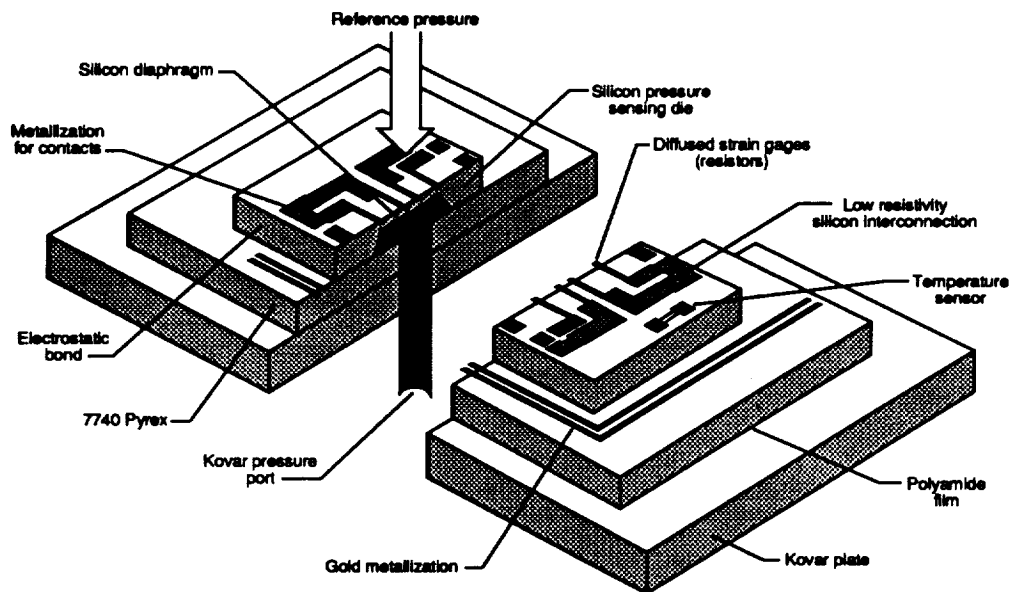


Fig. 8. The pressure sensors are bonded to a metallized Pyrex substrate. One of the sensors is shown in this cutaway drawing.

PC INTERFACE AND A/D CONVERSION

A modified commercially available 12-bit data acquisition interface card is used to scan the pressure inputs. Since the instrumentation module is equipped with its own instrumentation amplifier and multiplexing circuitry, the interface could be streamlined by connecting the instrumentation amplifier output directly to the sample-and-hold input on the PC card with coaxial cable (see fig. 9). This improves the signal-to-noise ratio since all millivolt level signal leads are contained within the instrument module and are just a few centimeters in length. Similarly, the multiplexing switches are also within the module. Linking the address and enable lines from the remote module to the timing circuitry on the PC card via line drivers and receivers ensures quiet

taken are first stored to RAM, then saved to diskette and displayed as real-time engineering units on the monitor. The data rate and sample time interval for a data record is pre-set by the scanning software parameters. The menu-driven software provides for access to data files for storage, recall of sensor calibration files, and for real-time display.

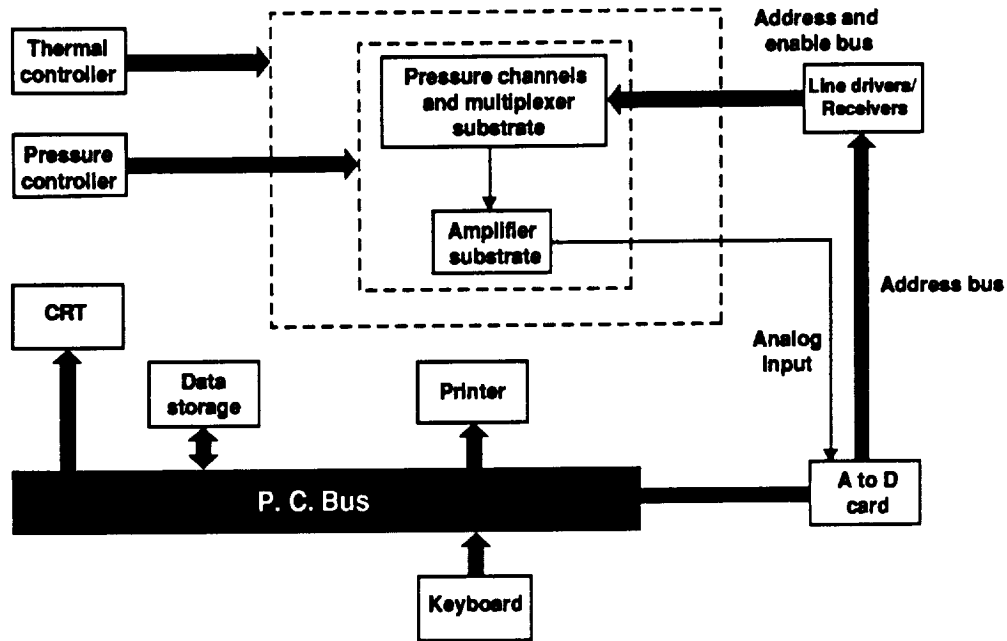


Fig. 9. PC interface with pressure/temperature calibration system.

CALIBRATION SYSTEM

A system capable of controlling temperatures from -184 C to +220 C and pressures from 0 to 344.74 Kpa was used to calibrate the sensing module. A thermocouple accurate to within ± 0.1 deg. C of reading was used to calibrate the temperature of sensors within the module.

DISCUSSION OF DATA

Due to the parallel circuit of the sensor supply bus which necessitates constant voltage excitation, and sensor resistance which decreases as temperature decreases, the sensors are more sensitive with decreasing temperature (see fig. 5). The hysteresis, however, is less than the resolution of the encoder. The offset plot for channel 1 (see fig. 4) shows this for several thermal cycles; a different symbol is used for each thermal cycle. The comparison of offset variation from channels 1-8 is shown in figure 10. The sensitivity plots for channels 1-8 reveal how sensors in one multiplexer row vary in sensitivity (see fig. 11).

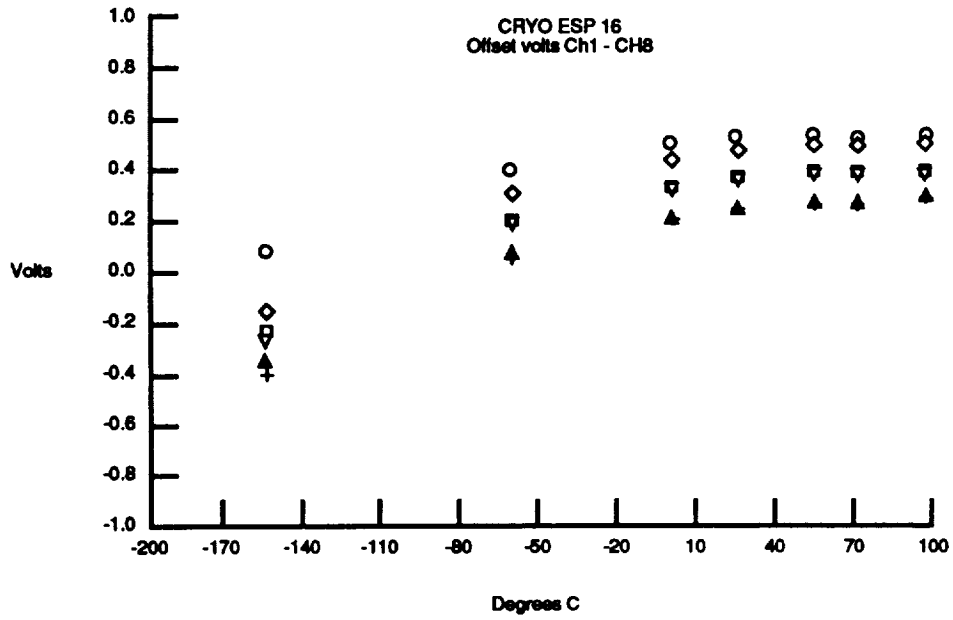


Fig. 10. Channel 1-8 raw offset plots vs. temperature.

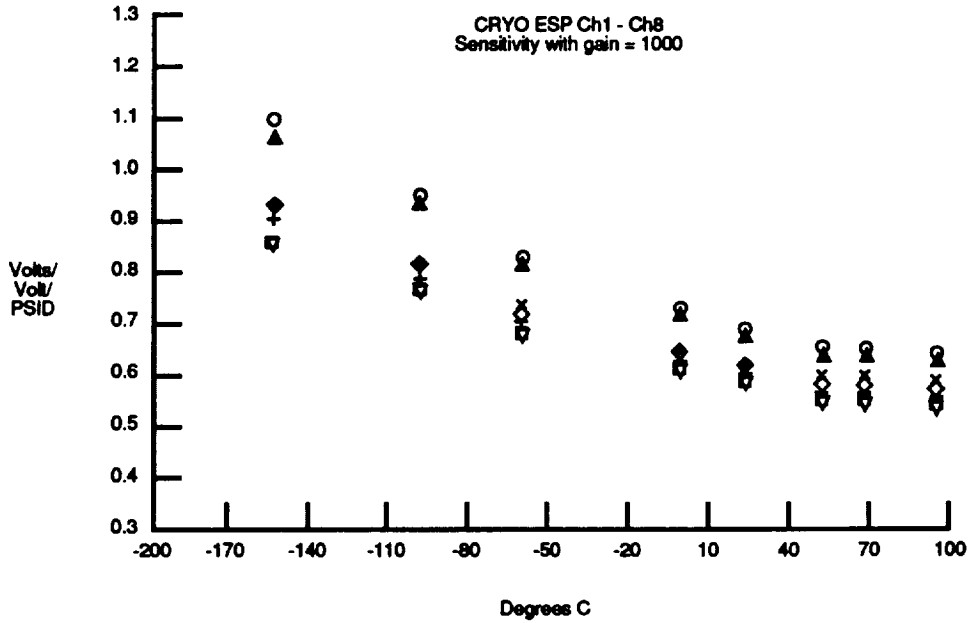


Fig. 11. Channel 1-8 raw sensitivity.

ERROR ANALYSIS

The measurement of calibration pressure is accurate to within $\pm 0.01\%$ of full scale (344.74 Kpa). The set point resolution is 3.447 Pa. Helium is used as the calibration gas. The uncertainty of the temperature controller is ± 0.5 deg. C with a temperature deviation of ± 0.1 deg. C after stabilization. The repeatability following a temperature reset is ± 0.25 deg. C. The uncertainty of the analog-to-digital conversion system used to scan the pressure module is $\pm 0.01\%$ F.S. The overall error of the multichannel pressure sensing system, based on several pressure and temperature calibrations repeated within 1 year, is 0.1% F.S. for -196 C to +100 C over the differential pressure range - 101.35 Kpa. to + 241.32 Kpa.

CONCLUSION

A miniature multichannel pressure measurement module measuring 5.5 cm. in length by 2.5 cm in width by 3 cm in height has been designed, developed, fabricated, calibrated, and cryogenically tested in cryogenic wind tunnel trial applications. It is accurate to within $\pm 0.1\%$ of F.S. error band in the pressure range of -101.35 Kpa. to 241.32 Kpa. and over the temperature range from -195.6 to +100 deg. C.

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Appendix A

Current Cryogenic Wind Tunnels

	Organization	Tunnel	Test Gas	Test Section Size (h, w, l) m	Speed or Mach Range	Stagnation Pressure, bar	Stagnation Temperature	Running Time
China	CARDC	closed circuit, fan	nitrogen	0.1 x 0.1	up to 0.4	atmospheric (?)	79 - 320 K	?
England	RAE - Bedford	closed circuit, centrifugal fan	nitrogen	0.3 x 0.3 x 1.5	up to 25 m/s	atmospheric	90 K - ambient	typically 1 hour
	University of Southampton	closed circuit, fan	nitrogen	0.11 x 0.11 x 0.25 (regular) 0.14 x 0.11 x 0.41 (MSBS)	14 - 72 m/s	atmospheric	79 - 380 K	typically 1 hour
France	ONERA/CERT	T2 closed circuit, Induction	nitrogen rich air	0.37 x 0.39 x 1.32 solid adaptive walls	0.3 - 1.0	1.6 - 5.0	95 K - ambient	up to 100 sec +
Germany	ETW GmbH	PETW closed circuit, fan	nitrogen	0.23 x 0.27 x 0.78	0.35 - 1.0 continuous 1.2, 1.35 fixed nozzles	1.25 - 4.5	90 - 313K	typically 1 hour
	DLR - Kohn	KKK closed circuit, fan	nitrogen	2.4 x 2.4 x 5.4	up to 0.38	up to 1.12	100 - 300K	up to several hours
	DLR - Go ttingen	Ludwig tube	nitrogen	0.40 x 0.35 x 2.0	0.25 - 1.0	up to 10	120 K - ambient	about 1 sec
Japan	NAL	closed circuit, fan	nitrogen	0.1 x 0.1 x 0.3	up to 1.02	up to 2	90 K - ambient	more than 2 hours
	University of Tsukuba	closed circuit, fan	nitrogen	0.1 x 0.1 x 0.3	up to 3 m/s	up to 2	100 K - ambient	up to 2 hours
	University of Tsukuba	closed circuit, fan	nitrogen	0.5 x 0.5 x 1.2	7 - 65 m/s	1.22 - 8.10	112 K - ambient	30 min at max R
	NDA	closed circuit, centrifugal fan	nitrogen	0.30 x 0.06 x 0.72	up to 0.83	up to 1.77	108 K - ambient	up to 100 min
United States	University of Illinois	closed circuit, fan	nitrogen	1.22 x 0.60 x 1.0	0 - 8 m/s	atmospheric	80 - 300K	several minutes
	NASA Langley	03m TCT closed circuit, fan	nitrogen	0.33 x 0.33 x 1.42 solid adaptive walls	0.05 - 1.0+	1.1 - 6.2	78 - 340K	up to several hours
	NASA Langley	U.S. NTF closed circuit, fan	nitrogen	2.5 x 2.5 7.62 slotted	0.2 - 1.20	1.0 - 8.9	78 - 340K	up to several hours
U.S.S.R.	TsAGI	T-04 closed circuit, induction	nitrogen rich air	0.2 x 0.2 x 0.74 perforated	0.1 - 1.15	1 - 6.5	100 - 300K	1.5 hours
	ITAM	MT-324 closed circuit, fan	nitrogen	0.2 x 0.2 x 0.8	up to 0.2	atmospheric	80 - 300K	several hours
	PMI-K	closed circuit, fan	mixture of gasses	0.22 circular open jet	0.5 - 10 m/s	1 - 10	130 - 300K	?

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13. ABSTRACT (Maximum 200 words) Pressure is one of the most important parameters measured when testing models in wind tunnels. For models tested in the cryogenic environment of the National Transonic Facility at NASA Langley Research Center, the technique of utilizing commercially available multichannel pressure modules inside the models is difficult due to the small internal volume of the models and the requirement of keeping the pressure transducer modules within an acceptable temperature range well above the -173 degrees C tunnel temperature. A prototype multichannel pressure transducer module has been designed and fabricated with stable, repeatable sensors and materials optimized for reliable performance in the cryogenic environment. The module has 16 single crystal silicon piezoresistive pressure sensors electrostatically bonded to a metalized Pyrex substrate for sensing the wind tunnel model pressures. An integral temperature sensor mounted on each silicon micromachined pressure sensor senses real-time temperature fluctuations to within 0.1 degrees C to correct for thermally induced non-random sensor drift. The data presented here are from a prototype sensor module tested in the 0.3 M cryogenic tunnel and thermal equilibrium conditions in an environmental chamber which approximates the thermal environment (-173 degrees C to +60 degrees C) of the National Transonic Facility.				
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