AN ADVANCED SOLID STATE PRESSURE TRANSDUCER FOR HIGH RELIABILITY SSME APPLICATION

R. L. Johnson and D. B. Wamstad
Solid State Electronic Division
Honeywell, Incorporated
Plymouth, Minnesota, 55441 U.S.A.

ABSTRACT

The objective of this research project is to define and demonstrate new methods to advance the state-of-the-art of pressure sensors for the Space Shuttle Main Engine. This includes improved reliability, accuracy, cryogenic temperature operation and ease of manufacture.

This paper presents the results of the "Feasibility and Breadboard Demonstration Phase" and the current status of the "Research Development Prototype Follow-on Phase." A technology breakthrough utilizing silicon piezoresistive technology was achieved in the first phase. Excellent silicon sensor performance, at liquid nitrogen temperature, was successfully demonstrated at NASA/MSFC.

The follow-on phase is in process. A transducer design concept for the SSME application utilizes packaging materials with similar thermal coefficients of expansion and maintains the transducer seals primarily in compression. The package mechanical integrity will be tested to the SSME requirements for temperature (-423°F to +250°F), pressure (9.5K psi), and vibration (400 g's). The silicon chip design will provide dual sensing outputs with laser trimmable integrated compensating electronics. The silicon resistor ion implant dose was customized for the SSME temperature requirement. A basic acoustic modeling software program was developed as a design tool to evaluate the frequency response characteristics for the package design. Successful completion of this research project will provide ten prototype SSME Solid State Pressure Transducers for NASA testing.

INTRODUCTION

Previous research and development at Honeywell has demonstrated that silicon piezoresistive pressure-sensing diaphragms can be integrated with electronic components on a single chip to produce small, accurate, and rugged transducers. Also, the techniques used for precisely forming the pressure sensing diaphragm to a controlled thickness allow a common chip design to be used for a wide range of full scale pressures. The design can thus be used for a "family" of pressure sensors. A capsule summary of Honeywell's proposed concept of pressure instrumentation for the space shuttle main engine application is given below:

- Electrical conversion of sensor behavior integrated on the same chip as the solid state piezoresistive elements (single chip approach).
- Pressure ranges established simply by changing the silicon diaphragm thickness.
- Each transducer uniquely calibrated by laser trimming of on-chip thin film resistors.
- Temperature compensation achieved by on-chip signal conditioning circuitry.

The NASA Contract number of this research of pressure instrumentation study is NAS8-34769. Mr. Tom Marshall of the Marshall Space Flight Center, Huntsville, Alabama, is the technical monitor.

FEASIBILITY STUDY AND BREADBOARD DEMONSTRATION PHASE

The objective of this phase was to develop breadboard type hardware capable of demonstrating the feasibility of the advanced solid state sensor concept and to provide a laboratory demonstration of MSFC of two SSME Breadboard Pressure Transducers.

Circuit Development

The initial work of the feasibility study was a literature study of the behavior of silicon piezoresistors at cryogenic temperatures. The change in absolute resistance and the change in piezoresistance to pressure as a function of temperature both had to be determined in order to accurately condition the sensor's output signal. From the literature study, it was determined that peak doping levels of 3×10^{19} atoms/cm^3 to 2×10^{20} atoms/cm^3 for boron piezoresistors would yield compensatable performance and still provide adequate sensitivity to pressure.

After the behavior of existing experimental piezoresistors and other candidate circuit elements were characterized at cryogenic temperatures, a transducer circuit was designed to compensate and calibrate the sensors over the temperature range of -320°F to +165°F. A simplified schematic diagram of the SSME Breadboard Pressure Transducer circuit is given in Figure 1. Since only a portion of the available 10 volt excitation is required for the silicon sensor bridge to provide the required output level, the remainder of the excitation voltage is therefore available for signal conditioning of the sensor output.

In addition to the pressure sensing bridge and a reference non-pressure sensing bridge, the circuit mechanization consists of seven (7) laser trimmable thin film resistors and six (6) diodes (base-to-emitter pn junction of small signal transistor devices). The thin film resistor (TRF) networks are utilized to calibrate and compensate the sensor output over the full operating range at temperature and pressure. The following four functions are uniquely calibrated:

1) Null set at zero pressure
2) Span set at full scale pressure
3) Null change with temperature
4) Span change with temperature

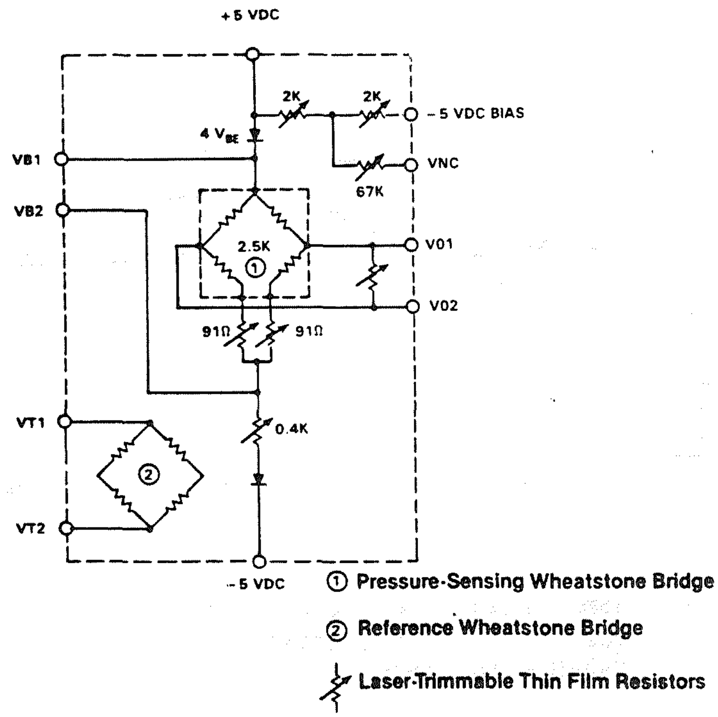


Figure 1: Simplified Schematic Diagram of SSME Breadboard Pressure Transducer

Span (pressure sensitivity) compensation of the silicon sensor bridge is accomplished by counteracting the change in pressure sensitivity to temperature by an opposite change in bridge excitation with temperature. For piezoresistance sensors, the sensitivity decreases with increasing temperature and increases proportionally with increasing bridge ex-citation. Therefore, properly controlling the bridge voltage as a function of temperature will cancel the effect of the sensor's strain sensitivity as a function of temperature. This span or sensitivity compensation technique is achieved in the circuit of Figure 1 by the interaction between the temperature coefficient of the sensor bridge itself and the circuit elements in series with the bridge.

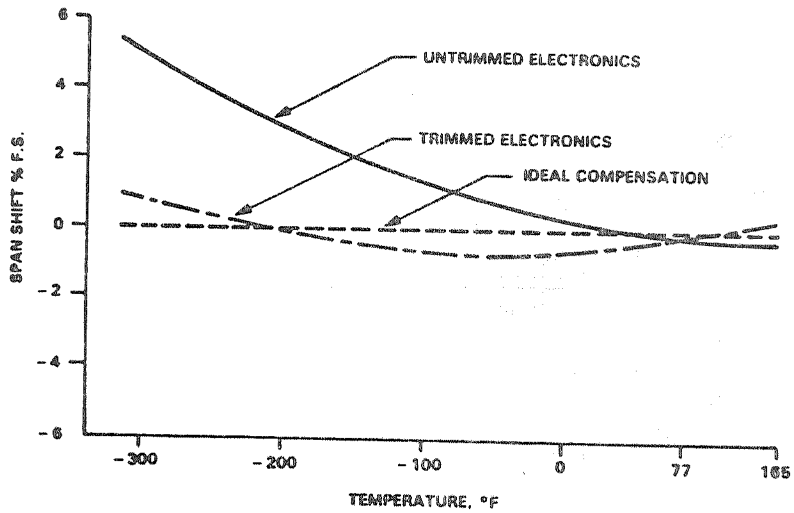
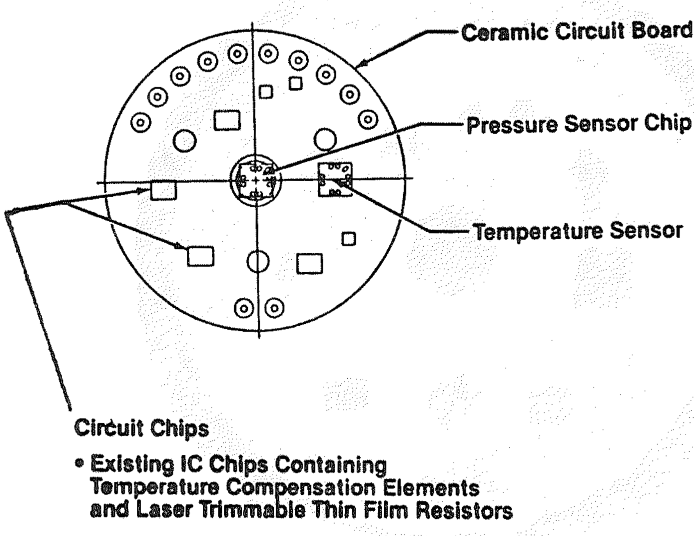


Figure 2: SSME Breadboard Pressure Transducer Span Shift Characteristics (-320°F to 165°F)

A typical pressure sensitivity compensation curve for the breadboard pressure transducer design is presented in Figure 2. By using laser trim calibration, span shifts of less than 1% over the temperature range of -320°F (LN_2) to +165°F are attainable.

Breadboard Hardware Development

The design of the breadboard hardware for feasibility demonstration is presented in Figure 3. For the breadboard hardware, a hybrid mechanization of the electronics was designed using existing IC chips as shown in the top portion of Figure 3. For the prototype research pressure transducer, all the electronics, including the sensor bridge, will be integrated on a single chip. The ceramic circuit board is mounted into a stainless steel test vessel which houses the pressure sensor chip mounted on a pyrex tube as shown at the bottom of Figure 3.



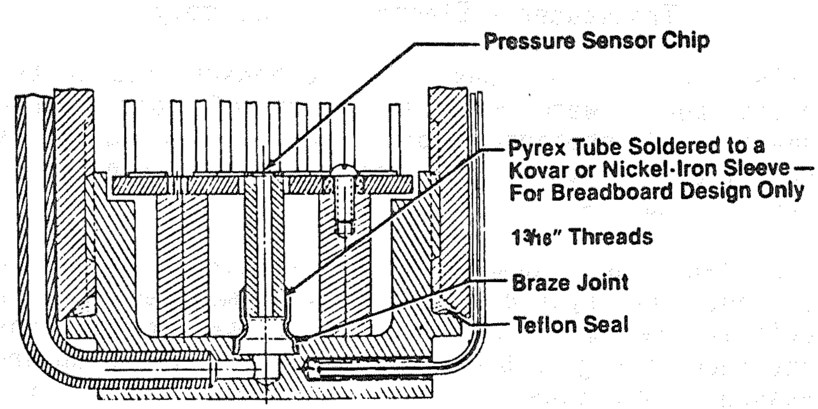


Figure 3: SSME Breadboard Pressure Transducer
Test Vessel

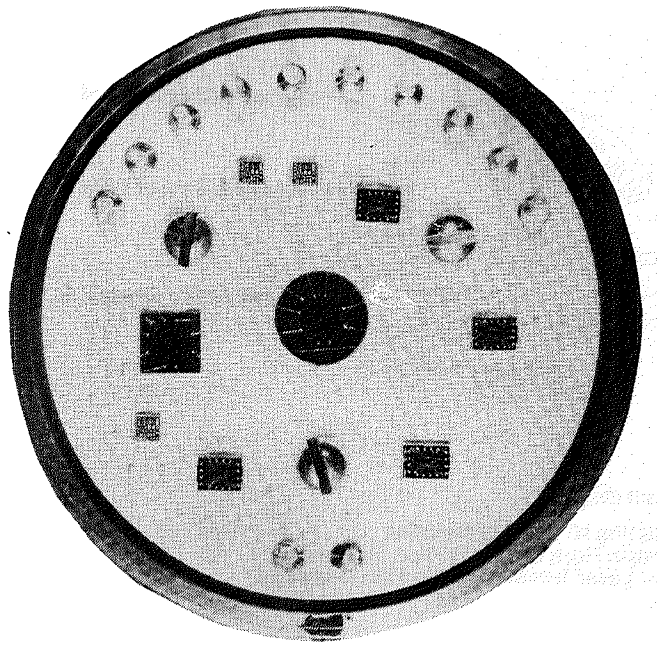


Figure 4: SSEM Breadboard Pressure Transducer
Transducer - Electronics Assembly

Electrical connections from the Sensor Chip to the circuit board were made by means of gold interconnects. A photograph of a completed electronics assembly of the SSME breadboard pressure transducer is shown in Figure 4.

To facilitate demonstration testing in liquid nitrogen, the hybrid assembly was mounted into a specially designed housing as presented in the photograph of Figure 5 which shows the SSME Breadboard Pressure Transducer in its final form for demonstration testing. Pressure connection to the device was made via a copper tube soldered into the base of the test vessel. The leadwires from the transducer were brought out through a long metal tube and terminated with an appropriate connector for electrical interface.

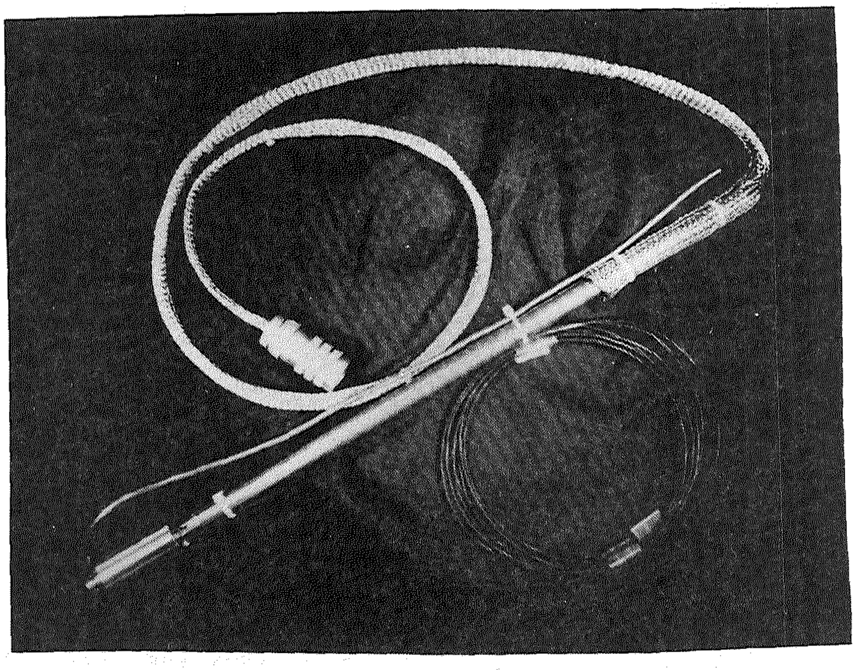


Figure 5: SSME Breadboard Pressure Transducer - Final Form

Breadboard Hardware Demonstration

Upon completion of the calibration and characterization of the SSME Breadboard Pressure Transducers, two units were delivered to and demonstration tested at the Marshall Space Flight Center in Huntsville, Alabama. Figure 6 shows the test setup used for the demonstration.

The demonstration consisted of performing a baseline room temperature pressure test, followed by a liquid nitrogen (LN_2) test procedure, and concluding with post LN_2 room temperature pressure test. The baseline pressure test consisted of an upscale and downscale pressure profile using pressure increments of 20% full scale (the breadboard transducer used a 10 psi full scale sensor).

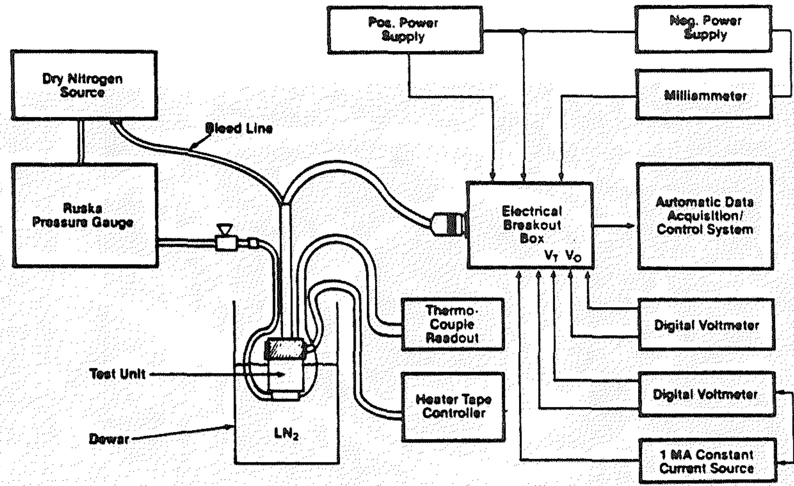


Figure 6: SSME Breadboard Pressure Trandsucer-Demonstration Test Setup.

The LN_2 test consisted of submerging the test unit in a LN_2 Dewer until the LN_2 was approximately one third the way up the large diameter portion of the device. A powered heater tape strapped to the top part of the test body was used to generate a 165°F thermal gradient across the body of the breadboard pressure transducer. Under this test condition, the sensor end of the transducer was at -320°F and the top part of the transducer was at -165°F. An up-down pressure profile was performed while maintaining the thermal gradient condition. In addition to the pressure profile, the null output was monitored during the temperature transition from room down to liquid nitrogen temperature. After the LN_2 test, the devices were allowed to restabilize and the baseline room temperature pressure test was repeated.

The results of the breadboard demonstration were very successful and the feasibility of the advanced solid state pressure sensing concept was clearly demonstrated.

A capsule summary of the significant accomplishments of the feasibility and breadboard demonstration phase is presented below.

- Accurate Calibration and Compensation of the Breadboard Pressure Sensor Using Laser Trim Technology
  - Null Voltage Set to Zero Within 1 Microvolt.
  - Full Scale Voltage Set to Within 10 Microvolts.
- Successful Breadboard Demonstration at NASA/MSFC.
- Key Results at Liquid Nitrogen (-320°F) Temperature
  - Null Shift: 0.1% FS
  - Sensitivity Shift: 1.9% FS
  - Pressure Hysteresis: 0.02% FS (0.01% FS at SSED)
  - Thermal Hysteresis: (Non-Return to Zero) 0.03% FS (0.005% FS at SSED)
  - Transient Null Shift: <1.0%FS Maximum (Measured During Temperature Excursion from Room Temperature to -320°F with a 165°F Thermal Gradient Across the Sensor Housing).

DEVELOPMENT RESEARCH PROTOTYPE PHASE

The objective of the "Development Research Prototype Phase" is to design, develop and deliver ten prototype pressure transducers. These are targeted to meet the SSME transducer performance design goals. This phase consists of a study, experimental effort, prototype design and development phase. Three studies have been completed for this project and consist of the following:

1) Transducer Package Concept Study - Silicon chip mounting and packaging concepts were generated and analyzed to determine suitability for the SSME application. A concept which utilizes materials with similar thermal coefficients of expansion and maintains the transduced materials and seals primarily in compression was selected.

2) Materials and Process Study - A study was completed to select materials and determine processes for the selected transducer package concept. The materials and process selection was based on the temperature, pressure, vibration and pressure media requirements for the SSME application.

3) Acoustic Frequency Response Study - Based on this study an acoustic modeling software program was developed as a design tool to evaluate the frequency response characteristics for the transducer final package design.

The experimental phase of this project is partially complete and consists of the following:

1) Silicon Resistor Characterization at Cryogenic Temperature - Silicon resistor implant doses were experimentally varied to customize the silicon piezoresistors for the SSME temperature requirement ranging from -423°F to +250°F. The data from this task is presently being analyzed.

2) Pressure Sensor Chip Mounting Characterization - The mechanical integrity will be experimentally determined for the silicon chip mounting concept, selected in the study phase. Mechanical models will be tested to the SSME requirement for temperature (-423°F to +250°F), pressure (9.5K psi) and vibration (400 g's).

The performance and survivability of present solid state piezoresistive pressure transducers have been successfully demonstrated at cryogenic temperature (-320°F), based on the NASA Breadboard Demonstration, and at high pressure (10K psi), based on existing commercial sensors. The combined SSME requirements for temperature, pressure, vibration and pressure media have not been demonstrated and are extremely challenging. These will be demonstrated at the conclusion of the prototype phase. The following proposed Pressure Transducer Concept, dependent on the experimental results, will be designed, built and evaluated.

Transducer Design Goals and Approach

The SSME Pressure Transducer Design goals, based on the combined effects of cryogenic temperature, high pressure, vibration, absolute pressure sensing and package design are extremely challenging. The basic SSME design goals are summarized in Table 1.

The transducer design approach implements the NASA requirement for direct mounting of the pressure transducer to the SSME. This requires the pressure sensing element to be in direct contact with the high pressure cryogenic pressure media. It also requires, based on the state of the hydrogen/oxygen/nitrogen pressure media, that the silicon integrated circuits not be in direct contact with the pressure media. The design approaches incorporated in the selected pressure transducer concept are listed in Table 2.

Table 1. Summary of SSME Pressure Transducer Design Goals.

CONDITION	DESIGN GOALS
Transducer Configuration	- Same external configuration as RC7001
Pressure Ranges	- 0 to 600 psia - 0 to 3500 psia - 0 to 9500 psia
Pressure Rating	- 1.5xF.S. (No permanent null or calibration change) - 2.5xF.S. or 20K psi Maximum (No permanent damage)
Pressure Media	- Liquid/Gaseous Hydrogen - Liquid/Gaseous Oxygen - Helium - Nitrogen
Temperature Range	- -200°C to + 120°C (Goal of -253°C)
Vibration	- 0 to 2000 Hz; 400 g's (With superimposed random and steady-state vibration)
Acoustic Frequency Response	- Dynamic Design Goal of 300 Hz Minimum
Full Scale Output	- 30 ± 0.3mV at 10 VDC Excitation
Thermal Zero Shift	- ± 0.005% F.S./Degree
Electrical-To-Pressure Calibration	- ±0.1% F.S. at 80% F.S. Correlation points at Ambient Temperature

Table 2. Design Approaches Incorporated in the NASA Pressure Transducer Concept.

DESIGN PARAMETER	DESIGN APPROACH
Sensing Element and Circuit	- The sensing element, diaphragm, and circuit are contained on a single chip. - The circuit provides a fully compensated and calibrated linear output voltage proportional to pressure.
Integrated Circuit Protection	- The integrated circuit on the silicon is protected by the absolute transducer vacuum reference.
Method of Calibration	- Laser circuit trim capability is provided by thin film resistors on the silicon chip.
Pressure Range Change	- The operating pressure range is changed simply by changing the thickness of the silicon diaphragm.
Pressure Media	- To insure high reliability the circuit side of the silicon chip is protected from the pressure media. - The transducer package materials were selected for pressure media compatibility.
Vibration	- The attributes of silicon pressure transducers such as small size, low mass, integrated electronics and essentially no moving parts all contribute to high vibration capability. - The length of the electrical interconnects from the silicon chip to the terminal board will be controlled for high vibration capability.
Cryogenic Temperature	- Excellent silicon sensor performance, at liquid nitrogen temperature was successfully demonstrated at NASA/MSFC. - The implant dose of the ion implanted sensor elements will be customized for cryogenic temperature performance. - The transducer package materials were selected for cryogenic temperature compatibility.
High Pressure	- The transducer design concept maintains the transducer seals primarily in compression and utilizes high strength materials with similar coefficients of expansion.
Acoustic Frequency Response	- Acoustic modeling software was developed to analyze the frequency response characteristics and will be utilized in the final design to maximum frequency response. - Pressure port length will be minimized and Helmholtz Resonator Side Chambers added.

Transducer Package Design

The SSME Transducer Package Design is documented in Figure 7 and Figure 8. This encompasses an absolute silicon pressure sensor chip with lase trimmable circuit electronics mounted to a silicon nitride backplate and terminal board. The chip mount vacuum reference of the absolute transducer is established through the hermetic seals of the silicon, silicon nitride and the pyrex cover glass. The sensor chip mount is housed in a common package with electrical interface and pressure port provision.

Pressure Transducer Silicon Chip Mount

The pressure transducer silicon chip mount design is extremely important. Sensor performance, in terms of accuracy, repeatability and stability, is dependent on its interface with the transducer package and pressure media. There are four basic SSME requirements which dictate the pressure sensor chip mount design. These are:

1. Pressure Media Interface - The high pressure (9.5K psi), cryogenic temperature (-320°F) and pressure media (LOX, LH_2, gaseous helium, nitrogen, oxygen, hydrogen, air and water vapor) require the active circuit side of the pressure sensor chip be separated from the pressure media. This is accomplished by applying the pressure to the backside of the pressure sensor chip.

2. High Pressure/Low Temperature - The combined high pressure and low cryogenic temperature requirements dictate that the pressure media be applied directly to the chip.

3. Active Laser Trimming - Active laser trimming of on-chip thin film resistor networks to calibrate sensor performance is normally completed after sensor packaging. This is done to eliminate the packaging and assembly process effects on transducer

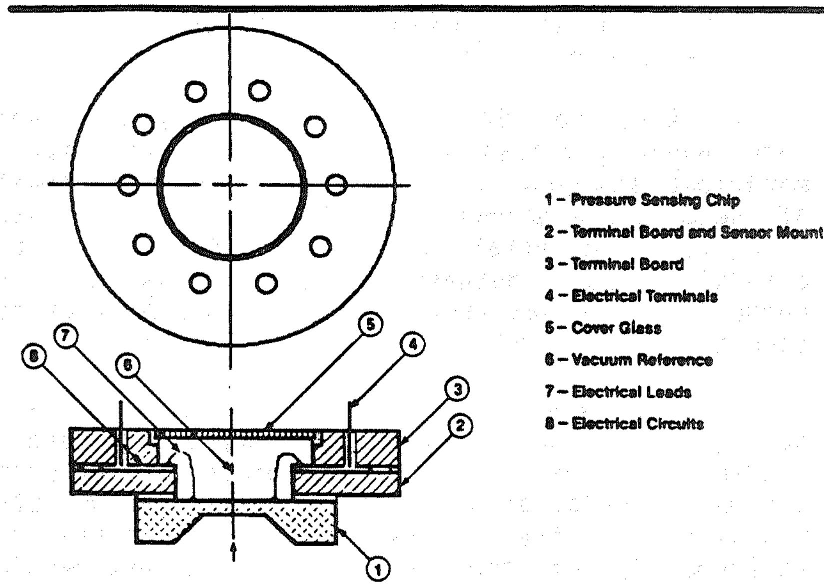


Figure 7. Pressure Transducer Silicon Chip Mounting Design

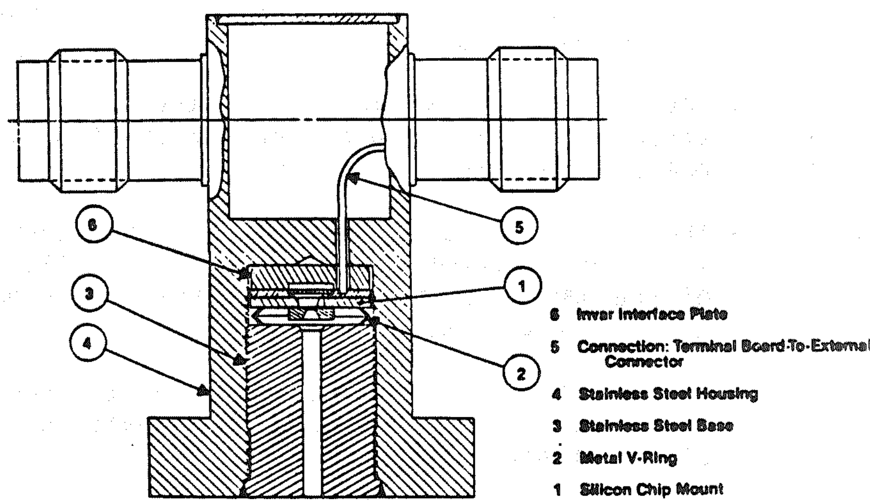


Figure 8. Pressure Transducer Package Design

calibration. This dictates that the trimmable network be visible after packaging and further impacts the pressure sensor chip mounting.

4. Absolute Sensor - The absolute sensor requirement provides an additional challenge. The materials and processes utilized in the construction of the pressure transducer influence the sensor vacuum integrity. Materials were selected based on their diffusion and outgassing characteristics, high hermeticity capability and temperature pressure compatibility.

Testing was completed on a special sensor configuration to simulate the compressive pressure loading impact on transducer performance. The purpose of this testing was to determine the strain transmitted to the silicon chip (effect on transducer performance) by the impact of compressive loads applied to the outer edge of the silicon nitride. The key findings of this testing are:

- Comprehensive loading can result in substantial stress transmission to the sensor chip.

- The stresses transmitted to the sensor are strongly dependent on the method of clamping in the test fixture.

- The stress transmitted to the sensor is strongly dependent upon the condition (flatness) of the mating surfaces between the test samples and the test fixture.

- Changes in the piezoresistors ranged between 0-2% when close attention was paid to the aforementioned conditions.

Based on the results of this experimental testing, the original transducer package design concept was changed to minimize stress transmission to the sensor chip by either pressure or temperature. This design change involved adding an Invar interface, with controlled surface flatness, between the silicon nitride and stainless steel, adding a surface flatness requirement to the silicon nitride parts and adding a metal compressive C-Ring between the silicon nitride and stainless steel (see Figure 2). This change will uniformly distribute the structural compressive load over the required transducer pressure and temperature range.

The pressure transducer silicon chip mount design utilizes materials with closely matched coefficients of expansion; silicon, silicon nitride, pyrex and invar. These will minimize the thermal stresses over the large temperature differential of 682°F required for the SSME application. To insure package survivability at high pressure and cryogenic temperatures the design maintains the transducer seals primarily in compression.

The acoustic response study determined methods of improving the frequency response characteristics. These primarily consist of minimizing the pressure port length and adding Helmholtz Resonator chambers in the housing wall. The influence of the pressure port length is detailed in Figures 9. As the length of the pressure port decreases the resonant frequency increases. Pressure port length of 2.245 inches has the first frequency response harmonic occuring at 2000 Hz. When the pressure port length is decreased to 1.000 inches, the frequency response harmonic increases to 3000 Hz. The use of Helmholtz Resonator chambers, as shown in Figure 10, decrease the peak pressure pulse. These features will be incorporated in the final design for the prototype SSME pressure transducers.

SUMMARY

The performance and survivability of present solid state piezoresistive pressure transducers have been successfully demonstrated at cryogenic temperature (-320°F), based on the NASA Breadboard Demonstration, and at high pressure (10K psi), based on existing commercial sensors. The combined SSME requirements for temperature, pressure, vibration and pressure

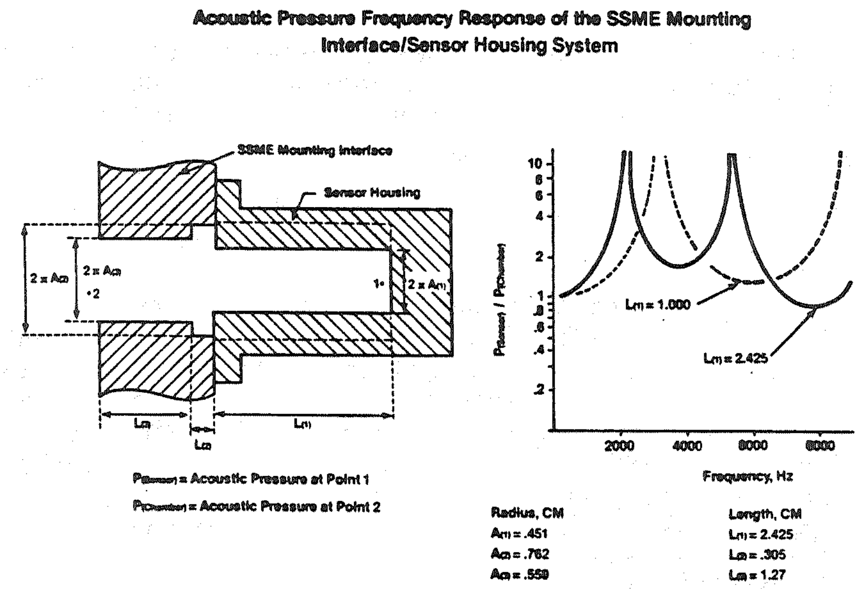


Figure 9. Influence of Pressure Port Length on Acoustic Frequency

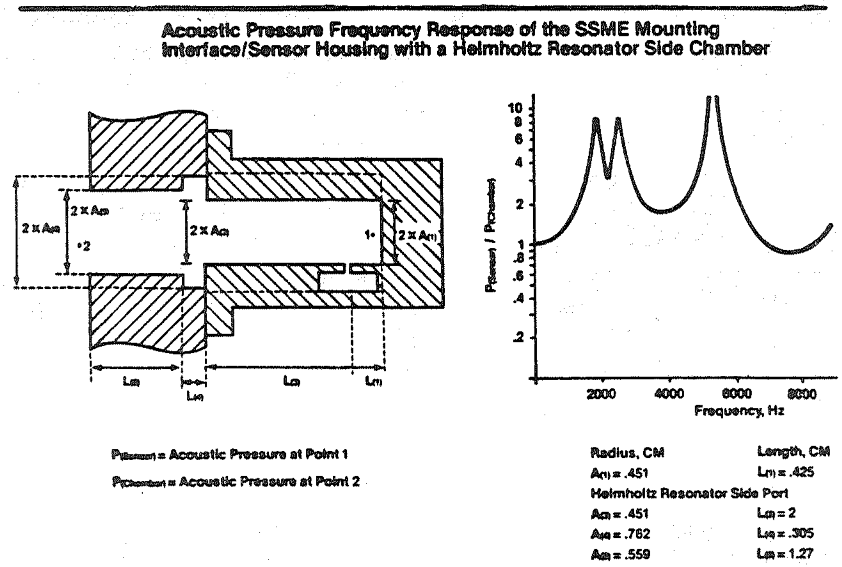


Figure 10. Influence of Pressure Port Side Chambers on Acoustic Frequency Response

media have not yet been demonstrated and are extremely challenging. These will be demonstrated at the conclusion of the prototype phase.

The intrinsic attributes of silicon pressure sensor technology, as sumarized below, all contribute to the attainment of the research objectives.

- Solid State Reliability and Accuracy

- High Vibration and Pressure Capability
  - Small size
  - Low mass

- Integration of Sensor and Electronics on Single Chip
  - Reduces Package Complexity
  - Eliminates Errors Due to Thermal Gradients

- Extended Temperature Range Capability
  - Increased to -423°F and +250°F
  - Eliminates Need to Remote Mount Transducer

- Precision Laser Trim Calibration

- Enhancement of Frequency Response Increases Engine Performance Monitoring Capability

- Common Design for All Pressure Ranges
  - Enhances Ease of Manufacture
  - Cost Effective

CONCLUSIONS

The intrinsic attributes and innovativeness of Honeywell's Silicon Pressure Sensing Technology will significantly advance the state-of-the-art of pressure Transducers for the SSME application.

This in conjunction with successful completion of the NASA/MSFC Research Study, will provide the technology base for the development of Space Qualified Advanced Pressure Transducer Hardware for the current Operational Space Shuttle, as well as future "Smart Sensors" for the next generation of Space Vehicles.

ACKNOWLEDGEMENTS

Successful accomplishments and completion of this research project require the efforts of many scientists and engineers at Honeywell. These include: W.T. Boord, E.B. Brynowsky, M.C. Glenn, G.E. Gustafson, R.F. McMullen, J.J. Shea and J.B. Starr.