Final Report

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NASA-JSC CONTRACT NO. NAS 9-13446
DRL NO. T-857
LINE ITEM NO. 4
DRD NO. MA-183T

# ENVIRONMENTAL CONTROL SYSTEM TRANSDUCER DEVELOPMENT STUDY

74-10325

July 19, 1974

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Prepared for

NASA Johnson Space Center
Houston, Texas

GARRETT

AIRESEARCH MANUFACTURING COMPANY
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M.J. Brudnicki
Principal Investigator

R.E. Vesque
Program Manager

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OF CALIFORNIA

## ABSTRACT

A development test program conducted on various transducers developed for recent aerospace projects is described in this report. The program objective was to verify stability and performance not only of existing transducers, but also of associated improvements that would make these articles compatible with Shuttle ECS requirements. These requirements are aimed at incorporating design and development features into the transducers to provide the following:

(a) Improvement of overall transducer ruggedness and reliability

(b) Review of materials and processes with changes to provide a common transducer for all ECS fluids that will be unaffected by long quiescent periods in the space environment, and that will require no maintenance or refurbishment for 100 or more launches

(c) Incorporate self-check features where possible and simplify checkout and maintenance

The transducers evaluated during the program included three different models of pressure transducers, a three-way valve for isolating pressure transducers from closed liquid loops during maintenance, surface-type platinum-wire resistance temperature sensors, and a nucleonics gaging system for monitoring the contents of a zero-g bladder-type water storage tank. Portions of the related development activities were subcontracted to the transducer manufacturers, particularly when the development improvement involved the proprietary features of the transducer. A complete description of all tests and development improvements is contained in this report and the associated appendixes.

The data in the report are presented in the international system of units, followed by the customary units in parentheses. All data recorded during test are presented in the appendixes in customary units only. The ruler shown adjacent to the test articles in each of the AiResearch Manufacturing Company photographs is calibrated in inches.


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# SECTION 1

# INTRODUCTION AND SUMMARY

## SECTION I
## INTRODUCTION AND SUMMARY

This report describes a development program for improving the reliability of transducers that are suitable for use in the Shuttle Environmental Control System (ECS). The program was undertaken to make both Apollo ECS transducers and those used in more recent aerospace programs rugged and reliable by determining their chronic failure modes and mechanisms, and to conduct a development test program to reduce or eliminate any inherent weaknesses. The initial work, consisting primarily of the analysis of Apollo failure reports logged against the ECS tranducers, was performed for NASA JSC by AiResearch Manufacturing Company under NASA Contract NAS 9-12452. This work is summarized in AiResearch final report, "Environmental Control System Transducer Development Study," Report No. 72-8537-1, dated February 10, 1973.

The follow-on work described herein was performed by AiResearch for NASA JSC under Contract NAS 9-13446. The purpose of this development program was to continue the development of remedial designs to reduce or eliminate the chronic failures experienced on Apollo ECS transducers. The selection of transducers, and development improvements made during the course of contract NAS 9-13446, were made in order to investigate and verify transducer techniques and products that were developed for aerospace programs more recent than those developed for the Apollo ECS. The work tasks and the scope of each development program were described by program plan for review and concurrence by the NASA contract technical monitor. In most cases, portions of the development were conducted by subcontract because of the proprietary nature of the transducer design techniques and processes. Following are the task activities performed during this program.

### Stability Test Program on Statham Instruments, Inc. Strain Gage Pressure Transducers

Four pressure transducers were evaluated during this program. Two were rated at 0 to 345 kPa (0 to 50 psia) and two at 0 to 1034 kPa (0 to 150 psia). These units are equivalent to the pressure transducers that have been developed for the main Shuttle engines. The tranducers incorporate four thin-film strain gage elements that are vacuum deposited on a specially shaped metal beam. The sensed pressure acts on a diaphragm that deflects the beam via a push rod.

Statham Instruments, Inc., Oxnard, California, performed the stability test under a subcontract issued by AiResearch. The development test program covered a period of six months, during which time 100,000 pressure cycles per month were applied to each of the four test articles, for a total of 500,000 cycles. Performance record tests were conducted each month at room temperature, 219°K (-65°F), and 394°K (+250°F). The test articles proved to be stable, with all excursions resulting from the pressure cycles and high and low temperatures within ±1 percent of the original calibration data. Section 2 presents a detailed description of this stability test program.

## Performance Tests on the National Semiconductor Corporation Absolute Pressure Transducer

A performance test program was conducted by AiResearch on two Model LX1600A absolute pressure transducers manufactured by National Semiconductor Corporation, Santa Clara, California. The pressure transducer incorporates a Wheatstone-bridge arrangement of four piezoresistors diffused into a silicon chip. Integrated circuit technology is used in the fabrication, calibration, and test, resulting in a low-cost, lightweight end product. These transducers are designed primarily for application in the automotive industry; however, they may be attractive for low-pressure monitoring applications in the Shuttle ECS.

The test results indicate that the LX1600A pressure transducers are repeatable and accurate at room temperature; however, they show a large shift in performance with changes in ambient temperature. The maximum shift in performance was indicated on serial No. 188, which showed an 8-percent shift at 333°K (+140°F) and a 14-percent shift at 233°K (-40°F). The test program and test results are described in greater detail in Section 2 of this report. Discussions with National Semiconductor Corporation personnel indicate that their Model LX3700, superseding Model LX 1600A, performs with substantially improved stability at extreme temperatures and incorporates a more rugged package to withstand handling and installation stresses.

## Performance Tests on the Fairchild Semiconductor Corporation Absolute Pressure Transducer

AiResearch conducted a performance test on Fairchild absolute pressure transducers Models 4207 and 4208. One test article of each model number was purchased from an electronic retail parts supplier as off-the-shelf units. Since these transducers are designed for application in the automotive industry, the projected cost of these units is $10 each for quantities in excess of 10, 000 units. The test results show good repeatability (within 1 percent of full scale) during high- and low-temperature tests and before and after approximately 500 pressure cycles. The test program, including performance curves and test data, is described in Section 2 of this report.

## Three-Way Isolation Valve Development Program

A three-way isolation valve was designed and a breadboard model fabricated to demonstrate by actual test that a faulty pressure transducer can be removed and replaced without destroying the hardfill of the closed liquid loop. The three-way valve was developed and fabricated by L. J. Engineering, Westminister, California, and the test program was conducted at AiResearch on a simulated water and Freon-21 thermal transport loop. The results indicate that it is feasible to include a permanently installed isolation valve between the liquid loop and each pressure transducer to simplify and reduce maintenance time on the ECS liquid loops. It is estimated that a production version of the isolation valve will weigh 85 grams (3 oz). The isolation valve also may have application for isolating other component items in the liquid systems. A complete description of the three-way valve and test program is contained in Section 3 of this report.

### Temperature Transducer Development Program

A temperature sensor stability test program was conducted on platinum resistance surface-type temperature sensors furnished by Tylan Corporation, Torrance, California, including development improvements and a built-in-test provision analysis. The cyclic temperature test program performed at AiResearch included various performance record tests, data reduction, and reporting. The sensors show good accuracy through a temperature range of 195°F (-109°F) to 422°K (+300°F) and are repeatable in performance to within ±1°C even after a 5-year shelf life. Eight of twenty-three sensors failed during the test program; the failures were caused by the loss of bond between the insulation on the lead wire and the fiberglass laminate surrounding the sensing element. Loss of the bond results in excessive loads being imparted to the 0.0254-mm- (0.001-in.) diameter wire platinum resistance element, resulting in breakage of the wire. Tests of improvements made to prolong the life of the bond between the insulation of the leadwire and fiberglass laminate did not prove successful during this development program. A detailed description of the test and development program is contained in Section 4 of this report; criteria governing the use of these sensors also are contained in the results and conclusions in Section 4.

### Development of the Interfaces of a Nucleonics Gaging System to a Zero-g Bladder-Type Water Storage Tank

A nucleonics gaging system was fitted to an existing bladder-type water storage tank that was used in the Apollo ECS. The major development activity consisted of shaping the radioactive source tube and the Geiger-Mueller detector to appropriate areas on the outside surface of the water tank to provide an accurate indication of the water quantity. The development interfacing was subcontracted to General Nucleonics, a division of TYCO Laboratories, Pomona, California. The gaging system used for this development is similar to the nucleonics oil quantity indicating system used on various Air Force airplanes. The source consists of an inert radioactive (Krypton-85) gas contained in a 6.35-mm- (1/4-in.) OD aluminum tube with the ends of the tube redundantly sealed. Gaging system safety to maintenance personnel has been verified by the Air Force. A detailed report of the development program and safety aspects of the nucleonics gaging system is contained in Section 5.

### Results and Conclusions

The transducers evaluated during this program represent a small number of available configurations that are compatible with the Shuttle ECS requirements. The scope of this program was limited to the accomplishment of certain tasks identified and mutually agreed to by NASA and AiResearch. It was not intended to evaluate every available transducer for application to Shuttle.

The transducers evaluated during this program show that improvements have been made in accuracy, size, weight, and cost over the transducers used in the Apollo ECS program. For example, the pressure transducers used in the ECS of the Apollo command service module averaged 0.284 kg

(10 oz) in weight, and cost more than $5,000 each. The pressure tranducers used in this test program are less than one-half as heavy and less than one-fifth as costly. Similar savings can be shown for the temperature transducers. The tests conducted during this program also show the transducers to be stable with age and cyclic life.

Each section and subsection of this report contains results and conclusions appropriate to the specific transducer.

# SECTION 2

# PRESSURE

# SECTION 2
# PRESSURE

This section contains test reports on three configurations of pressure transducers manufactured by three different companies. The reports are identified by company name, and each comprises a subsection, as follows:

Statham Instruments, Inc. Pressure Transducers

National Semiconductor Corporation Pressure Transducers

Fairchild Semiconductor Components Group Pressure Transducers

## Statham Instruments, Inc. Pressure Transducers

Introduction. --AiResearch awarded a cost-sharing subcontract to Statham Instruments Inc., Oxnard, California, to conduct a verification test on four strain gage pressure transducers. The four test units were fabricated to the same tolerance as catalog items.

The objective of the test program was to determine the repeatability (stability) of the pressure transducers as a function of pressure cycles and time. An equation was derived using the least sums squares method from the original test data recorded before the start of cyclic testing. All subsequent performance test data were compared with the original derived equations for each unit. The data show that after subjecting each of the four units to 500,000 pressure cycles, the performance of the test articles is within ±1 percent full scale of the original test data. The results indicate that pressure transducers of this type will not need a periodic recalibration of the signal conditioning equipment.

Background. --In order to cope with the hostile environments in certain Shuttle subsystems, it is desirable to provide pressure sensors containing a minimum of component items that are prone to malfunction in these extreme environments. The electronic components needed for conditioning the output signal of the pressure transducers, therefore, are contained in a centralized signal conditioner and power supply. Vehicle maintenance will be greatly simplified if the pressure transducers can be used for many missions over a long period of time without the need for recalibration of the signal conditioning equipment. This program provided information on the stability of one type of pressure transducer capable of meeting the above objective.

Description of pressure sensor. --The pressure sensors selected for the verification test program utilize four strain gage elements that form the transducer bridge. The four test units are shown in Figure 2-1.

The typical mechanical configuration of this sensor assembly consists of a diaphragm (force collector) that is connected to a bending beam through a rigid linkage pin. Pressure introduced into the transmitter asserts a force on the face of the diaphragm that causes calibrated amounts of displacement. A displacement of identical magnitude is translated to the bending beam by the linkage pin, thereby imparting strain in this member. By careful placement of strain gages on the surface of the bending beam, points of maximum strain are monitored. A typical bending beam is shown in the middle of Figure 2-2. Since strain gages exhibit a change in resistance as a function of strain, transduction of mechanical strain to a change in electrical output is accomplished. In actuality, the displacements of these members are minutely small, and in effect, the assembly can be considered to have no moving parts. The sensor subassembly is vacuum sealed in a hermetic stainless steel case utilizing electron-beam welding techniques to ensure environmental protection. Redundant protection is achieved by welding another stainless steel hermetic outer case over the whole transmitter assembly.

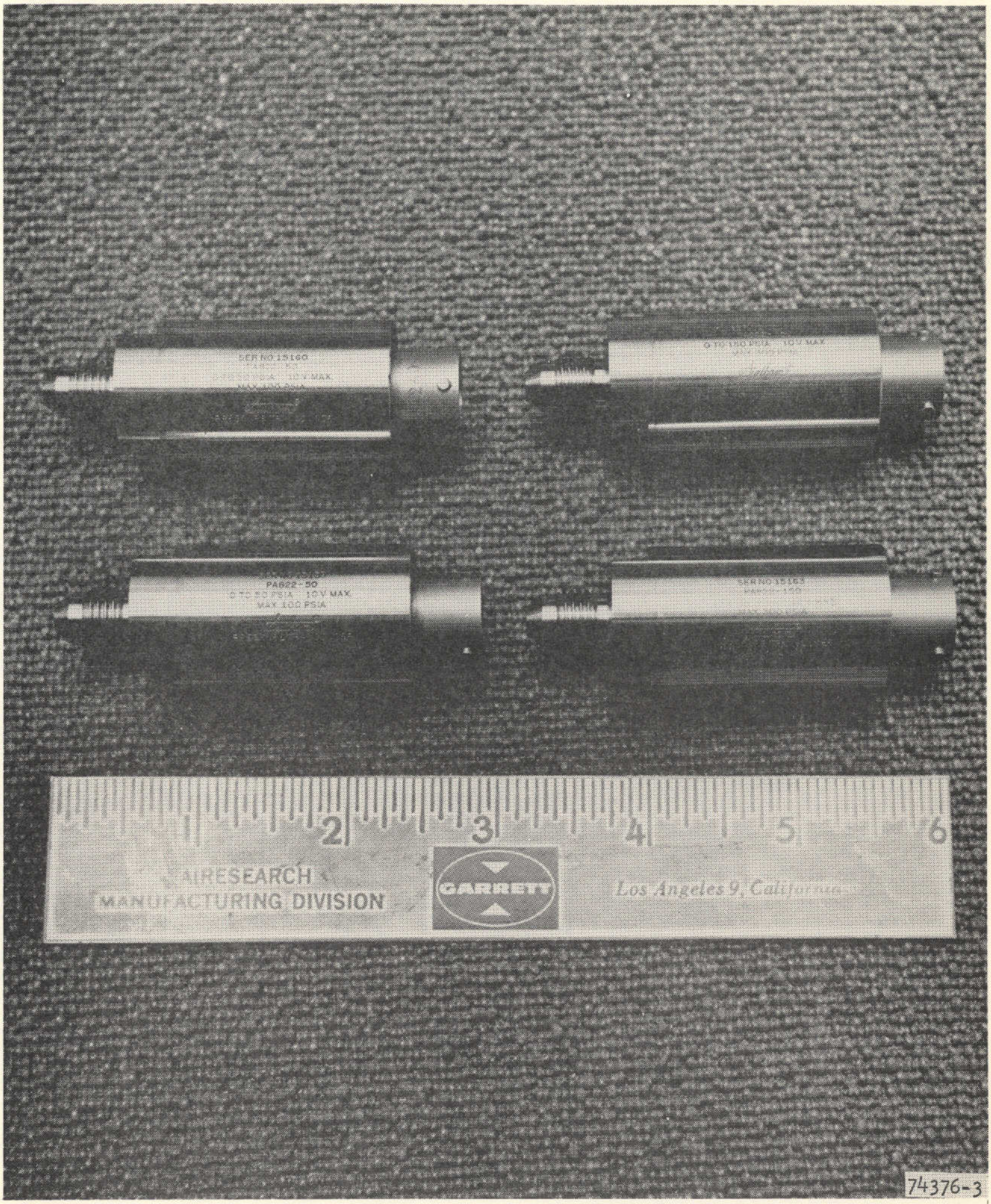



Figure 2-1. Statham Instruments Strain Gage Pressure Transducers (6-in. ruler shown for comparison)

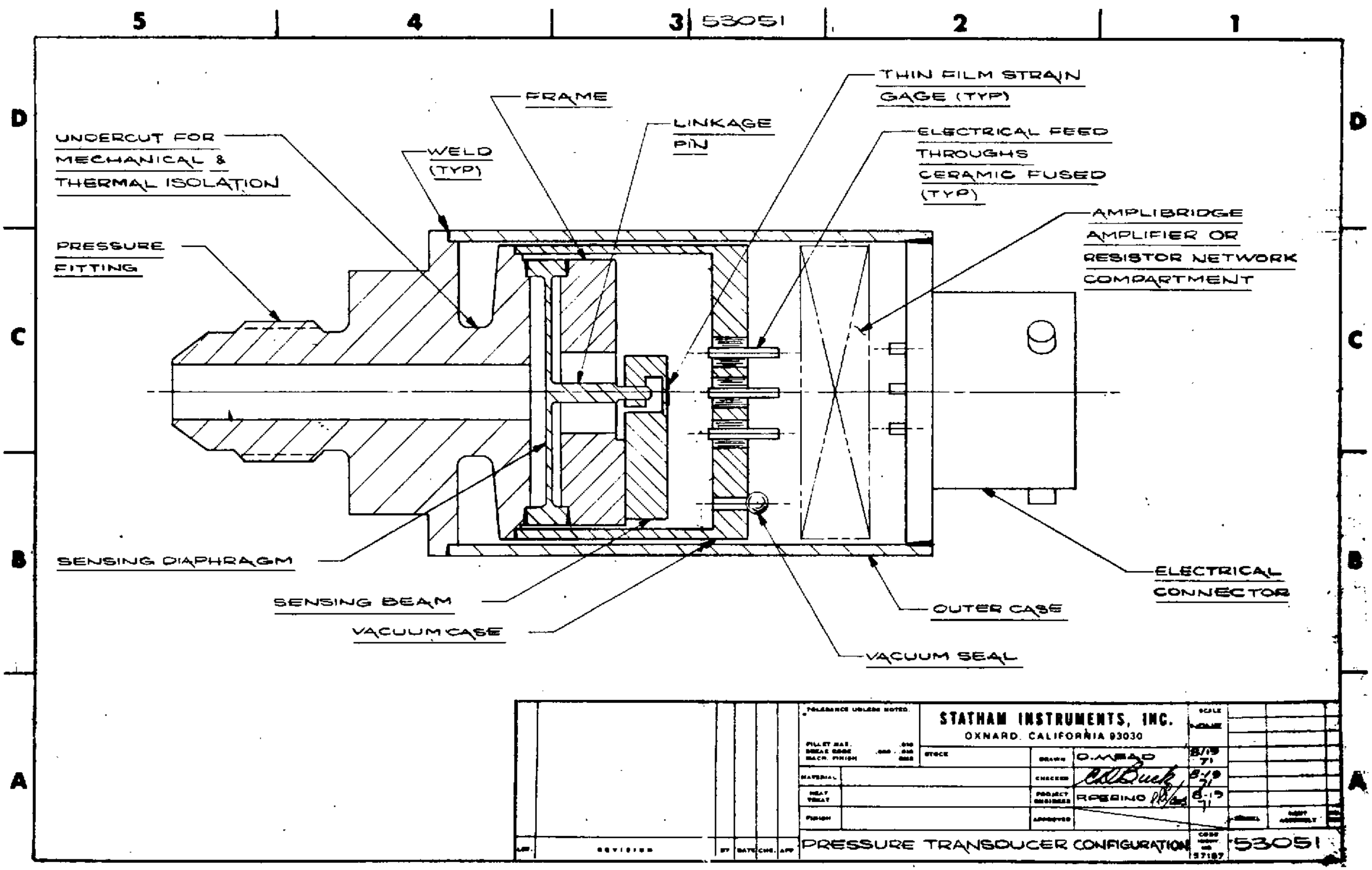



Figure 2-2. Cross-Sectional View of Statham Strain Gage Pressure Transducer

Four thin-film strain gages are vacuum deposited in strategic locations on the top surface of the bending beam and interconnected electrically into a fully active four-arm bridge circuit. The bending beam is prepared for the thin-film strain gages by first depositing a special ceramic material to form a suitable electrical insulation barrier. The thin-film strain gage material was specially developed for its inherent long-term stability, gage factor, and resistance characteristics required for optimum strain gage performance.

Transducer performance characteristics. --Following is a description of the performance characteristics of the Statham transducer.

Stability. --The ultimate stability of a strain gage bridge is highly dependent upon the symmetry of the characteristics of the four individual strain gages. Other factors influencing stability are the aging of organic materials and oxidation of the strain gages. In the thin-film strain gage process, all four strain gages are simultaneously deposited from the same parent material, thereby producing virtually identical characteristics. Only metals and ceramics are used in this transducer. The strain gages are fully oxidized during the deposition process. These factors are important for achieving long-term stability.

Thermal coefficients. --The two primary effects of temperature are changes in the zero output and the sensitivity of the transducer. The thermal zero coefficient results in a translation of the output curve, while the thermal sensitivity coefficient produces a change in slope.

The thermal zero coefficient of a properly designed transducer is due mainly to the mismatch in the temperature coefficient of resistance of the four strain gages. Ideally, the strain gages should have zero temperature coefficient of resistance but in actual practice that is not possible. Since all four thin-film strain gages are deposited at the same time, the temperature coefficients of resistance are essentially identical.

The thermal sensitivity coefficient is determined by the product of thermal coefficient of Young's modulus for the sensing element and the thermal coefficient of gage factor for the strain gages. Most metals have a positive thermal coefficient of Young's modulus. Therefore, it is desired that the strain gages have equal magnitude negative thermal coefficient of gage factor. By proper selection of the strain gage material and control of the deposition conditions, it is possible to control the thermal coefficient of gage factor independent of the temperature coefficient of resistance. In the thin-film strain gage transducer, the techniques described above produce intrinsically compensated transducers that do not require auxiliary electrical compensation.

Hysteresis and creep. --With the high-strength alloys typically used, both the basic hysteresis and creep of the metal sensing element are less than 0.05 percent full scale. The strain gage insulating material and adhesive (if used) are in the force circuit and affect these characteristics. This is particularly true at higher temperatures where organic materials tend to soften and deteriorate in performance.

The thin-film strain gage transducer uses a thin-film ceramic insulation. This insulation exhibits no hysteresis or creep up to the yield point of the metal and at elevated temperatures.

Nonlinearity.--Standard strain gages are linear throughout the strain range of the transducers. With this condition, the transducer nonlinearity is determined by the characteristics of the sensing element. Based on comparative tests with standard strain gages, the thin-film strain gage has negligible nonlinearity, and does not contribute to the nonlinearity of the transducer.

Size.--Microminiature sizes are not available in most transducers. Generally, the limiting item is the size of the electrical pickoff, whose resistance or impedance becomes progressively smaller as the size of the element decreases. The size of the thin-film strain gage transducer is not limited by this consideration. The resistance of the thin-film strain gage starts at infinity, and decreases during the coating process. Therefore, the resistance can be retained at a desired value even though the physical size of the strain gage is reduced. The final size of the transducers then becomes limited by the mechanical configuration required for the force-summing device.

Power rating.--The bridge resistances can be made any desirable value. Values ranging from the conventional 350 to 5000 ohms are readily produced. This permits optimizing the transducer bridge resistance to the specific application. Each leg has the maximum area consistent with other design factors in order to permit internally generated heat to be dissipated over a substantial area. The strain gage bridge is separated from the metal sensing element by a thin film of ceramic insulation that has a high thermal conductivity. Thus, the strain gages are effectively heat-sinked to the sensing element. High-resistance bridges permit higher excitation voltages at the same power input. This increases the output voltage level and provides a higher signal-to-noise ratio. Where power dissipation is critical, these bridges can be operated at the same voltage as lower resistance bridges, which reduces the power requirement proportionally.

Test requirements and results.--The test program was conducted by Statham Instruments Inc., in accordance with a Statement of Work (SOW) prepared and monitored by AiResearch Manufacturing Company of California. Statham's report summarizing the test program results is presented in Appendix A, together with a copy of the AiResearch SOW showing the directions given to Statham on the scope of the work, etc. The test requirements specified that (1) performance of each unit be recorded at 219°K (-65°F), room temperature, and 394°K (+250°F) in suitable pressure increments between zero and maximum operating pressure; (2) a minimum of 100,000 pressure cycles be applied to each of the four units each month; and (3) the performance be measured each month and at the end of the test program.

General performance.--The output vs input of the four pressure transducers is plotted in Figures 2-3 and 2-4. These units were fabricated to standard catalog tolerances and consequently do not have coincidental performance curves. The amount of spread between each pair of transducers is shown in Figure 2-5.* In order to permit removal and replacement of transducers or subsystems containing new transducers without having to recalibrate the signal-conditioning equipment, it is desirable for all transducers made to a specific part number to have similar output-vs-input characteristics. Representatives of Statham Instruments Inc., indicate that the full-scale sensitivity (represented by the slopes of the curves of Figures 2-3 and 2-4) can be controlled during manufacture to fall within ±1/2 percent full scale of each other. This requirement adds approximately 10 percent to the cost of the transducer. The zero balance also may be restricted to fall within ±1.0 percent of full scale for an additional 10 percent of the cost of the transducer.

Linearity, hysteresis, temperature shift, and stability.--An equation was fitted to the performance data recorded for each of the four test articles before any pressure cycles were conducted. The equations were derived using the least sums square method for the initial 297°K (75°F) test condition. All subsequent performance data consisting of 219°K (-65°F) and 394°K (+250°F) ambient temperature tests and the data recorded following the completion of 500,000 pressure cycles were compared to those derived equations and plotted as a deviation in percent of full scale from these equations. The results are plotted and indicated on Figures 2-6 through 2-13 as a deviation in percent of full scale. Increasing pressures are denoted by solid lines while decreasing pressures are shown by dotted lines. The separation between the dotted and solid lines represents the hysteresis of the unit. The deviation of the dotted and solid lines from zero for the ambient test condition of 297°K (75°F) before pressure cycling (e.g., Figure 2-6) decribes the nonlinearity of the transducer. The increased deviation of the dotted and solid lines from zero for the ambient test condition of 297°K (75°F) (Figure 2-7) is attributable to changes that have taken place in the pressure transducer as a result of the pressure cycles. The before and after cycling test data are shown in Figures 2-6 through 2-13 for each of the four test articles. The deviations from zero for the high and low ambient temperatures describe the performance of the integral temperature-compensation devices and techniques used during fabrication and assembly of the transducers.

The data show that the transducers performed within ±1 percent of the original test data in spite of being subjected to high and low ambient temperatures and a total of 500,000 pressure cycles. The deviation of serial no. 15159 (Figure 2-7) at 394°K (250°F) after 500,000 pressure cycles is slightly

*The performance data recorded for serial numbers 15159 and 15163 were taken as baseline. All comparative data that fall above the baseline data are shown negative and all data that fall below are shown positive, as illustrated in Figure 2-5. This convention is typical for the data plotted in Figures 2-6 through 2-13.

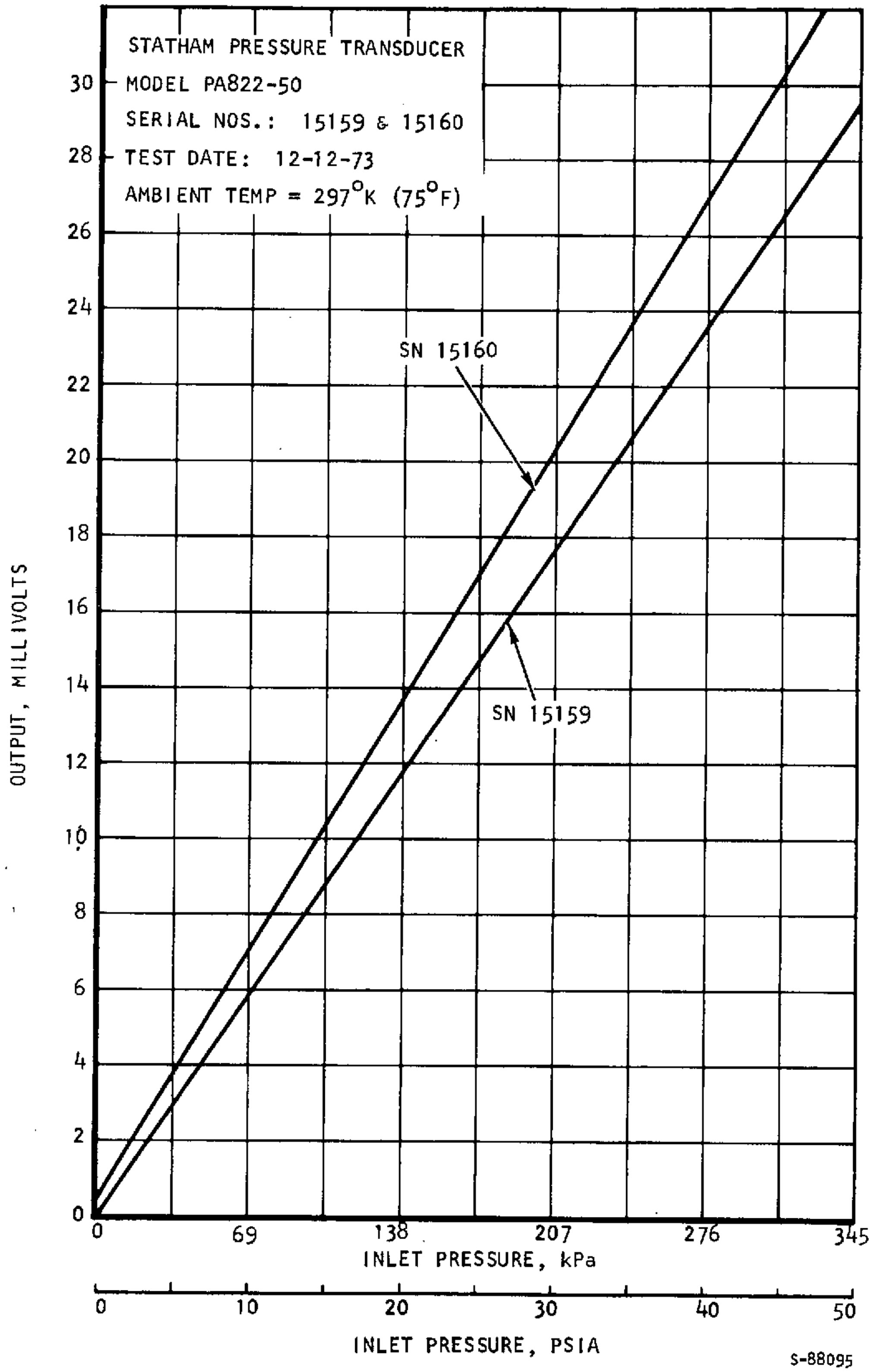



Figure 2-3. Output vs Input of 0- to 345-kPa (0- to 50-psia) Pressure Transducers

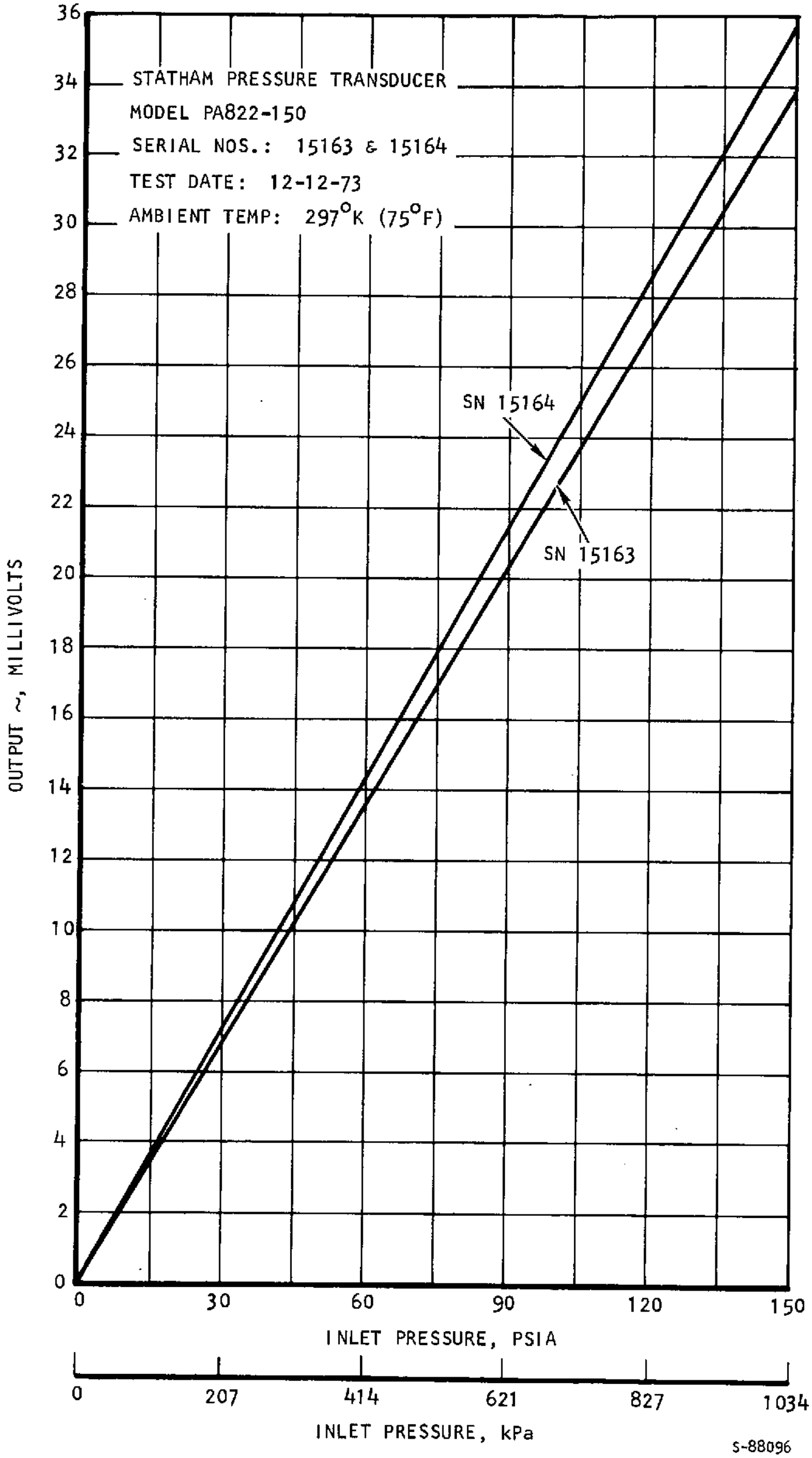



Figure 2-4. Output vs Input of 0- to 1034-kPa (0- to 150-psia) Pressure Transducers

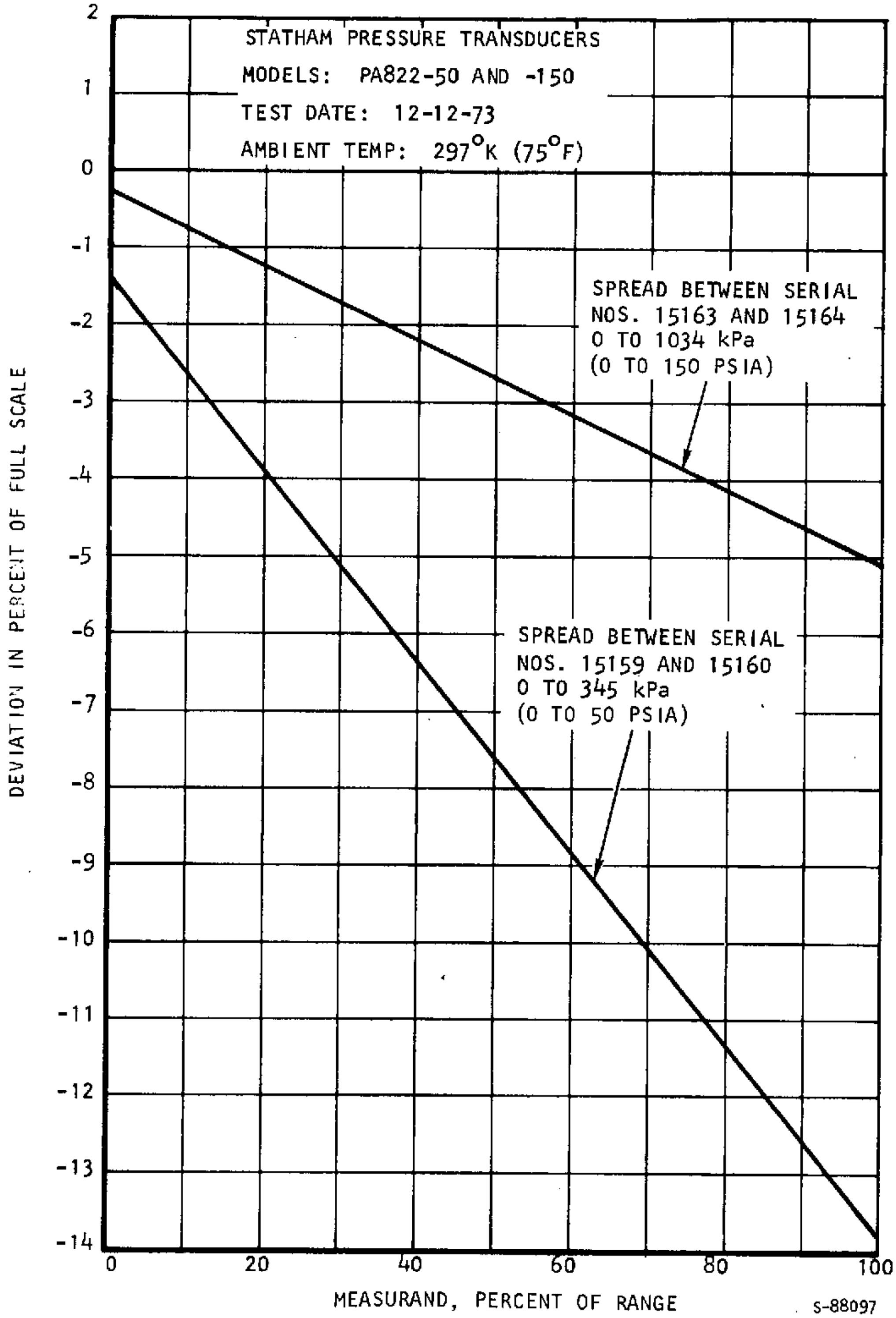



Figure 2-5. Typical Spread Between Catalog Pressure Transducers

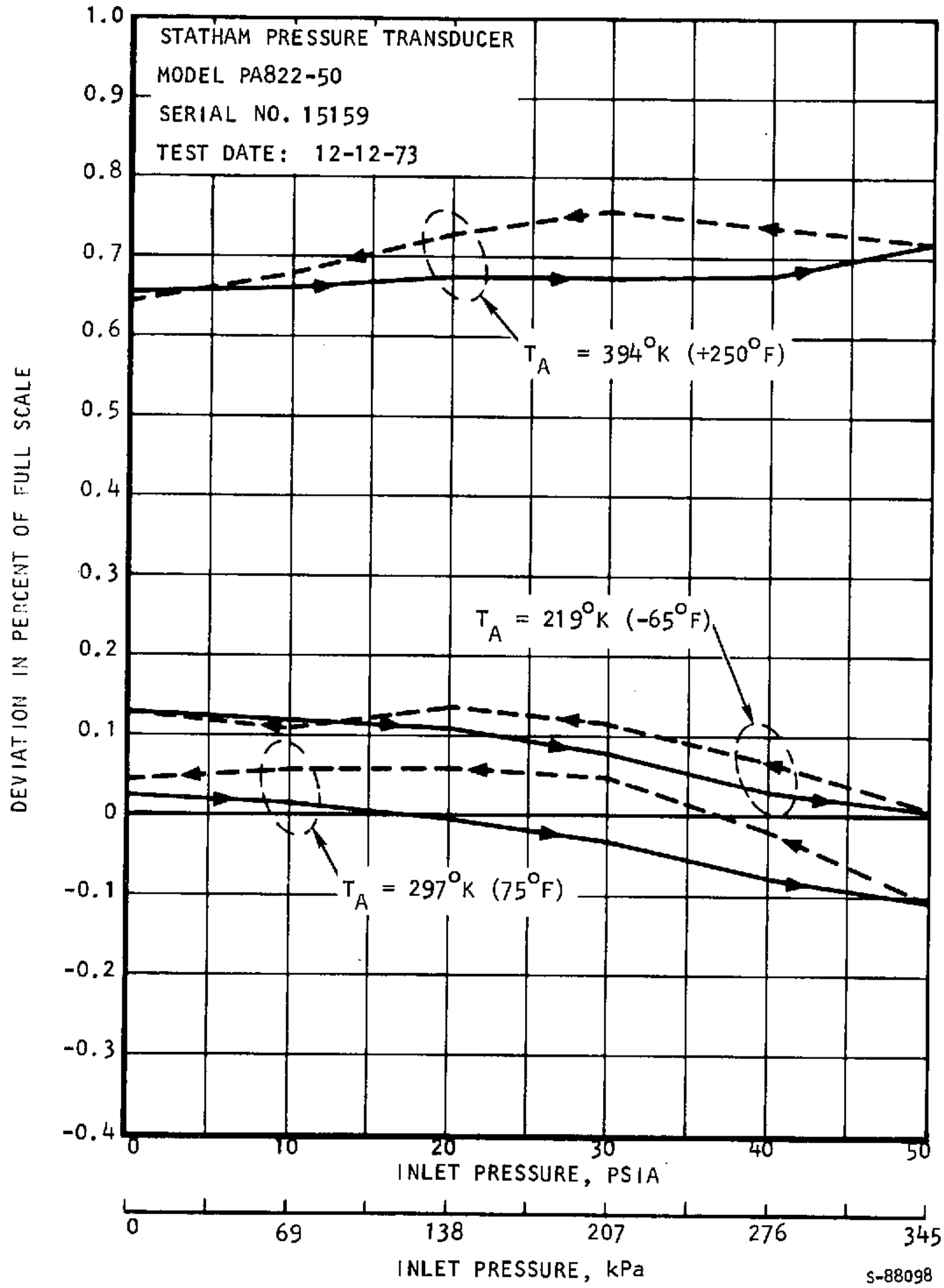



Figure 2-6. Performance Shift vs Temperature before Pressure Cycling

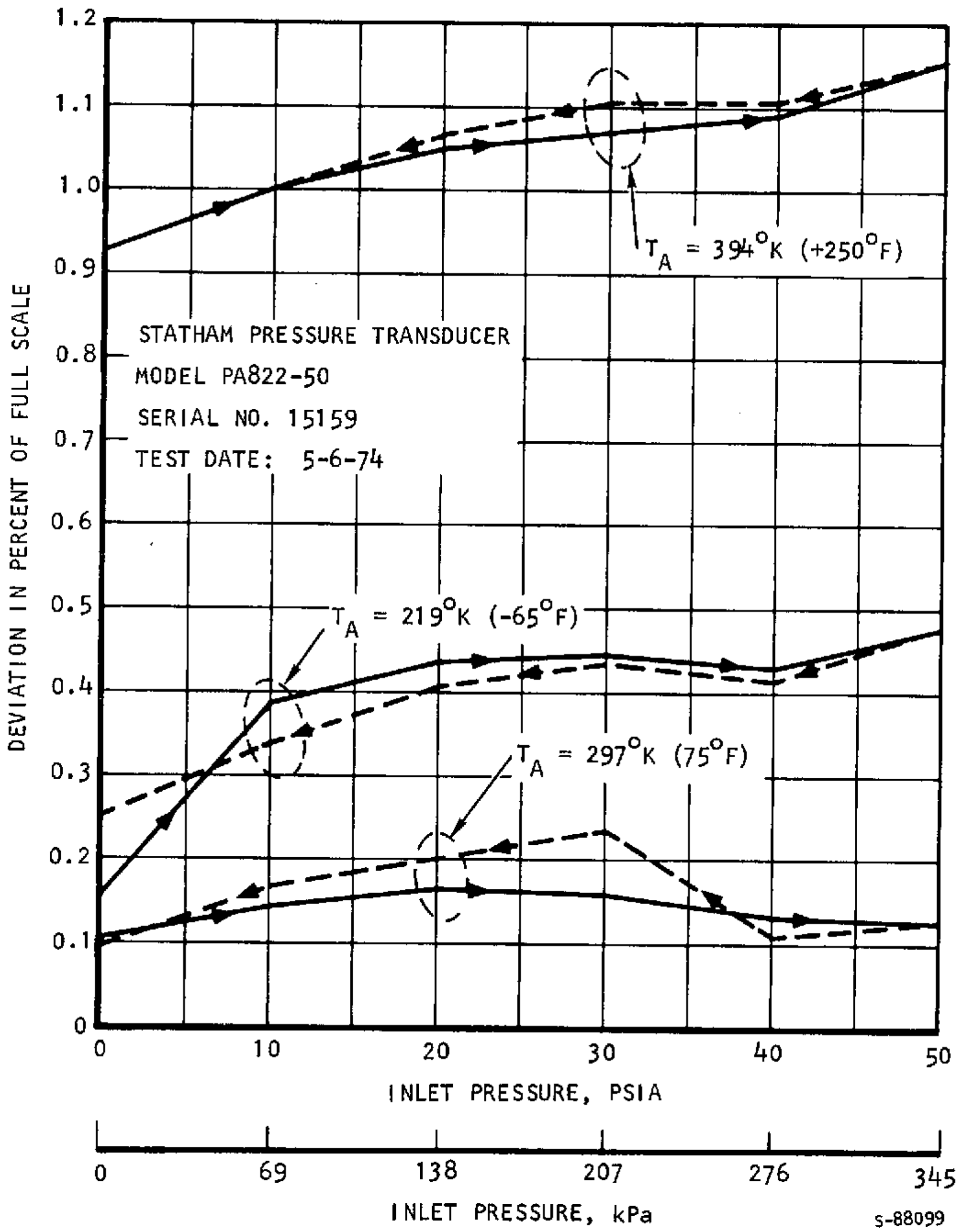



Figure 2-7. Performance Shift vs Temperature after 500,000 Pressure Cycles

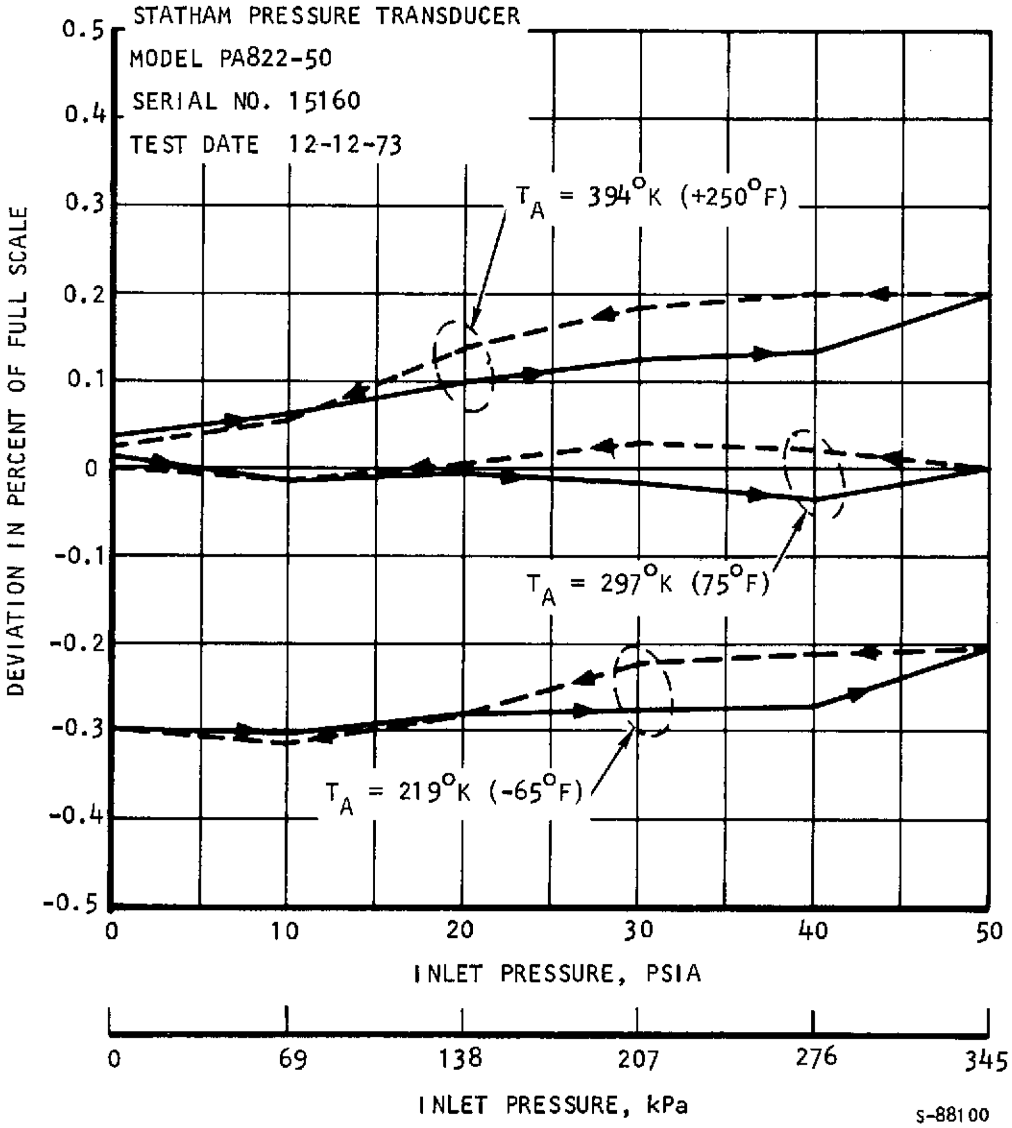



Figure 2-8. Performance Shift vs Temperature before Pressure Cycling

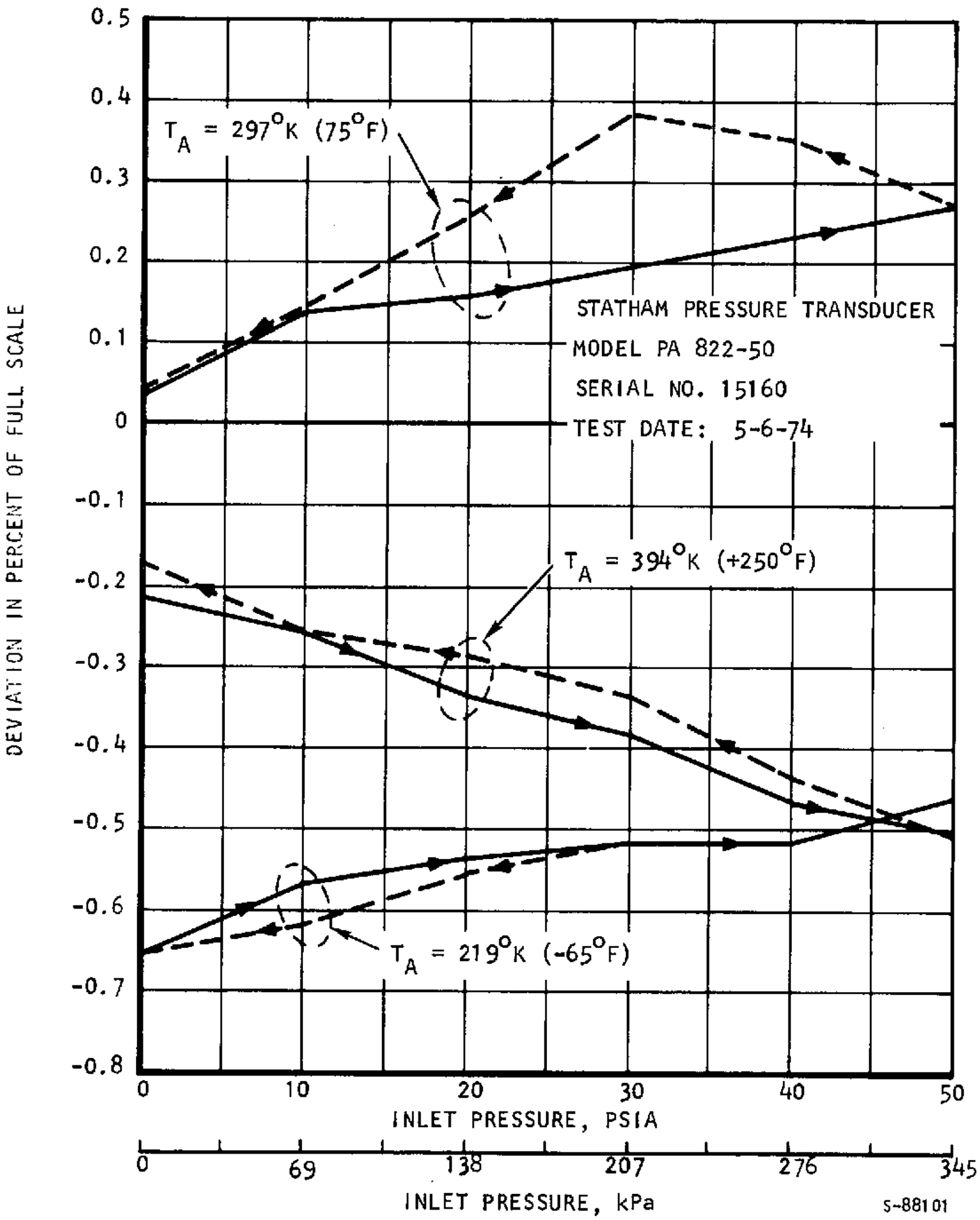



Figure 2-9. Performance Shift vs Temperature after 500,000 Pressure Cycles

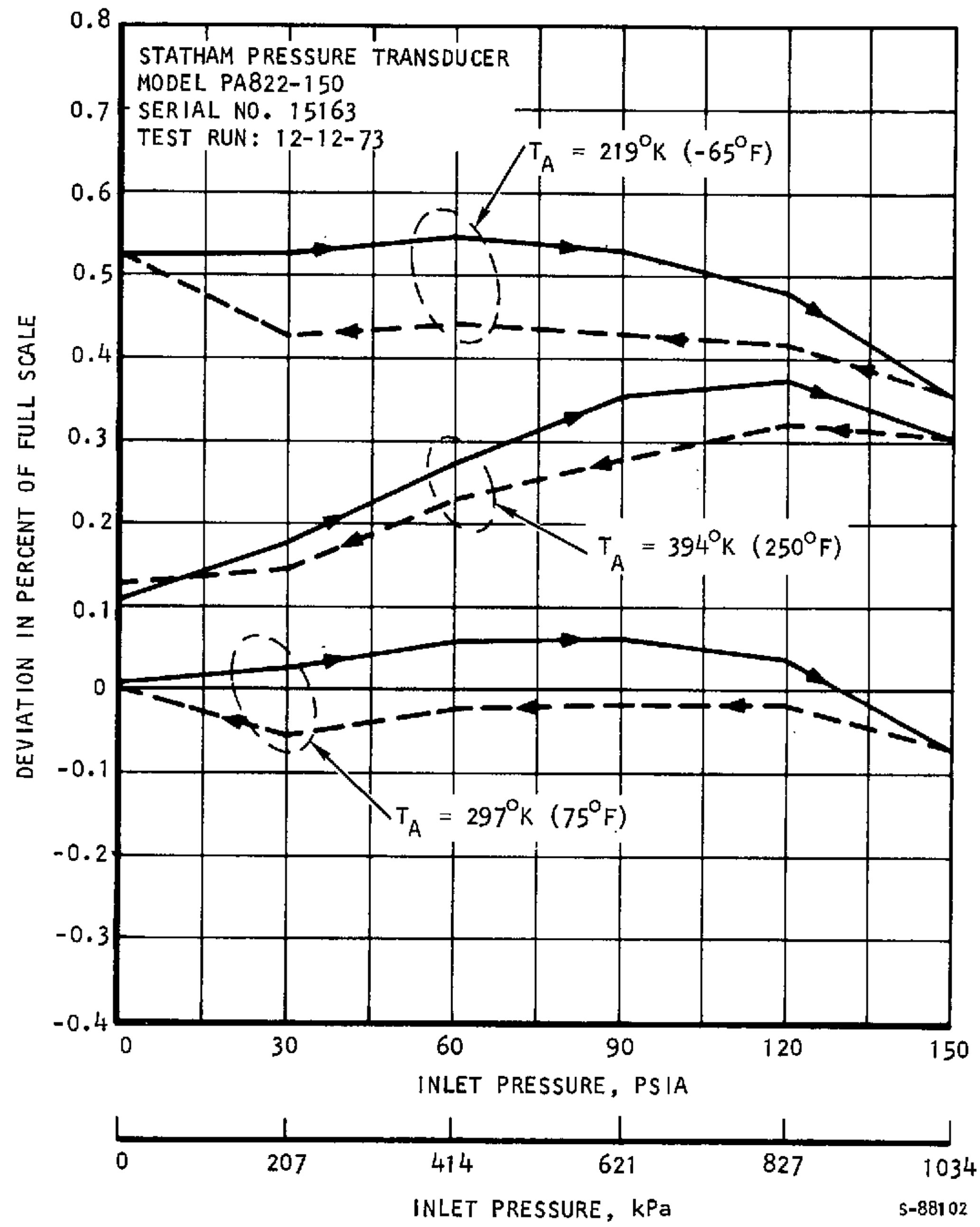



Figure 2-10. Performance Shift vs Temperature before Pressure Cycling

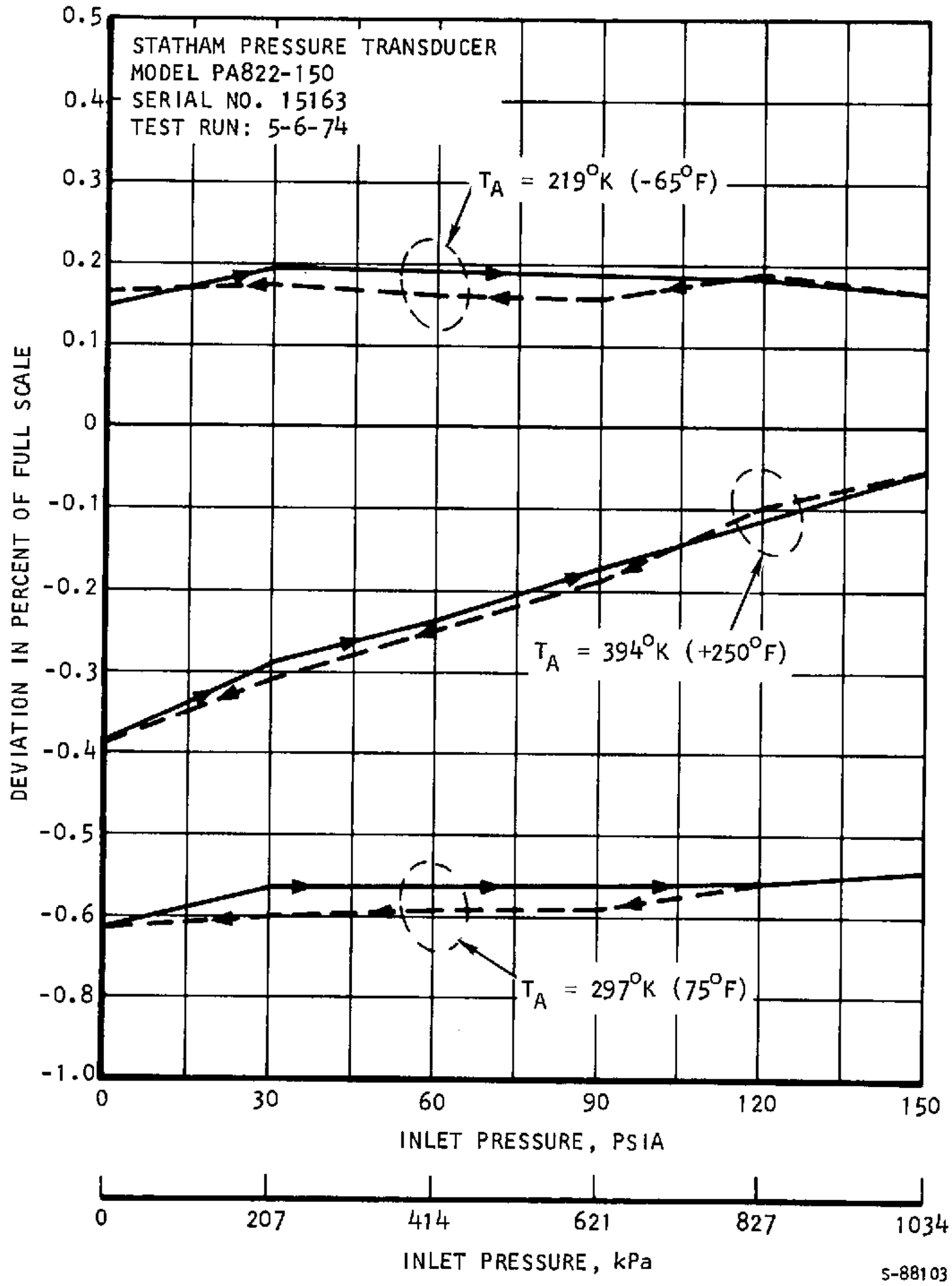



Figure 2-11. Performance Shift vs Temperature after 500,000 Pressure Cycles

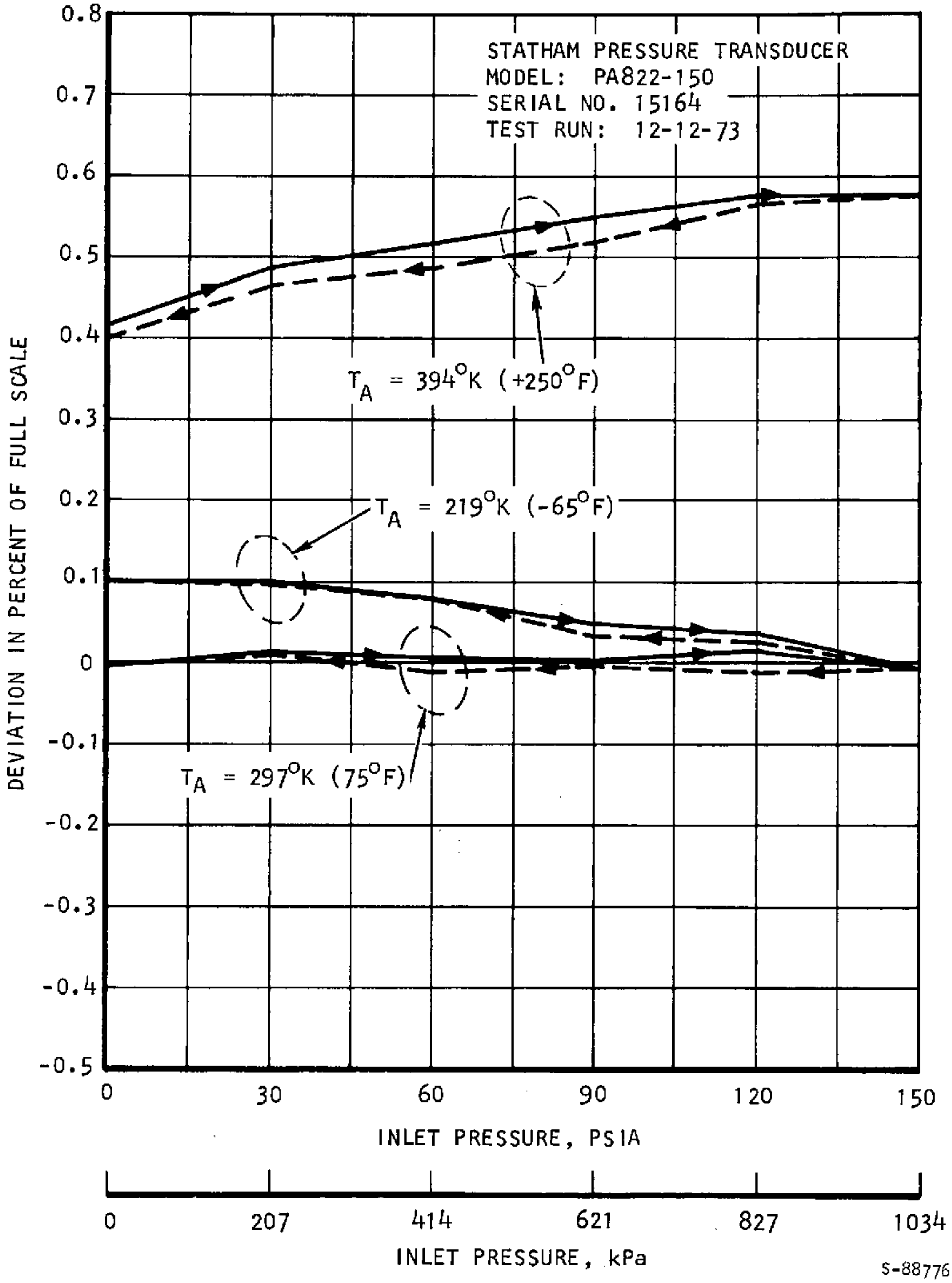



Figure 2-12. Performance Shift vs Temperature before Pressure Cycling

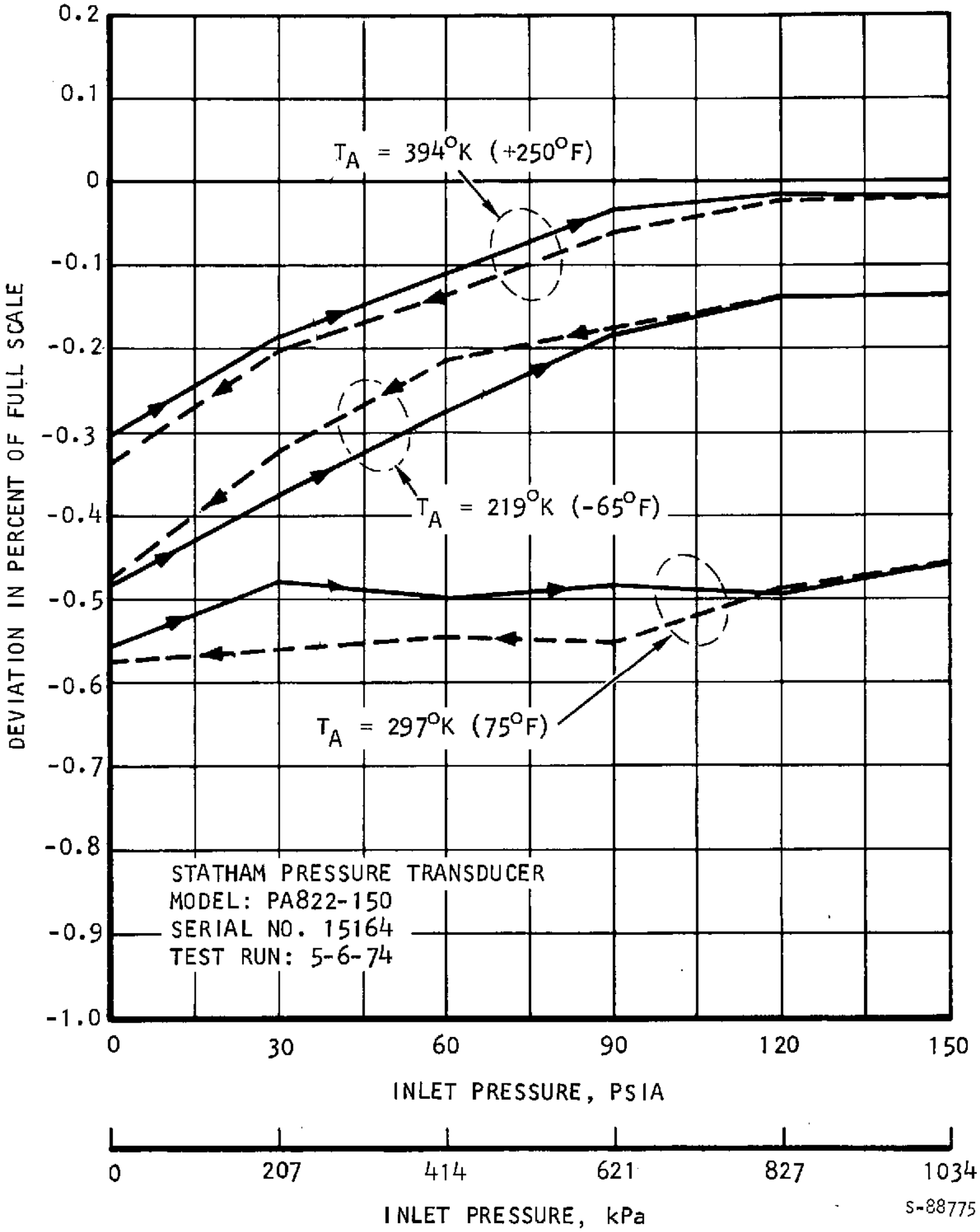



Figure 2-13. Performance Shift vs Temperature after 500,000 Pressure Cycles

above 1 percent of the data based on the least squares equation; however, the original temperature compensation shown in Figure 2-6 for the 394°K (250°F) test condition initially is somewhat high. The transducers are integrally temperature-compensated during fabrication, resulting in very little output deviation as a result of 219°K (-65°F) and 394°K (+250°F) ambient temperatures.

Results and conclusions. --AiResearch elected to reduce the test data in relation to an equation that was fitted to the first set of performance test data. This equation in effect simulates the initial calibration of the Shuttle centralized signal conditioner for each ECS transducer. The test data show that any changes in performance from the transducer as a result of age, life cycle, and ambient temperature changes result in a deviation from the original calibration of no more than ±1 percent. An additional ±1.5 percent deviation should be allowed to accommodate the full-scale sensitivity and zero balance differences from sensor to sensor. Therefore, it is estimated that pressure transducers of the type tested are compatible with the 100-mission-/10-year-life requirement of Shuttle and that they may be replaced during maintenance tasks without the need for recalibration of the signal conditioner, resulting in simplified maintenance. The total error that may be expected over long-term usage (including removal and replacement of transducers) is less than ±3.0 percent of full scale. An error of this magnitude is acceptable for monitoring most ECS operational parameters.

## National Semiconductor Corporation Pressure Transducers

Introduction. --A new family of pressure transducers is being developed for the high-volume industrial requirements of the automotive and appliance fields. These transducers incorporate integrated circuit (IC) technology in their design, fabrication, calibration, and test. As a result, the transducers are extremely small and lightweight. The cost of these units is currently under $100 each for prototype quantities, with an eventual selling price of approximately $10 each predicted for quantities of over 10,000 units. The pressure transducers are available as absolute, differential, and gage units and are suitable for low-pressure (0 to 206.8 kPa) (0 to 30 psia) application.

This section of the report describes the results of a verification test program conducted by AiResearch Manufacturing Company of California on two absolute pressure transducers, model LX1600A, manufactured by National Semiconductor Corporation, Santa Clara, California.

Background. --Pressure transducers have undergone a comparatively slow development from mechanical to electromechanical to the more recent integrated circuit technology, because the demand has been for a multitude of short-run configurations that did not warrant the expenditure for high-volume, low-cost transducers. Mechanical transducers originally were custom-built by craftsmen who first used potentiometer wipers and unbonded strain gages, then cemented strain gages, and more recently deposited and diffused pickoff elements. Test and calibration also have contributed greatly to the high cost of state-of-the-art transducers.

The high-volume industrial requirements for pressure transducers in the automotive and appliance industries have permitted major investments in the development and manufacture of high-quality, lightweight, low-cost pressure transducers. This new family of transducers is taking advantage of integrated circuit (IC) technology for fabrication, calibration, and test; the price of the end product will be similar to the price of the integrated circuit.

Description of pressure transducer. -The National Semiconductor pressure transducer consists of a Wheatstone-bridge arrangement of four piezoresistors diffused into a silicon chip. The silicon chip is a 1-mil-thick pressure diaphragm that has been etched out of one wall of a vacuum reference cell or cavity, as shown in Figure 2-14a. The pressure transducer device is contained on a single ceramic substrate, along with an array of thick-film signal-processing resistors, mechanical enclosures, and two operational amplifiers that serve as a buffer amplifier and output amplifier, as shown in Figure 2-14b.

All four of the basic transduction elements shown in Figure 2-15 are contained in one small package. The physical dimensions of the absolute pressure transducer model LX1600A are shown in Figure 2-16, while the differential pressure transducer is shown in Figure 2-17. The gage pressure transducer is configured similar to the absolute pressure transducer.

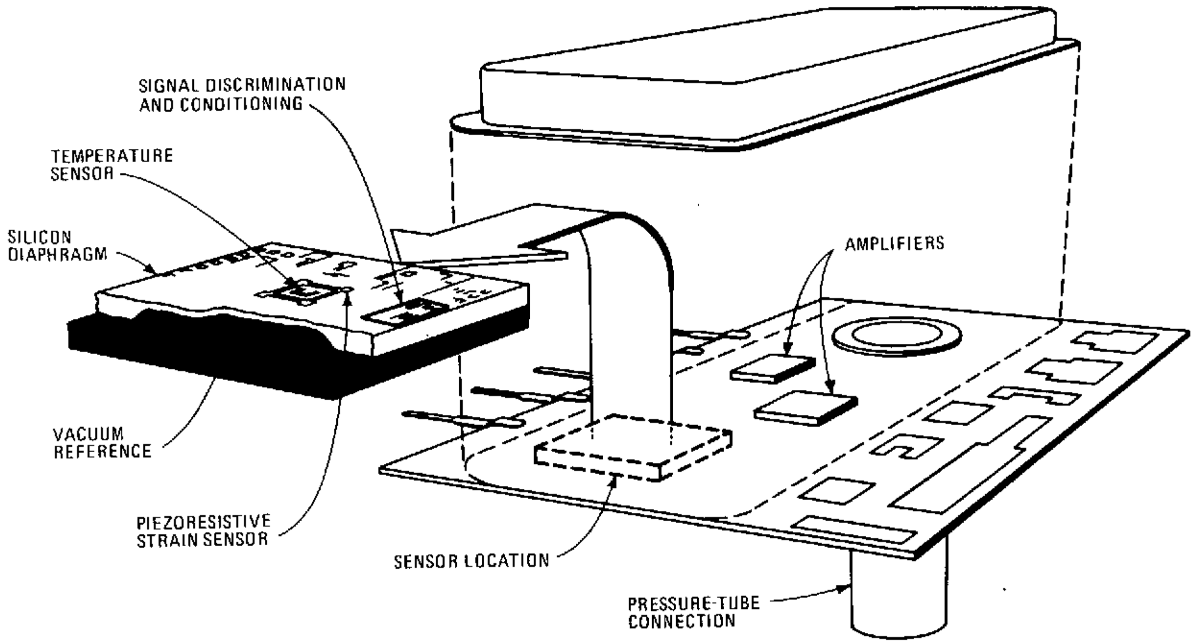



Figure 2-14a. Exploded View of Absolute Pressure Sensor

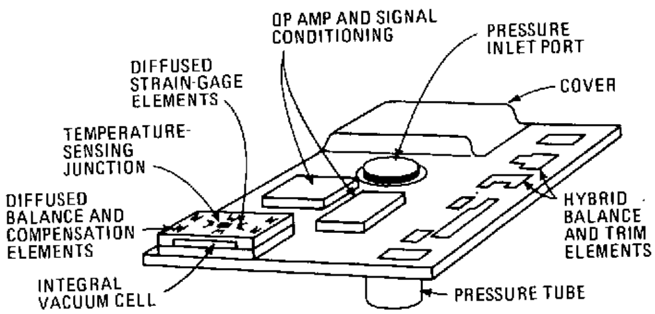



Figure 2-14b. Absolute Pressure Transducer

Figure 2-14. National Semiconductor Corporation Pressure Transducer

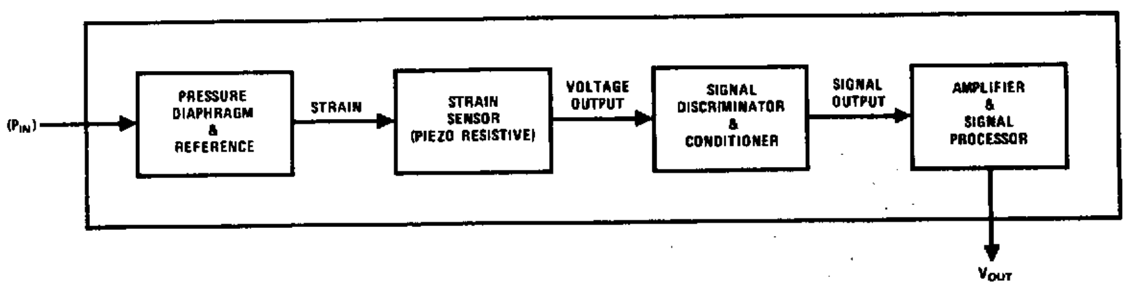
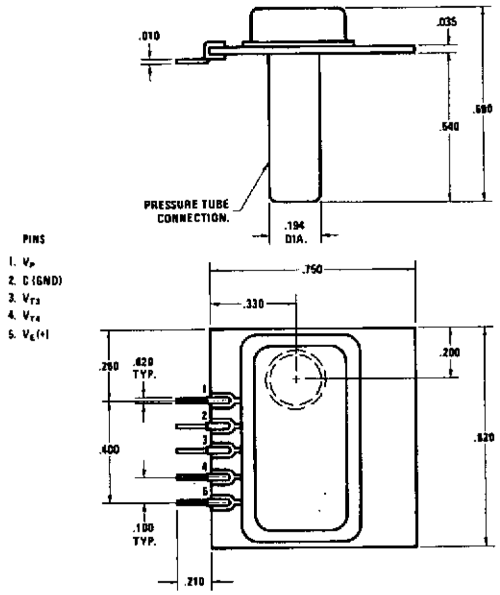
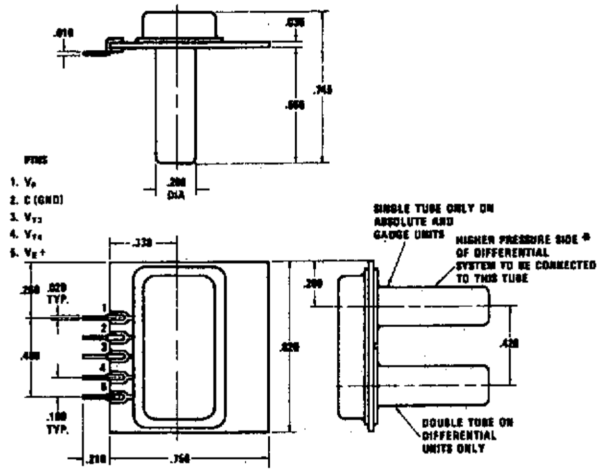



Figure 2-15. Block Diagram




(Dimensions shown are in inches)

Figure 2-16. Absolute Pressure Transducer

Figure 2-17. Differential Pressure Transducer

The actual weight of the LX1600A absolute pressure transducer is 5 grams. The units representative of this weight are shown in Figure 2-18.

Performance and design data taken from the National Semiconductor brochures are presented in Table 2-1.

<u>Verification test program.</u>--Two absolute pressure transducers, model LX1600A, serial numbers 175 and 188, were procured from National Semiconductor Corporation, Mountain View, California, for the test program described herein. Laboratory tests were conducted on these units by AiResearch during the early part of 1973. The test procedure and actual test data are contained in Appendix B. A portion of the test data was reduced and plotted; it is described in the following paragraph.

The test data taken on January 15, 1973, (Appendix B) were reduced for the 295.5°K (72°), 233.3°K (-40°F), and 333.3°K (+140°F) test runs. The data are shown on the performance-vs-temperature curves of Figures 2-19 and 2-20. A smooth curve was calculated using the least squares method from the 295.5°K (72°F) test data for both serial numbers 175 and 188. The deviation between actual performance and the least squares equation was calculated as an error in percent of full scale for the 295.5°K (72°F), 233.3°K (-40°F), and 333.3°K (+140°F) test runs. All three sets of temperature test data were related to the least squares equation calculated for the 295.5°K (72°F) test data. A separate least squares equation was calculated for each of the two serial-numbered units. Figures 2-21 and 2-22 show the deviation resulting from linearity and hysteresis and also the shift in performance at high and low ambient temperatures.

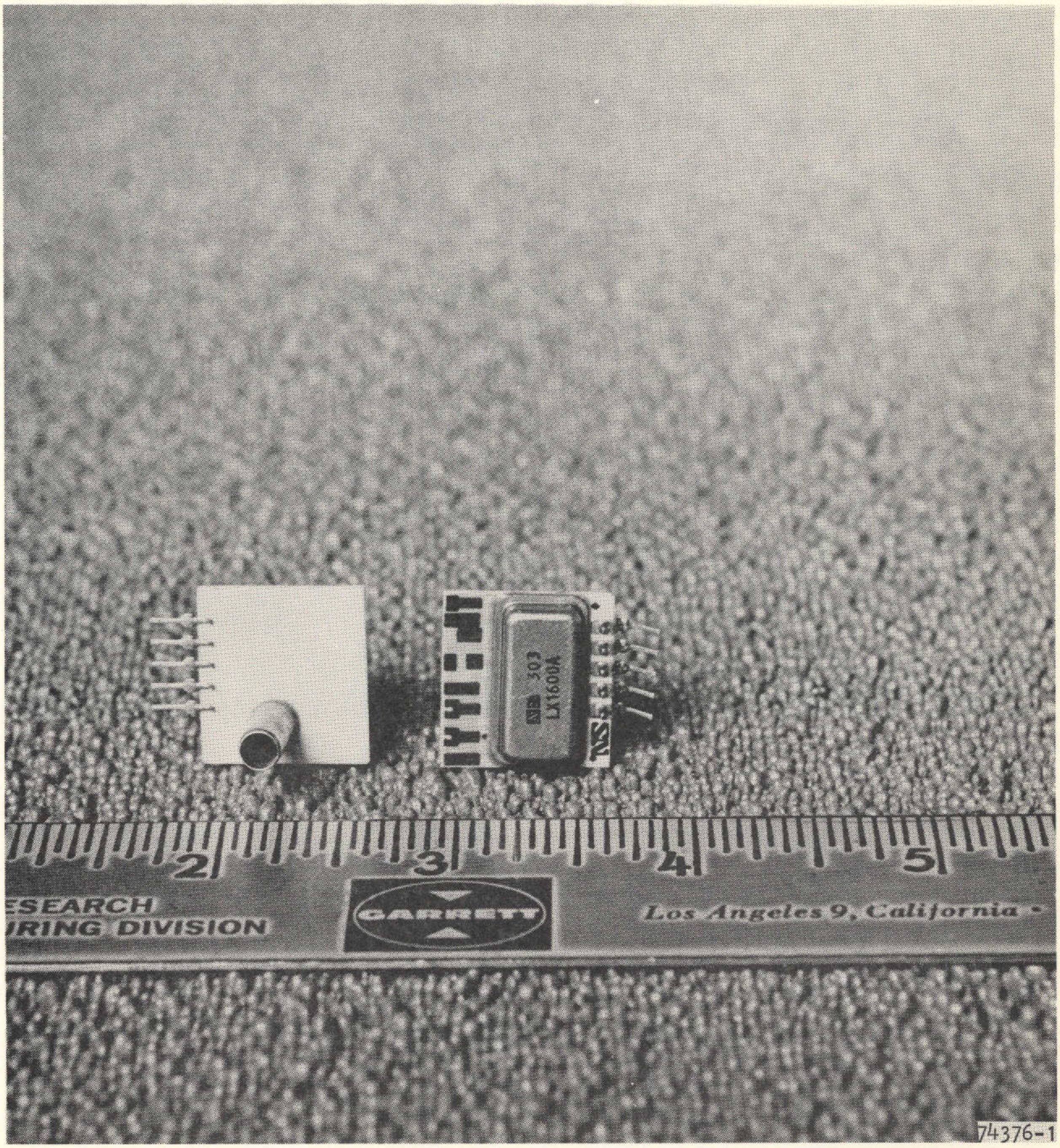



Figure 2-18. National Semiconductor Model LX1600A Absolute Pressure Transducer (two units shown) (6-in. ruler shown for comparison)

## TABLE 2-1

## PERFORMANCE AND DESIGN CHARACTERISTICS

Absolute Maximum Ratings

| | |
|---|---|
| Excitation voltage | 30 vdc |
| Output current | 5 mA |
| Temperature sensing current | 100 μA |
| Operating and storage temperature range | 233.3°K to 388.8°K (-40°F to +240°F) |
| Bias current at 15v excitation | 15 mA |
| Lead temperature (soldering, 10 sec) | 573.3°K (572°F) |

Nominal Characteristics 294.4°K (+70°F, 15v excitation)

Absolute Transducers

| Output Voltage ±1.5% Span (±150 mv) | | Calibrated Pressure Range, psia* LX1601A LX1701A | LX1602A LX1702A | LX1603A LX1703A |
|---|---|---|---|---|
| 2.5v | Low-pressure End-point | 10 | 0 | 0 |
| 7.5v | Midrange | 15 | 7.5 | 15 |
| 12.5v | High-pressure End-point | 20 | 15 | 30 |
| Maximum allowable overpressure | | 40 | 40 | 50 |

Gage and Differential Transducers

| Output Voltage ±1.5% Span (±150 mv) | | Calibrated Pressure Range, psig* LX1601G LX1701G LX1601D | LX1602G LX1702G LX1602D | LX1603G LX1703G LX1603D | LX1604G LX1704G LX1604D |
|---|---|---|---|---|---|
| 2.5v | Low-pressure End-point | -5 | 0 | 0 | -15 |
| 7.5v | Midrange | 0 | 7.5 | 15 | 0 |
| 12.5v | High-pressure End-point | +5 | 15 | 30 | +15 |
| Maximum allowable overpressure | | 30 | 40 | 50 | 40 |

*SI conversions are as follows:
psia x 6895 = Pa
(psig + 14.696) 6895 = Pa
psid x 6895 = Pa

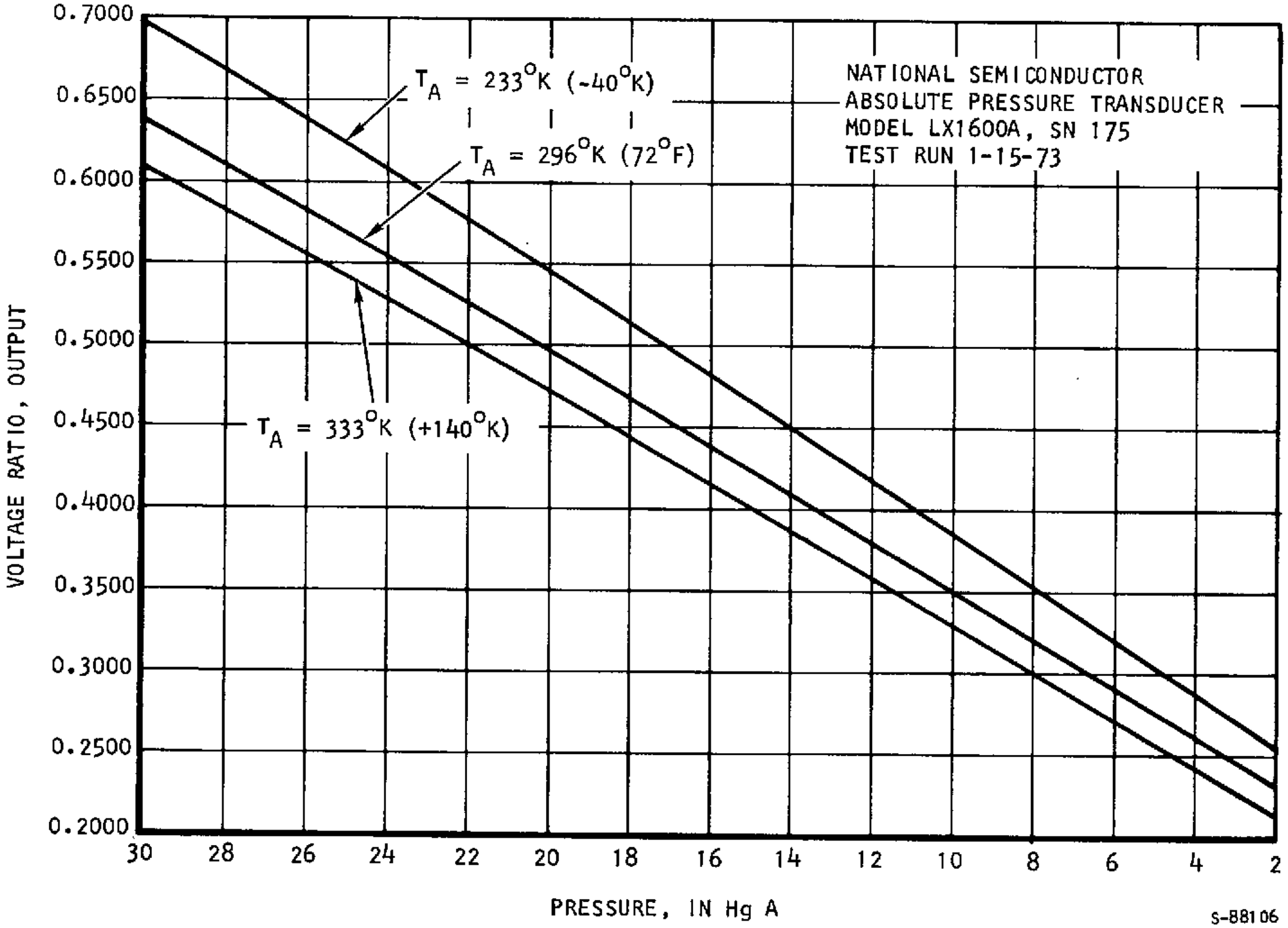



Figure 2-19. Performance vs Temperature

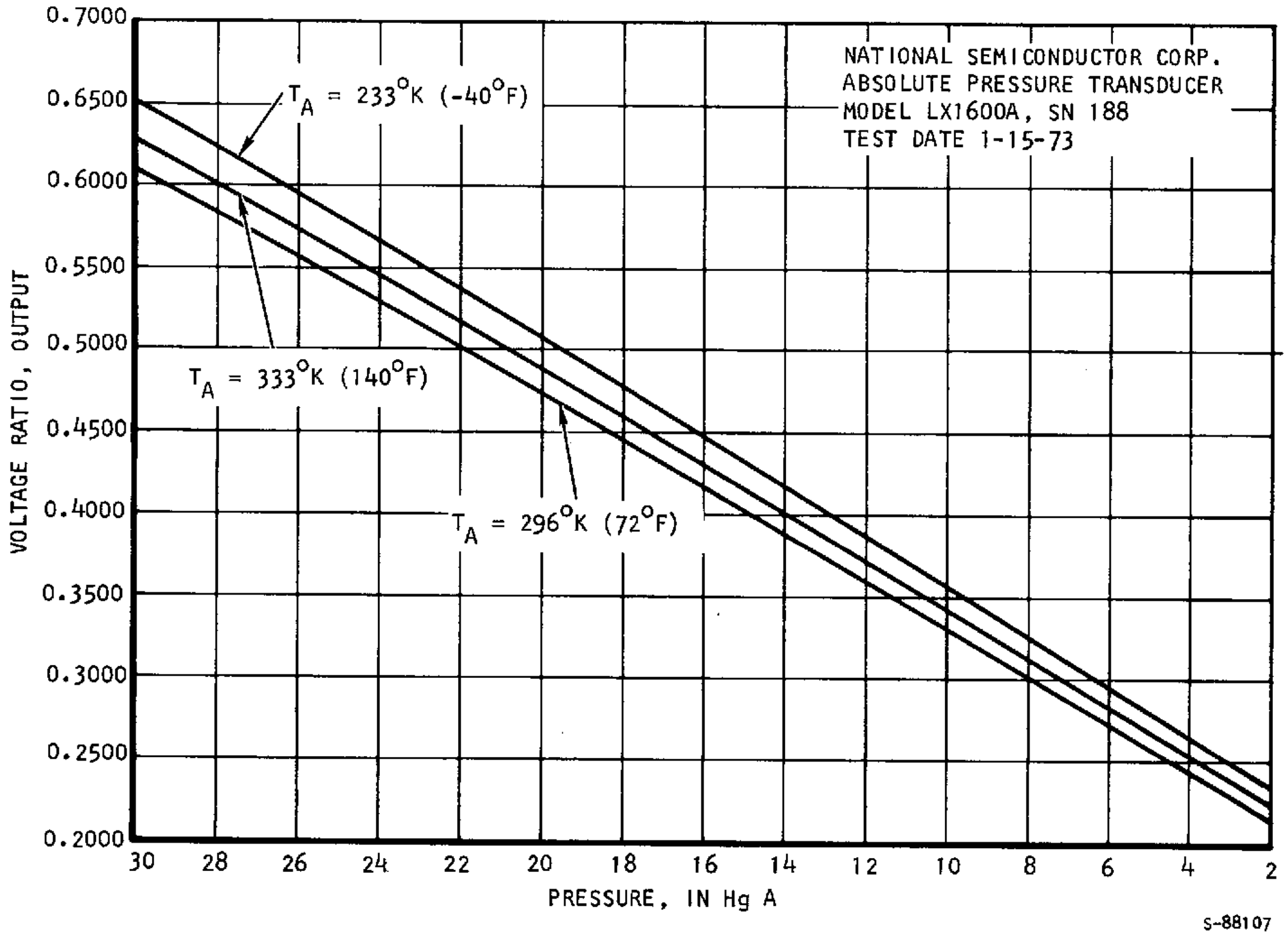



Figure 2-20. Performance vs Temperature

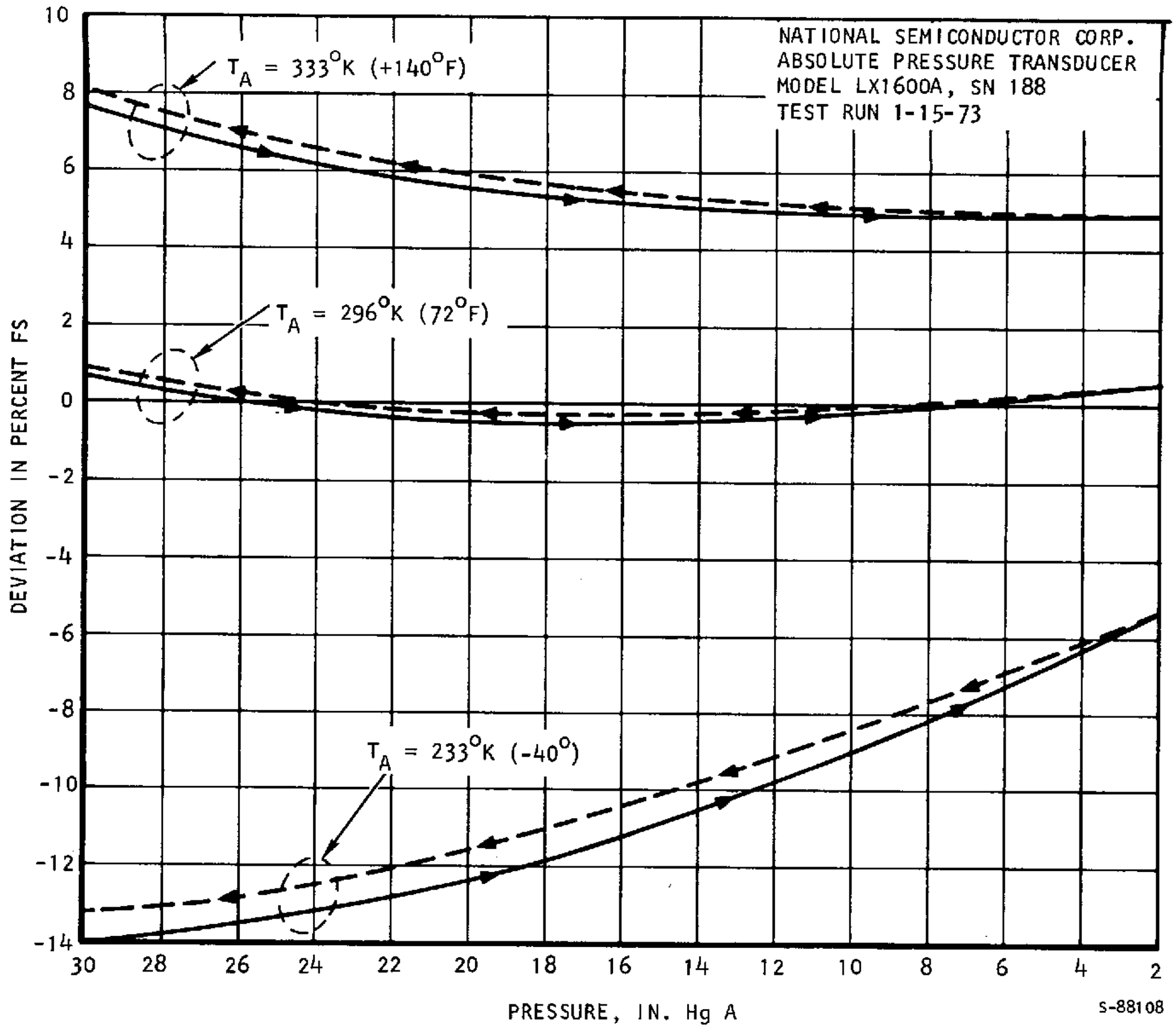



Figure 2-21. Performance Shift vs Temperature

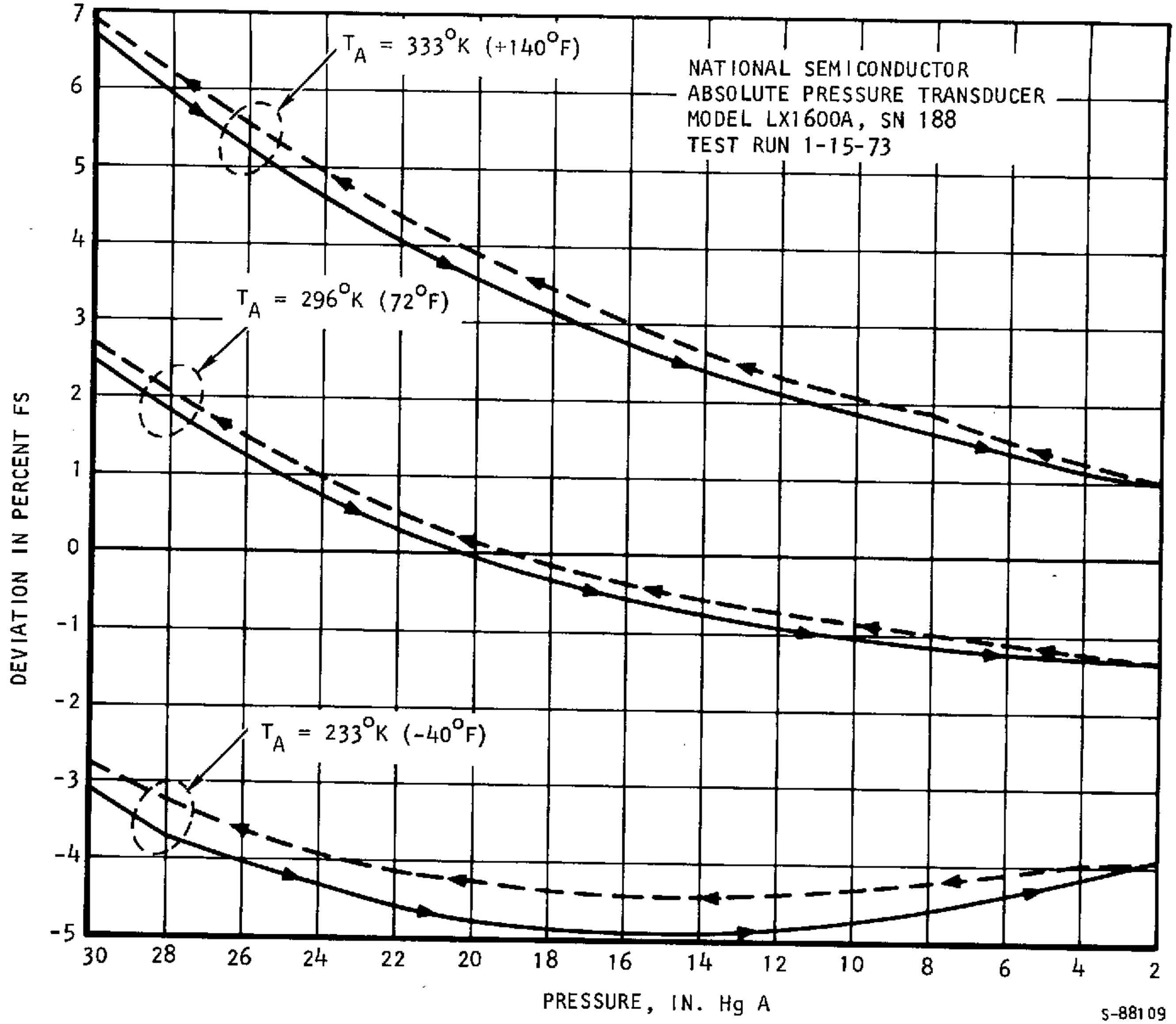



Figure 2-22. Performance Shift vs Temperature

Results and conclusions. --The performance of the two National Semiconductor Corporation absolute pressure transducers tested by AiResearch shows a large deviation with changes in ambient temperature. The linearity and hysteresis of serial number 175 at 295.5°K (72°F) (Figure 2-21) causes a deviation of less than ±1 percent of full scale. This represents an acceptable degree of accuracy for many aerospace applications; however, the performance shift experienced at high and low ambient temperatures would not be acceptable for most applications without additional temperature compensation. These pressure transducers are a relatively new development and undoubtedly will be improved as mass production techniques and tooling are refined. The small size, low weight, and low cost are attractive features that warrant a continuing interest in adapting these transducers to applications in the aerospace industry.

National Semiconductor Corporation personnel state that a Model LX3700 currently supersedes Model LX1600A; it performs with improved temperature stability and incorporates a more rugged package to withstand handling and installation stresses. The Model LX1600A is available to support existing installations; however, Model LX3700 is recommended by National Semiconductor Corporation for all new design applications.

Model LX3700 was not tested by AiResearch during the course of this program.

## Fairchild Semiconductor Components Group Pressure Transducers

Introduction. --This subsection describes a low-cost, automotive-type pressure transducer manufactured by Fairchild Semiconductor Components Group, Mountain View, California, and includes the results of a verification test program conducted by AiResearch Manufacturing Company of California on two of the pressure transducers.

Background. --Federal requirements for reduced emissions from automotive engines in 1975, and the need for greater fuel economy, have motivated automobile manufacturers to develop electronic fuel injection systems that require low-cost, accurate, absolute pressure transducers. The severity of the environment, i.e., temperature, vibration, shock, cleanliness, and rugged handling, as well as the extreme cyclic life requirements (including long service life capability) ensure that transducers meeting these requirements have more than adequate capability for most aerospace applications.

The large demand potential has generated ideas and methods for the development of a low-cost, rugged, and reliable transducer that meets the goals of the automotive industry. These automotive transducers soon may find application in other areas such as:

- Altitude sensing
- Fluid level sensing
- Environmental control
- Air conditioning coolant pressure monitoring
- Low-pressure gas reservoir monitoring
- Aircraft instrumentation
- Process instrumentation

After consideration of their potential applications, it was decided to test two off-the-shelf Fairchild absolute pressure transducers.

Description of test articles. --The absolute pressure transducers used in this test program were manufactured by Fairchild Semiconductor Components Group, Fairchild Camera and Instrument Corporation, 464 Ellis Street, Mountain View, California 94042. The test units are identified as Model SH 4207, Serial No. 31006 and Model SH 4208, Serial No. 30874. The units are identical in appearance (Figure 2-23); however, Model SH 4207 is priced at $160 each as compared with $100 each for Model SH 4208, because of additional screening for greater accuracy. The projected cost of these units is $10 each for quantities in excess of 10,000 units; these production levels are anticipated in the second half of 1974.

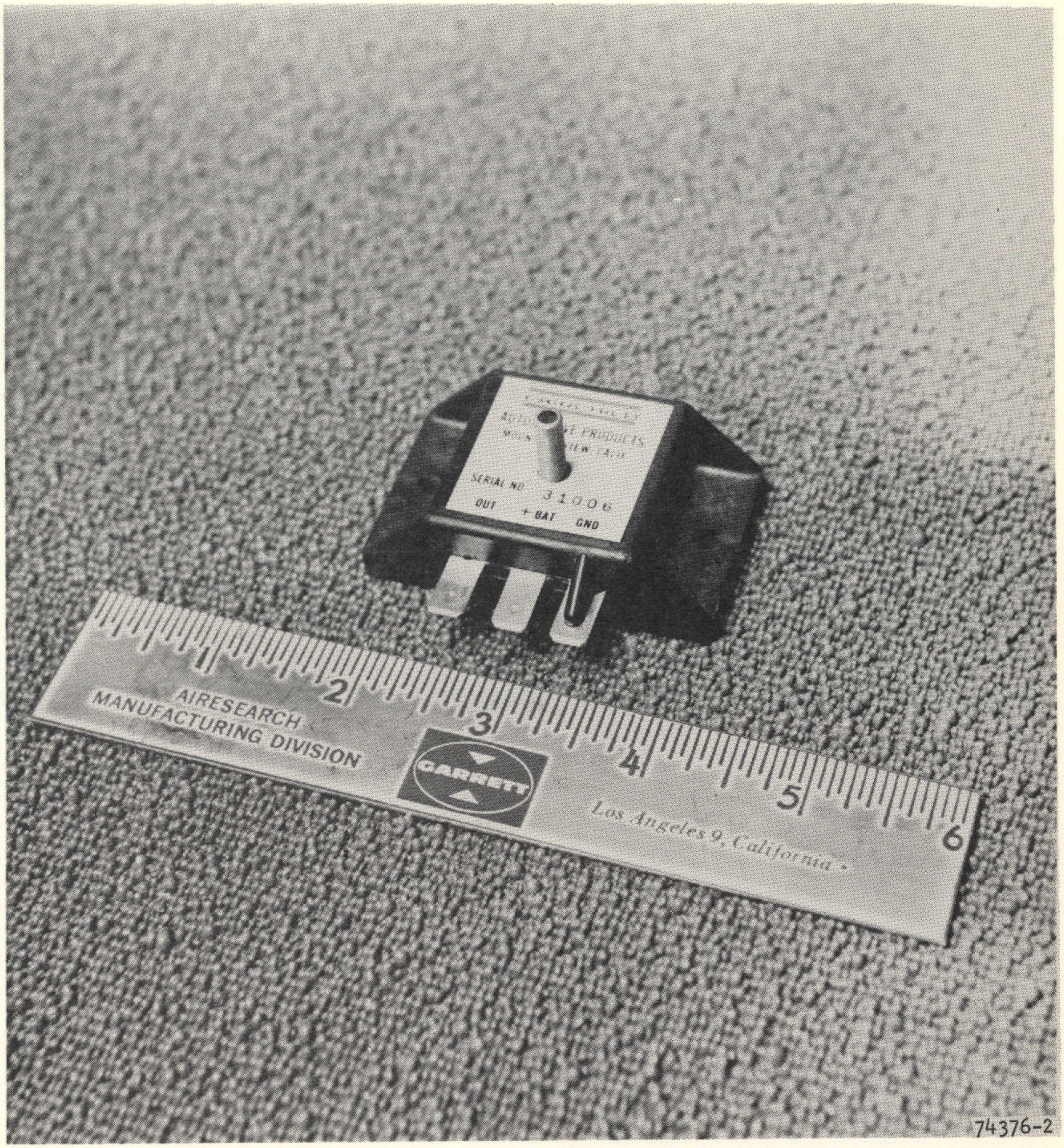



Figure 2-23. Fairchild Absolute Pressure Transducer, Model 4207 (6-in. ruler shown for comparison)

The two test units were procured from an electronic retail parts supplier as off-the-shelf units.

The pressure transducers incorporate a single-crystal diffused silicon strain gage with a self-contained zero-pressure reference chamber. Two linear operational amplifiers are incorporated for temperature compensation, offset adjustment, and scale factor control. A single-chip voltage regulator is incorporated for accurate control of the voltage supplied to the sensor and amplifier from an external voltage source that may vary between 8 and 32 vdc. The transducer delivers a voltage in response to changes in absolute pressure in accordance with the following relationship:

$$V_{out} = 1.500 + 0.1\ P_{abs}$$

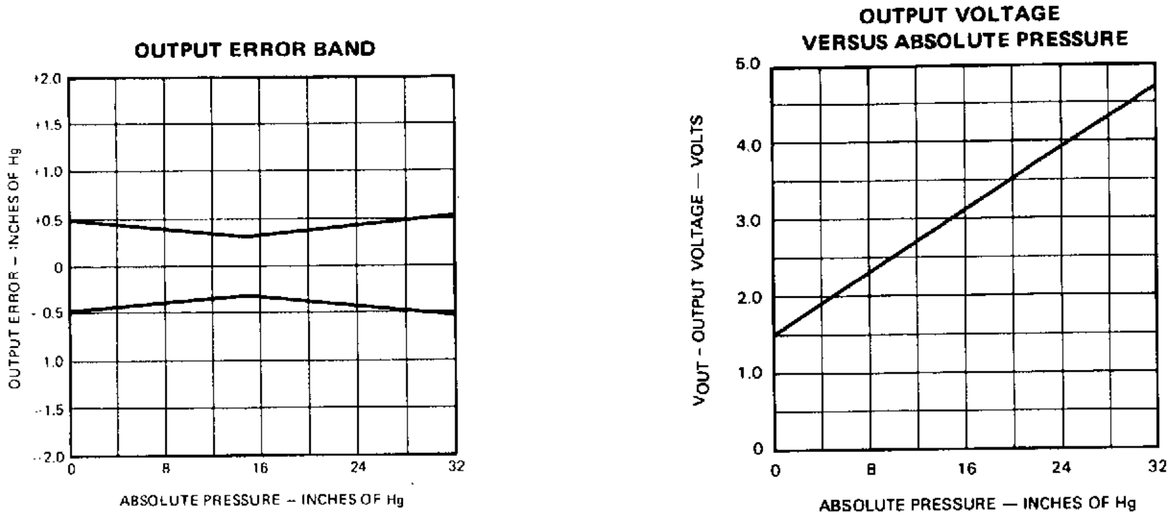
(where $P_{abs}$ is given in in. Hg and $V_{out}$ in volts).

Criteria. --Following are the operating characteristics of the Fairchild transducer:

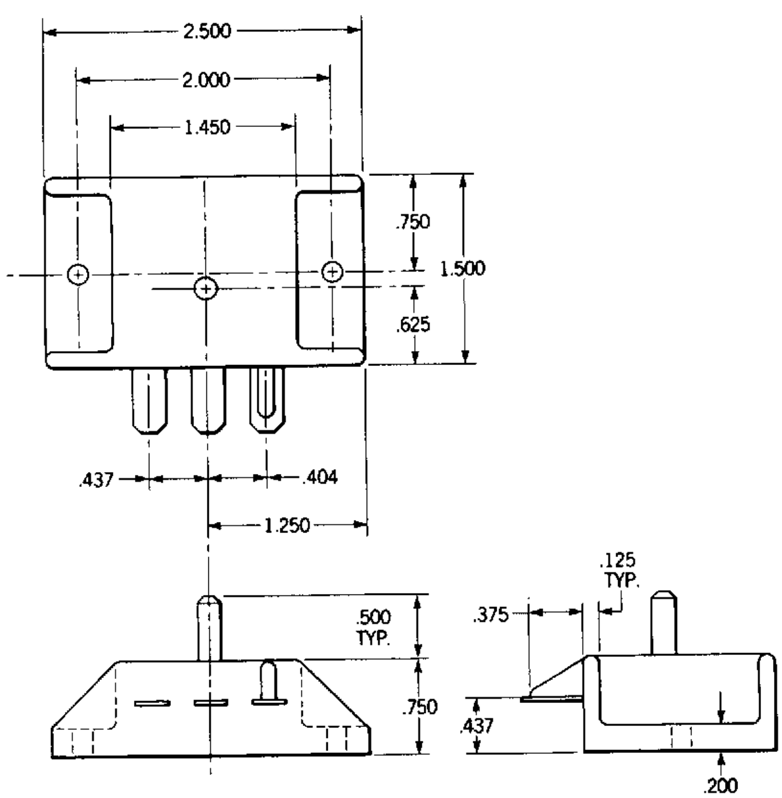
| | |
|---|---|
| Input voltage | 8 to 18 vdc |
| Applied pressure | 0 to 32 in. Hg<br>Full scale = 32 in. Hg abs |
| Output characteristics | See typical performance curves in Figure 2-24 |
| Ambient temperature | 256°K (0°F) to 367°K (200°F) |

The absolute maximum ratings are as follows:

| | |
|---|---|
| Operating temperature range | 233°K (-40°F) to 367°K (200°F) |
| Storage temperature range | 233°K (-40°F) to 367°K (200°F) |
| Input voltage | 32 vdc |
| Applied pressure | 60 in. Hg abs |
| Envelope and weight | See outline dimensions in Figure 2-24. Actual weight of test articles is 52 grams. |




Typical Performance Curves




Outline Dimensions

(Dimensions are noted in inches)

Figure 2-24. Fairchild Transducer

Verification Test Program. --The two pressure transducers, Models 4207 and 4208, were subjected to performance tests at room temperature, 231°K (-44°F), 334°K (+142°F), and 563 pressure cycles. An equation representing the input-output characteristics was calculated from the initial performance test data recorded for each of the two test articles. The equation was determined by the least squares method, which in effect simulates the calibration of the signal conditioner for the applicable parameter to be monitored. All subsequent test data were compared to the calculated equations for each of the two test articles, and are shown in errors or deviations in percent of full-scale output. Figures 2-25 and 2-26 show the actual shift in performance resulting from high and low ambient temperatures and pressure cycling. The hysteresis resulting from the application of decreasing and increasing absolute pressures also is shown for each of the test conditions in Figures 2-25 and 2-26. Decreasing pressure is represented by a solid line and increasing pressure is represented by a dashed line. The test data gathered during the verification test program, including a test schematic and leakage test data, are contained in Appendix C.

Results and Conclusions. --The performance of the two Fairchild absolute pressure transducers tested by AiResearch shows that the transducers are repeatable to within 1 percent of full scale during the actual test temperature extremes of 231°K (-44°F) and 334°K (+142°F), including the application of 563 pressure cycles. The more expensive Model 4207 shows a deviation of approximately 1.2 percent as compared with approximately 0.9 percent for Model 4208. The more expensive model should have performed with better accuracy because of the extra screening it receives during manufacture. Neither of the test units was marked with a model number and consequently the units may have been incorrectly identified. Both transducers show excellent repeatability for off-the-shelf production articles. The small size, light weight, low cost, and good performance characteristics displayed by the two test articles are desirable features for satisfying the low-pressure monitoring applications in the Shuttle Environmental Control System.

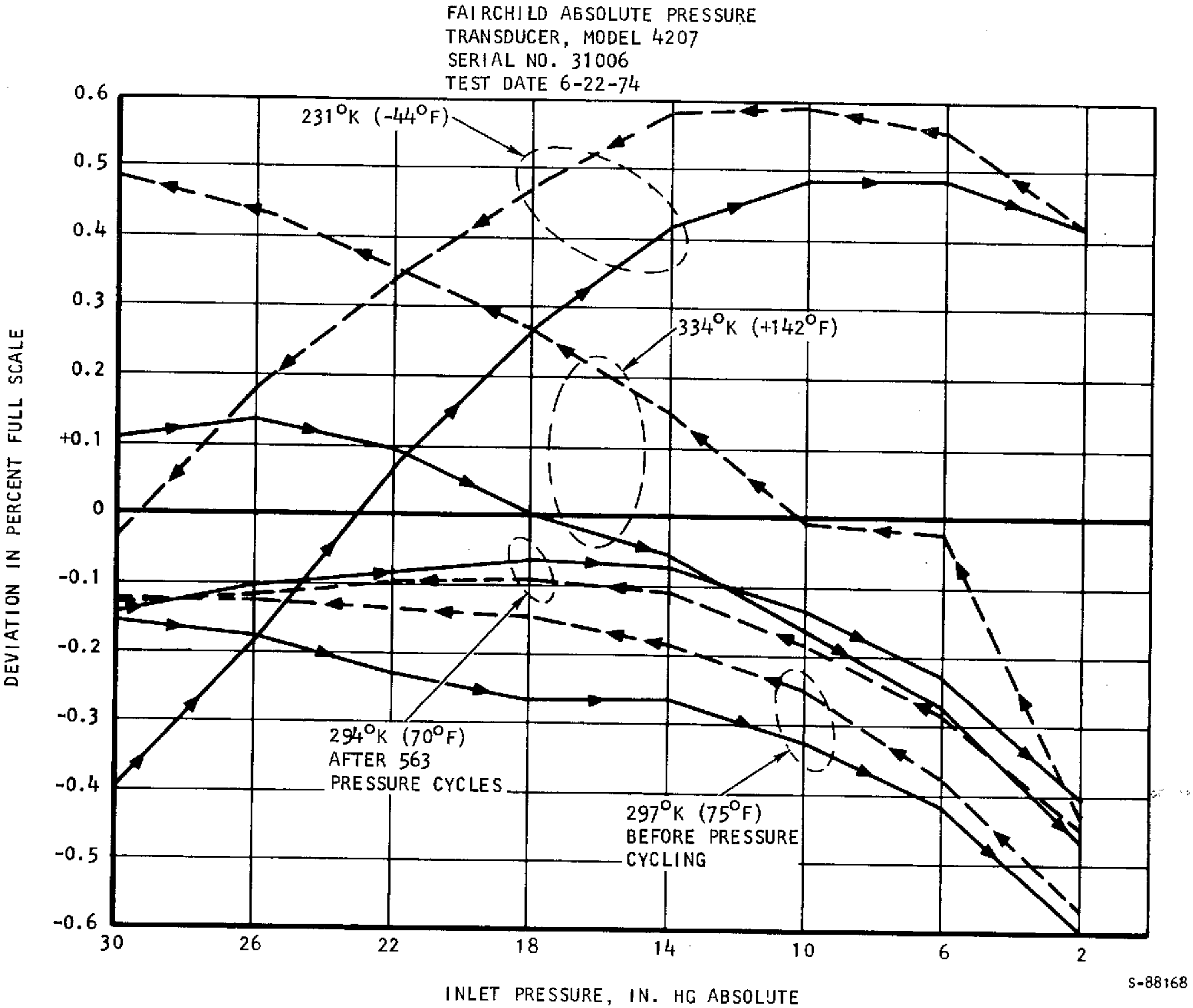



Figure 2-25. Performance Shift vs Temperature

AIRESEARCH MANUFACTURING COMPANY
OF CALIFORNIA

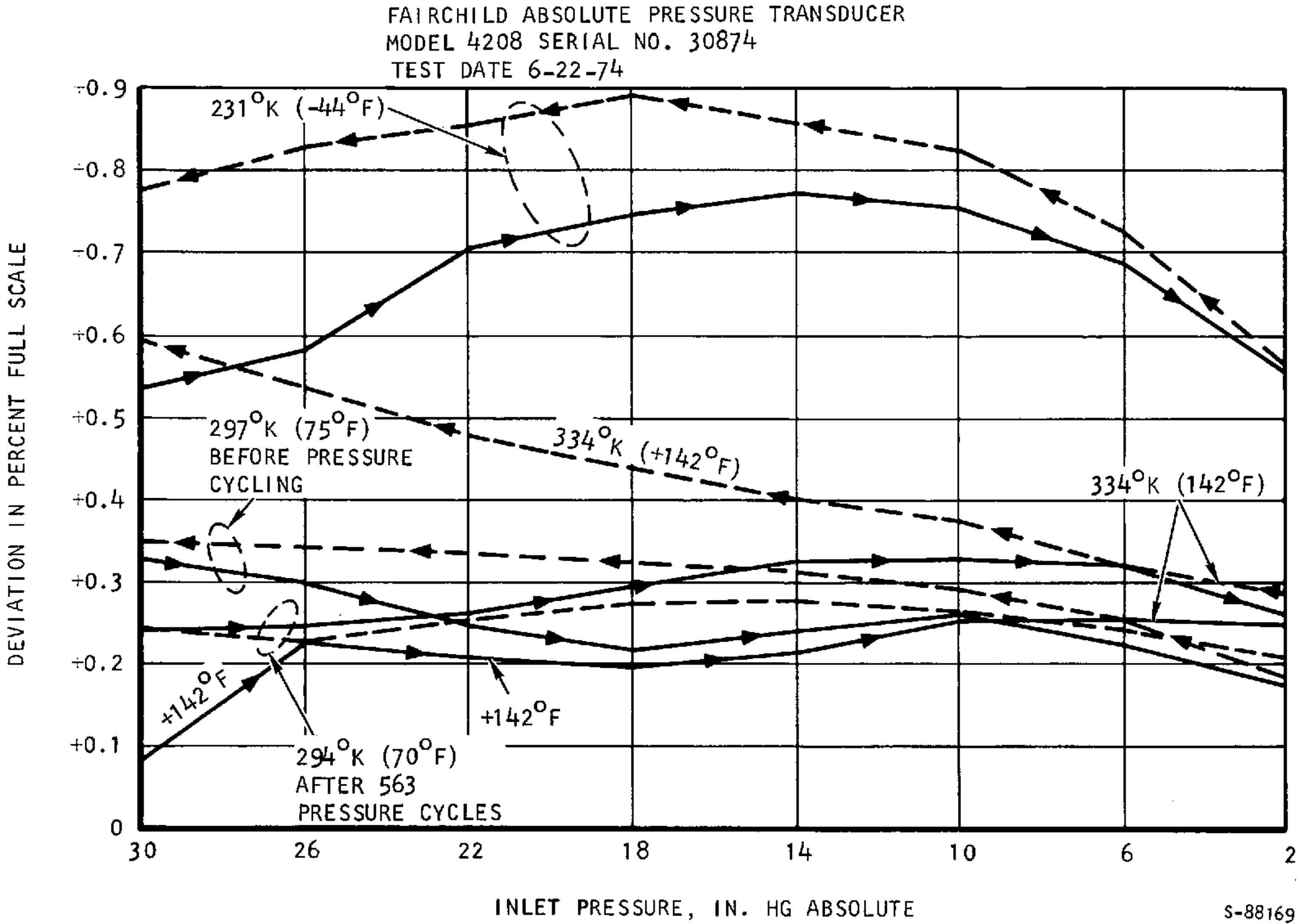



Figure 2-26. Performance Shift vs Temperature

# SECTION 3

# THREE-WAY ISOLATION VALVE

# SECTION 3
# THREE-WAY ISOLATION VALVE

This section presents the results of a breadboard development program for a three-way isolation valve to isolate pressure transducers from liquid systems, to permit removal and replacement of a faulty pressure transducer without destroying the hard-fill of the closed liquid loop.

## Background

Air inclusion in fluids used in coolant loops presents a problem in zero-g operation since there is a likelihood that the air bubble will migrate through the loop and ultimately cause cavitation at the recirculation pump. At one-g, a high point (air trap) can be so designed into the system that the air inclusion is harmlessly trapped.

The coolant loops in the Apollo environmental control system (ECS) required the coolant fluids to be deaerated; it was necessary to clean the loops meticulously and purge them of noncondensable gases by subjecting them to a low pressure by means of a vacuum pump. This process was very time-consuming and had to be repeated each time a component in the coolant loop required replacement. Once the coolant loop was installed in the vehicle, the technique for removing air inclusion following system repair necessitated use of even greater caution due to fluid spillage and the added requirement for interfacing with ground service equipment. It can be expected that pressure transducers must be replaced more frequently in Shuttle coolant loops because of the 100-mission or 10-year-life requirement.

## Design Program

The three-way isolation valve is designed for installation between each pressure transducer and the liquid loop. During normal usage, the valve porting allows the pressure transducer to be open to the liquid loop. The third (evacuation) port is shut off by the arrangement of the porting in the plug valve, which is capped with a standard coupling to act as a redundant seal. The housing containing the plug and actuation device also is capped to provide a redundant seal.

Prior to removal of a failed pressure sensor, the redundant caps are removed and the plug valve is manually moved to the ISOLATE position. The small amount of fluid contained in the sensing portion of the transducer remains in the failed transducer except in the case of Freon-21, in which case it quickly evaporates to ambient through the evacuation port. After the pressure transducer is replaced, the evacuation port is pumped down with a portable GSE vacuum pump. While the vacuum is maintained, the plug valve is manually moved to the NORMAL position, thus allowing the accumulator in the fluid loop to backfill the pressure transducer.

The primary concern in the design and development of the isolation valve was the selection of materials of construction that are compatible with Freon-21, one of the two coolant fluids planned for the Shuttle environmental control system. The most troublesome property of Freon-21 is the solvent property of the fluid. DuPont Company states: "Freon-21 is the best solvent in the Freon fluorocarbon series. The presence of one hydrogen and two chlorine atoms in the molecule is apparently an arrangement that imparts good solvent properties to the molecule." This solvent action results in comparatively greater effect on elastomers and plastics than most other heat transport fluids, as well as restricting the lubrication of sliding or bearing surfaces to the lubricity of Freon-21 alone, since greases are washed away by the Freon-21.

Several materials were considered for use in the construction of the three-way valve.

Freon-21, dichloromonofluoromethane ($CHCL_2F$), is a clear, odorless, fluorocarbon compound with a molecular weight of 102.93, produced by DuPont for use as a refrigerant, heat transport fluid, aerosol propellant, and solvent. Table 3-1 summarizes its physical properties; Figure 3-1 shows the vapor pressure of the fluid as a function of temperature.

TABLE 3-1

PHYSICAL PROPERTIES OF LIQUID FREON-21

| | SI Units | | U.S. Customary Units | |
|---|---|---|---|---|
| Boiling point at 1 atm | °K | 282.2 | °F | 48.06 |
| Freezing point | °K | 138.3 | °F | -211 |
| Critical temperature | °K | 451.8 | °F | 353.3 |
| Critical pressure | MPa | 5.17 | psia | 750 |
| Density at 298.3°K (77°F) | $kg/m^3$ | 1366.2 | lb/cu ft | 85.28 |
| Specific heat at 298.3°K (77°F) | J/kg.k | 1071 | Btu/lb°F | 0.256 |
| Heat of vaporization at boiling point | kJ/kg | 242.3 | Btu/lb | 104.15 |
| Thermal conductivity at 298.3°K (77°F) | $w/m^2$·K | 0.4 | Btu/hr $ft^2$°F | 0.063 |
| Viscosity at 298.3°K (77°F) | N.s/$m^2$ | 0.00034 | centipoise | 0.34 |
| Surface tension at 298.3°K (77°F) | dynes/cm | 20 | dynes/cm | 20 |
| Refractive index at 298.3°K (77°F) | | 1.354 | | 1.354 |
| Relative dielectric strength (nitrogen=1) | | 1.85 | | 1.85 |
| Dielectric constant | @28°C | 5.34 | @28°C | 5.34 |
| Solubility in water at 298.3°K (77°F) | Wt, percent | 0.95 | Wt, percent | 0.95 |
| Solubility of water in F21 at 298.3°K (77°F) | Wt, percent | 0.13 | Wt, percent | 0.13 |

Freon-21 has more effect on elastomers than most other heat transport fluids, and it is the property that must be carefully accounted for in design.

Table 3-2 summarizes Freon-21 swell data, arranged by increasing linear swell. Swell is an important measure of an elastomer's suitability, but other effects, such as loss of plasticizers or fillers and changes in mechanical strength and hardness, also may be the result of exposure.

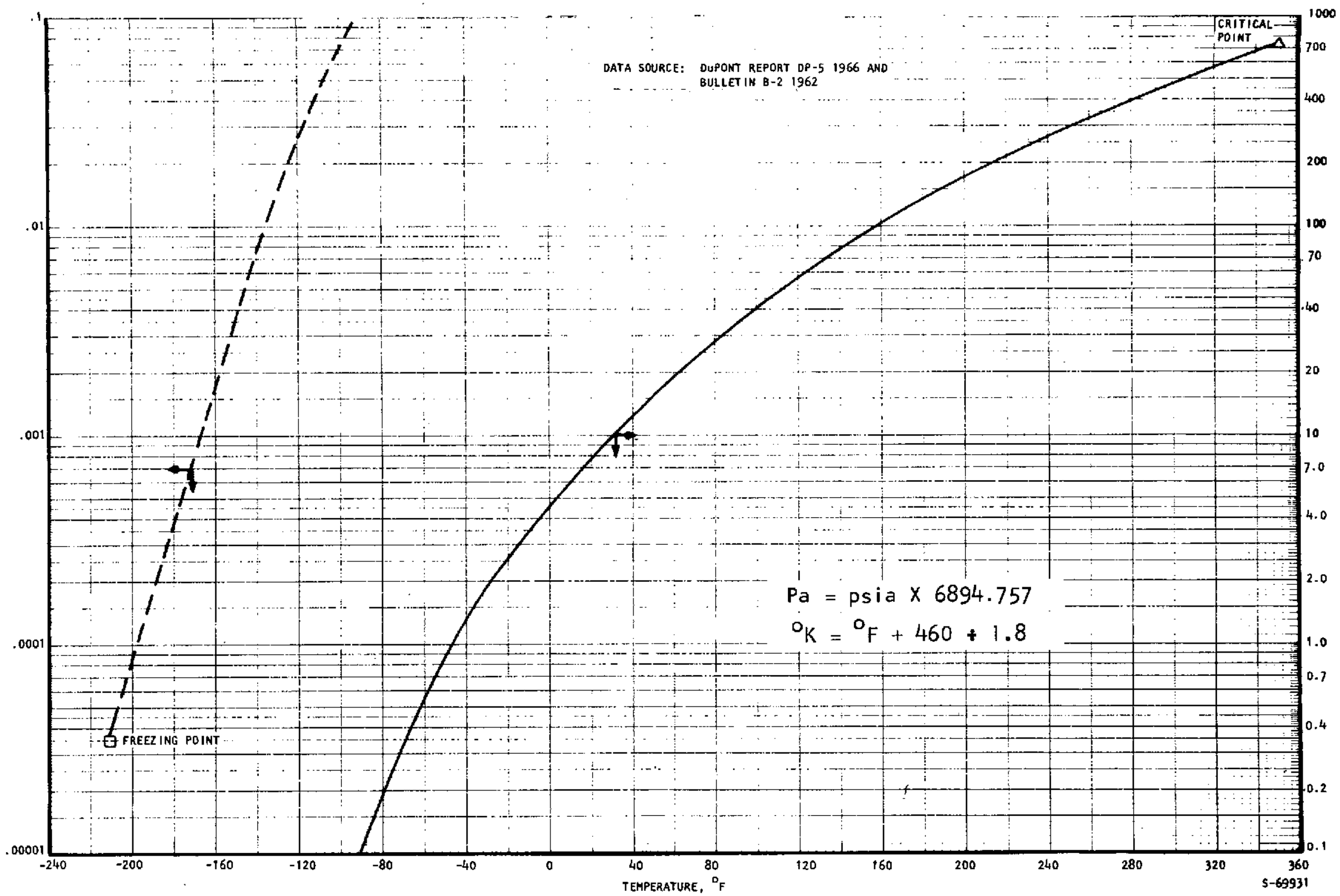



Figure 3-1. Vapor Pressure of Liquid Freon-21

TABLE 3-2

LINEAR SWELL OF ELASTOMERS IN FREON-21

| | Percent Increase in Length, 7-Day Exposure | |
|---|---|---|
| | Room Temperature | 327.8°K (130°F) |
| Compar 1003 (PVA) | 3.7 | 5.3 |
| Compar 1002 (PVA) | 6.4 | 6.0 |
| Compar 1001 (PVA) | 8.3 | 5.7 |
| Neoprene W | 22 | 25 |
| Viton B | 22 | 25 |
| Nordel (EPR) | 23 | 25 |
| Butyl rubber | 24 | - |
| Hypalon 40 | 24 | - |
| Viton A | 26 | - |
| Polysulfide rubber | 28 | - |
| Neoprene GN | 28 | - |
| Thiokol FA | 28 | - |
| Natural rubber | 34 | - |
| Adiprene L (urethane) | 41 | 41 |
| NBR | 48 | - |
| Silastic 50 (silicone) | 49 | 51 |
| SBR | 49 | - |
| Adiprene C (urethane) | 54 | 78 |

DuPont reports that Freon-21 has little or no effect on nylon, polyethelene, Teflon TFE, polyvinylidene chloride, and phenol formaldehyde resin. They do, however, report serious attacks on other plastics. Table 3-3 lists available data. Some other DuPont observations on compatibility of plastics and Freon compounds are presented below.

Teflon Tetrafluoroethylene Resin--No swelling observed when submerged in Freon liquid but some diffusion found with Freon-12 and Freon-22.

Polychlorotrifluoroethylene--Slight swelling but generally suitable for use with the Freon compounds.

## TABLE 3-3

## LINEAR SWELL OF PLASTICS IN FREON-21

| | Percent Increase in Length at Room Temperature |
|---|---|
| Cellulose acetate | Dissolved |
| Cellulose nitrate | Dissolved |
| Lucite acrylic resin | Dissolved |
| Methyl methacoylate | Dissolved |
| Nylon | 0 |
| Phenol formaldehyde | 0 |
| Polyethylene | 4.5 |
| Polystyrene | Dissolved |
| Polyvinyl alcohol | 13 |
| Polyvinyl chloride | 15 |
| Polyvinylidene chloride | 1 |
| Teflon TFE resin | 0 |

Polyvinyl Alcohol--Not affected by the Freon compounds (except Freon-21) but very sensitive to water.

Vinyl--Resistance to the Freon compounds depends on vinyl tape and plasticizer and considerable variation is found. Samples should be tested before use.

Orlon Acrylic Fiber--Generally suitable for use with the Freon compounds.

Nylon--Generally suitable for use with the Freon compounds but may tend to become brittle at high temperatures in the presence of air or water. Tests at 394.4°K (250°F) with Freon-12 and Freon-22 showed the presence of water or alcohol to be undesirable. Adequate testing should be carried out.

Polyethylene--May be suitable for some applications at room temperatures but should be thoroughly tested since greatly different results have been found with different samples.

Lucite Acrylic Resin--Dissolved by Freon-21 and Freon-22 but generally suitable for use with Freon-12 and Freon-114 for short exposures. On long exposure, tends to crack and craze and becomes cloudy.

Polystyrene--Considerable variation found in individual samples but generally not suited for use with the Freon compounds.

Phenolic Resins--Usually not affected by the Freon compounds; however, composition of resins of this type may vary greatly and samples should be tested before use.

Epoxy Resins--Resistant to most solvents and entirely suitable for use with the Freon compounds unless highly plasticized.

Delrin Acetral Resin--Suitable for use with the Freon compounds under most conditions.

DuPont comments regarding the effect of Freon-21 on metals are as follows:

"Most of the commonly used construction metals, such as steel, cast iron, brass, copper, tin, lead, and aluminum can be used satisfactorily with the Freon compounds under normal conditions of use. At high temperatures some of the metals may act as catalysts for the breakdown of the compound. The tendency of metals to promote thermal decomposition of the Freon compounds is in the following general order:

Least decompostion: Inconel <18-8 stainless steel <nickel

<copper <1240 steel <aluminum <bronze

<brass <silver: most decomposition.

"This order is only approximate and exceptions may be found for individual Freon compounds or for special conditions of use. Magnesium alloys and aluminum containing more than 2-percent magnesium are not recommended for use in systems containing Freon where water may be present. Experience with zinc and Freon compounds has been limited and no unusual reactivity has been observed; however, it is somewhat more chemically reactive than other common construction metals and it would seem wise to avoid its use with the Freon compounds unless adequate testing is carried out."

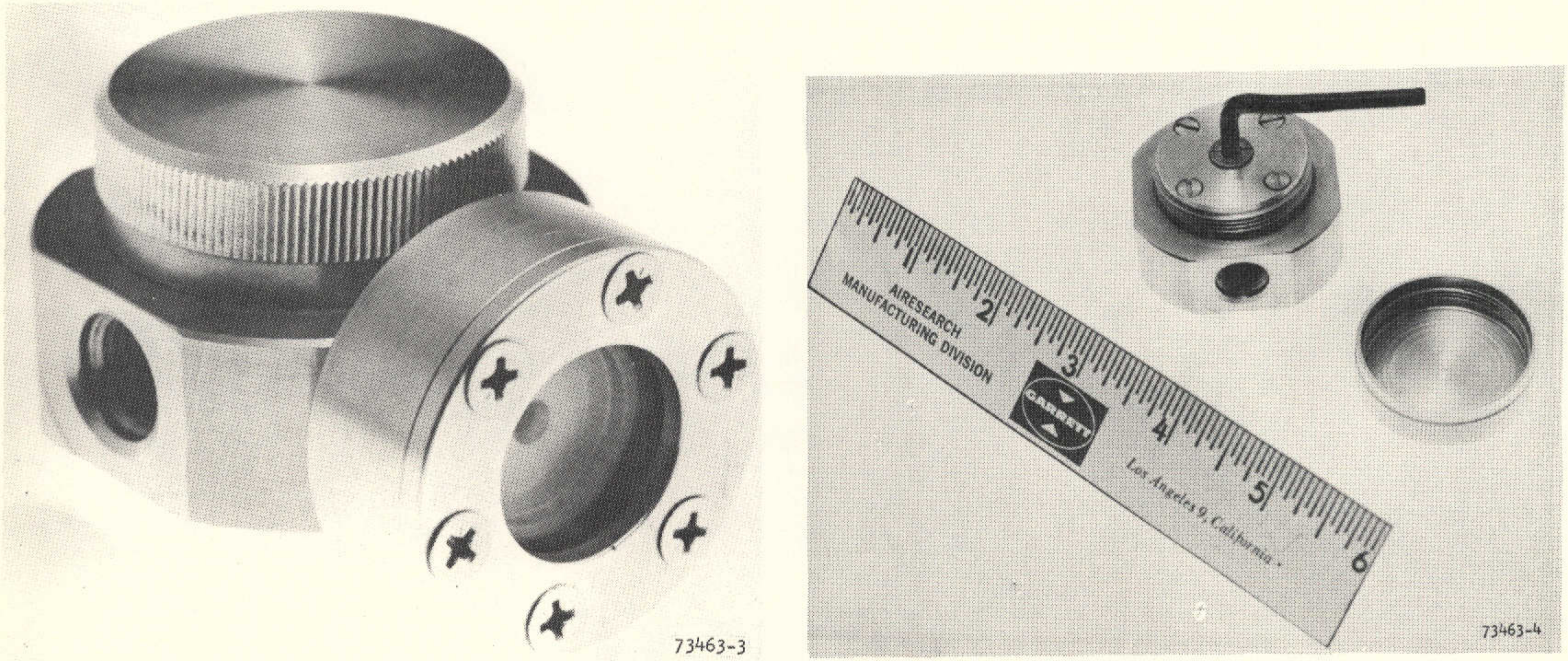
Corrosion tests at 327.8°K (130°F) for 60 days showed the following results:

| | |
|---|---|
| Freon-21 and free water on 1020 CR steel | 0.003 mm/month ($127 \times 10^{-6}$ in./month) |
| Freon-21 and free water on Al 25 aluminum | 0.009 mm/month ($357 \times 10^{-6}$ in./month) |
| Dry Freon-21 on copper | 0.0001 mm/month ($5 \times 10^{-6}$ in./month) |
| Dry Freon-21 on 1020 CR steel | 0.0002 mm/month ($8.5 \times 10^{-6}$ in./month) |

## Breadboard Development

The breadboard three-way isolation valve used in this development program was fabricated and assembled by L. J. Engineering, Westminster, California. In addition, two simulated pressure transducer housings were fabricated, each containing a glass window to permit a visual examination of the air inclusion resulting during the maintenance task of pressure transducer replacement. The breadboard valve and simulated pressure transducer housings are shown in Figure 3-2. The isolation valve was constructed from stainless steel and Teflon. To minimize fabrication costs, excess material was not removed from the valve body. A welded interface between the valve and coolant loop should be considered when designing the production version of the three-way isolation valve. Three female ports conforming to MS-33649-4 were incorporated in the body of the breadboard valve to facilitate attachment to the test setup.

Figure 3-3 shows the component parts of the three-way valve. The valve design takes advantage of the cold-flow property of Teflon to provide a leak-tight valve. The Teflon plug containing the three-way porting is heavily loaded in the valve body by four spring-type washers, causing it to flow out against the wall of the stainless steel body. The cross-drilled flow passages in the Teflon plug are reinforced with thin-wall stainless steel tubes so that the internal flow passages will not close up as the Teflon cold-flows. Four pins protrude into the Teflon block for transmitting the actuator torque to the Teflon plug. The low coefficient of friction inherent in Teflon allows the valve to be actuated




F-18527

Figure 3-2. Breadboard Three-Way Isolation Valve with Simulated Pressure Transducer Housing (6-in. ruler shown for comparison)

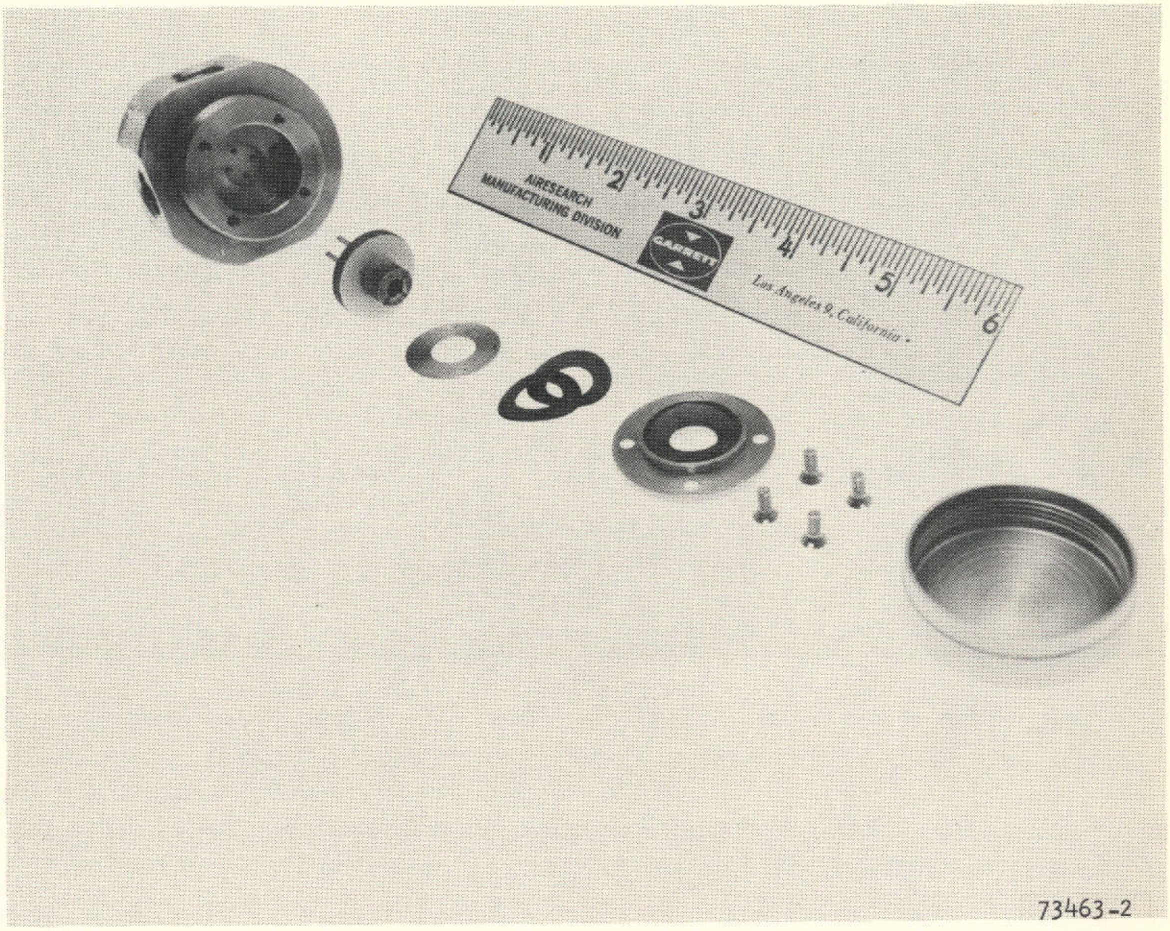



Figure 3-3. Exploded View of Three-Way Isolation Valve (6-in. ruler shown for comparison)

at less than 0.565 N.m (5 in.-lb.) The actuator contains four pins, a female 5/32 hexagonal cavity for mating with an Allen wrench, and a mechanical stop at each end of the 90-deg arc required for actuation. The spring load is transmitted to the actuator and ultimately to the Teflon plug through a metal washer paired with a Teflon washer to minimize the torque. The spring retainer compresses the four spring-type washers to a specified load and is held to the valve body with four screws. A cap is installed over the valve actuator to provide a redundant external seal if fluid escapes past the Teflon plug. The evacuation port normally is sealed with an AN814-4D plug for redundancy.

The performance and design data of the three-way isolation valve are summarized in Table 3-4.

TABLE 3-4

PERFORMANCE AND DESIGN DATA OF THREE-WAY ISOLATION VALVE

| | |
|---|---|
| Fluid medium | Freon-21 or water |
| Flow porting | 1 mm (0.040 in.) dia nominal |
| Pressure | |
| Normal | 1.7 MPa gage (250 psig) |
| Proof | 2.58 MPa gage (375 psig) |
| Burst | 3.4 MPa gage (500 psig) |
| Temperature | |
| Normal | 275°K (35°F) |
| Low | 219.4°K (-65°F) |
| High | 344.4°K (160°F) |
| Leakage | None with redundant cap and plug installed |
| Actuator | |
| Stroke | 90-deg arc, positive mechanical stops at each end of stroke |
| Type | Mates with 5/32 Allen wrench |
| Torque | 1.13 N.m (less than 10 in.-lb) |
| Envelope (production version estimate) | 645 $mm^2$ (1-in.-square) cross section, 44.5 mm (1.75 in.) long, coolant loop to valve interface to be welded |
| Weight (production version estimate) | 85.1 g (3.0 oz) |

## Test Program

Test setup. --The breadboard three-way isolation valve was connected to a water accumulator to simulate the Shuttle ECS pressurized water coolant loop. The vacuum pump and pressure gage were plumbed to the evacuation port of the three-way valve. Figures 3-4 and 3-5 show the test setup. An empty housing containing a glass window (shown in Figure 3-6) was connected to the three-way valve. The housing was made to simulate the pressurized cavity of a typical pressure transducer. The 6.4-mm- (1/4-in.-) thick glass window permitted visual observation of the air bubbles introduced into the coolant system with the system pressurized at 172.4 kPa (25 psig), 344.8 kPa (50 psig) and 689.5 kPa gage (100 psig). A second simulated transducer housing containing a transparent window was used to demonstrate the removal and replacement of a pressure transducer from a pressurized coolant loop.

The test setup used for demonstrating transducer removal and replacement on a Freon-21 coolant loop was identical to the test setup used for the water coolant loop test setup described above, except that a piston-type accumulator was used to simulate the pressurized Freon-21 coolant loop. This test setup is shown in Figure 3-7.

Test procedure. --The following test procedure was used for the transducer removal and replacement tests for the water coolant loop tests. The same procedure, with the water accumulator replaced by a piston-type accumulator containing Freon-21, was used for the Freon-21 coolant loop tests.

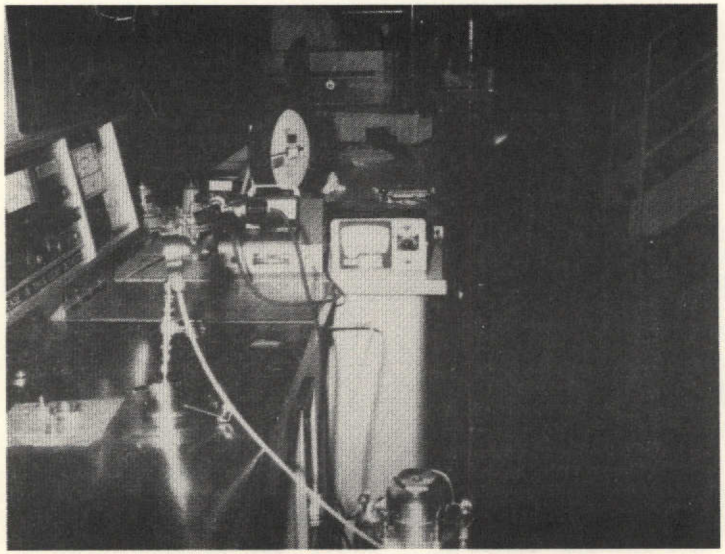
(a) The breadboard valve was connected to an accumulator containing distilled water, and capable of being pressurized to 689.5 kPa gage (100 psig).

(b) The redundant cap was removed from the valve and the valve-plug positioned so that the transducer (transparent housing) was open to the evacuation port. The valve-plug may be actuated with a 5/32 Allen wrench.

(c) A vacuum pump and vacuum gage were connected to the evacuation port. The vacuum gage was capable of indicating a pressure as low as 50 microns.

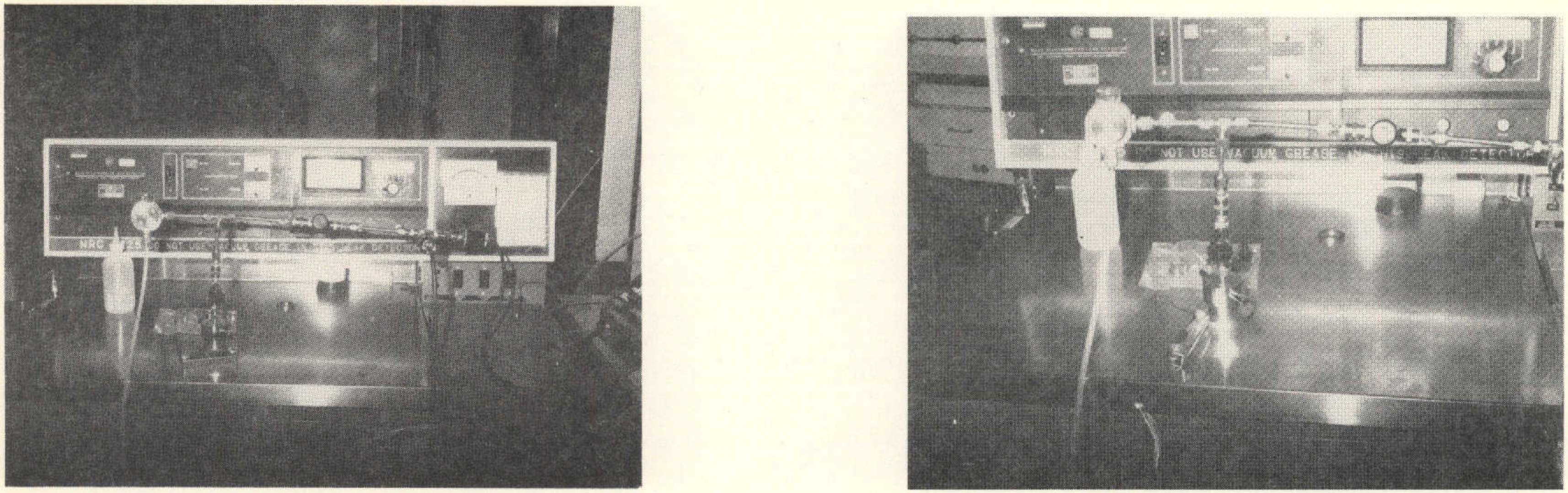
(d) The transparent housing was evacuated through the evacuation port to 1500 microns. The water accumulator was pressurized to 344.8 kPa gage (50 psig). While maintaining a vacuum of 1500 microns, the isolation valve was moved to the NORMAL position. Water from the accumulator filled the transparent housing. The air inclusion was monitored by measuring the size of the bubble(s) in the transparent transducer housing.

(e) The isolation valve was placed in the ISOLATE position. The transparent transducer housing was removed and replaced with the second transparent housing, simulating removal and replacement of a pressure transducer. The new transducer housing was evacuated to



F-18524

Figure 3-4. Test Setup, Three-Way Isolation Valve Connected to a Pressurized Water Accumulator



F-18525

Figure 3-5. Test Setup, Three-Way Isolation Valve Connected to a Pressurized Water Accumulator

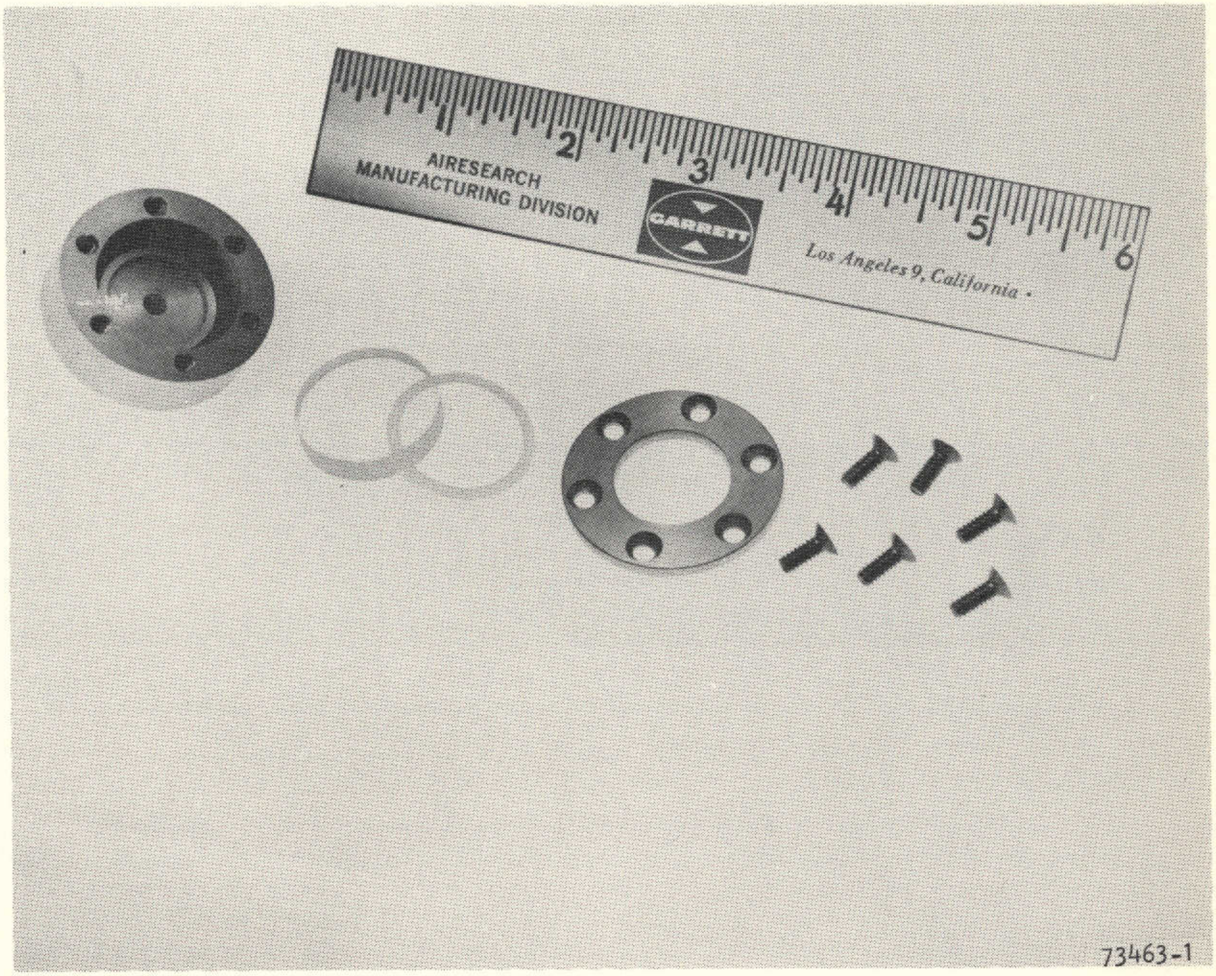
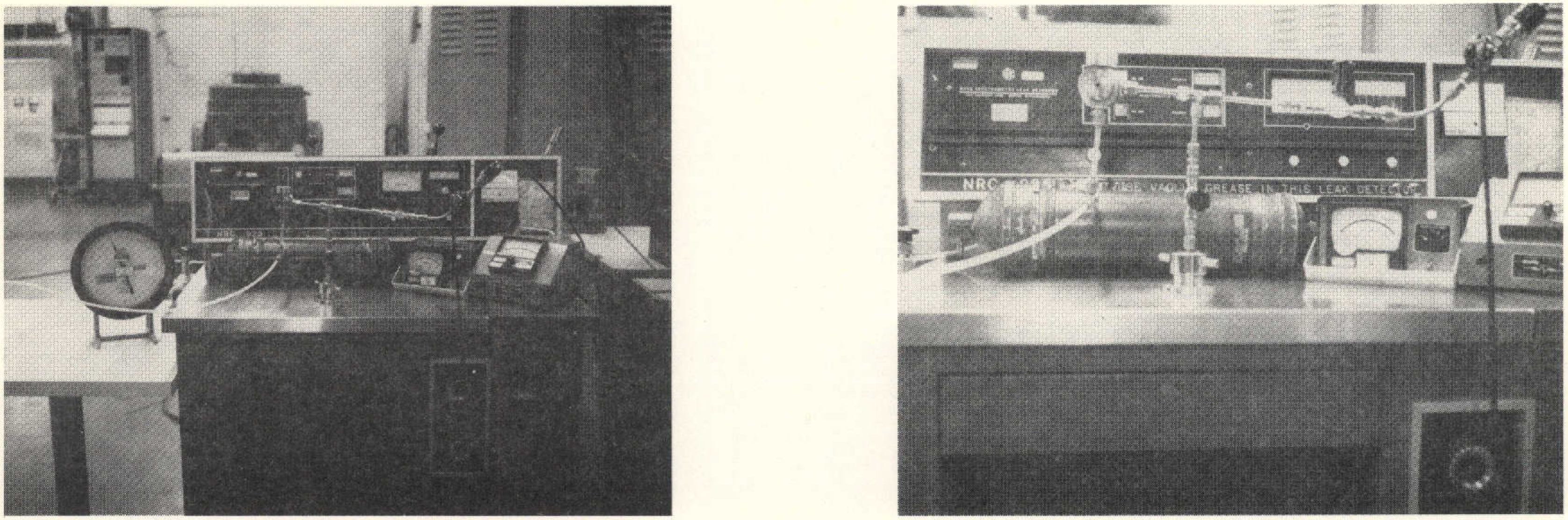



Figure 3-6. Exploded View of Simulated Pressure Transducer
(6-in. ruler shown for comparison)



F-18526

Figure 3-7. Test Setup, Three-Way Isolation Valve Connected to a Pressurized Freon-21 Accumulator

1500 microns and the valve-plug was moved to the NORMAL position. The air inclusion was monitored by measuring the size of the bubbles(s) in the transparent transducer housing.

(f) Step (e) was repeated by alternately replacing one transparent housing with the other for evacuation pressures of 1000, 500, 100, and 50 microns. The size of the air bubble(s) and the time required to pump the pressure to desired evacuation pressures were recorded.

(g) By trial and error, the stabilized evacuation pressure that would produce a 0.8-mm- (1/32-in.-) dia bubble in the transparent housing with the water accumulator maintained at 172.4 kPa gage (25 psig) was determined.

Test results.--The two simulated pressure transducer housings permitted one housing to be dried by a separate vacuum pump while the other was attached to the three-way valve for demonstration of air inclusion at several levels of coolant loop pressure and evacuation pressure. Many checkout tests were conducted at various evacuation pressures and at different system pressures. The air bubbles observed through the glass window of the simulated pressure transducers varied as test points were repeated, indicating leakage in the system. Several leakage points were identified by use of a helium detector, and corrected; the data then became repeatable. Table 3-5 gives the amount of observed air inclusion vs evacuation pressure resulting from removal and replacement of transducers in a pressurized water loop.

Each time a dry transducer housing was installed on the three-way valve, evacuation pressures of less than 500 microns were easily and quickly obtained in the laboratory using a portable vacuum pump. This indicated that a portable GSE vacuum pump could be used for the Shuttle ECS transducer replacement task. The data contained in Table 3-5 show that the replacement pressure transducer initially should be evacuated to less than 20 mm Hg abs and preferably to less than 10 mm Hg abs to preclude air inclusion during removal and replacement of a pressure transducer in the water coolant loop.

Table 3-6 describes the amount of observed air inclusion vs evacuation pressure resulting from removal and replacement of transducers in a pressurized Freon-21 loop. In the laboratory tests, the air bubble decayed in size after the three-way valve was moved to the position that allows pressurized Freon-21 to enter the evacuated cavity in the simulated pressure transducer. Tests were conducted on an empty (dry cavity) transducer housing that was not evacuated prior to subjecting it to pressurized Freon-21. The cavity was immediately half-filled with Freon-21; however, the entire cavity soon became filled with Freon-21, indicating that air is soluble in Freon-21. Air dissolved in Freon-21 could be hazardous in the Shuttle ECS Freon-21 loop because it will come out of solution in areas of the system where the temperature is high and the pressure is low. This condition typically exists in the inlet of the Freon-21 recirculation pump, which may result in pump cavitation and the loss of the thermal transport capability of the loop. All tests conducted below 500 microns (0.5 mm Hg abs) resulted in no visible air being introduced into the system. Consequently it is recommended that the replacement pressure transducer initially be evacuated to less than 500 microns before allowing Freon-21 to backfill the transducer from the accumulator in the coolant loop.

TABLE 3-5

AIR INCLUSION VS EVACUATION PRESSURE IN WATER COOLANT LOOP

| Water Coolant Loop Pressure, kPa | Water Coolant Loop Pressure, psig | Evacuation Port Pressure, mm Hg abs | Condition of Fluid in Transducer as Observed Through the Glass Window |
|---|---|---|---|
| 620.6 | 90 | 0.05 | No bubbles |
| 620.6 | 90 | 0.1 | No bubbles |
| 620.6 | 90 | 0.2 | No bubbles |
| 620.6 | 90 | 0.5 | No bubbles |
| 620.6 | 90 | 1.0 | No bubbles |
| 620.6 | 90 | 2.0 | No bubbles |
| 620.6 | 90 | 4.0 | No bubbles |
| 620.6 | 90 | 8.0 | No bubbles |
| 620.6 | 90 | 20.0 | No bubbles |
| 620.6 | 50 | 20.0 | No bubbles |
| 172.4 | 25 | 20.0 | Few small bubbles<0.25 mm (1/100-in.) dia |
| 172.4 | 25 | 25.0 | About 30 bubbles <0.4 mm (1/64-in.) dia |
| 172.4 | 25 | 30.0 | About 30 bubbles <0.4 (1/64-in.) dia |
| 172.4 | 25 | 45.0 | About 100 bubbles 0.4 mm (1/64-in.) dia and smaller |
| 172.4 | 25 | 100.0 | About 100 bubbles 0.8 mm (1/32-in.) and 0.4 mm (1/64-in.) dia |
| 172.4 | 25 | 200.0 | Many bubbles 1.6 mm (1/16-in.), 0.8 mm (1/32-in.), and 0.4 mm (1/64-in.) dia |
| 34.5 | 5 | 20.0 | No bubbles |
| 6.9 | 1 | 20.0 | No bubbles |

## Conclusions and Recommendations

The results of the breadboard development program show that pressure transducers can be isolated and replaced in closed-loop liquid systems without introducing air into the system by adding a three-way isolation valve between the closed liquid loop and each pressure transducer. The three-way isolation valve permits the failed transducer to be isolated from the closed liquid loop and replaced by a new transducer that is evacuated through the evacuation port of the three-way valve by use of a portable GSE vacuum pump. A pressure

TABLE 3-6

AIR INCLUSION VS EVACUATION PRESSURE IN FREON-21 COOLANT LOOP

| Freon-21 Coolant Loop Pressure | | Evacuation Port Pressure, mm Hg abs | Condition of Fluid in Transducer as Observed Through Glass Window |
|---|---|---|---|
| kPa | psig | | |
| 668.8 | 97 | 0.1 | No bubbles |
| 668.8 | 97 | 0.5 | No bubbles |
| 668.8 | 97 | 1.2 | No bubbles |
| 668.8 | 97 | 2.0 | No bubbles |
| 668.8 | 97 | 3.0 | No bubbles |
| 668.8 | 97 | 5.0 | No bubbles |
| 668.8 | 97 | 10.0 | No bubbles |
| 482.6 | 70 | 20.0 | One bubble about 0.4 mm (1/64-in.) dia that would disappear in approximately 2 sec |
| 344.8 | 50 | 0.5 | No bubbles |
| 344.8 | 50 | 1.0 | |
| 344.8 | 50 | 2.0 | One bubble about 1.6 mm (1/16-in.) dia that would disappear in approximately 1.5 min |
| 344.8 | 50 | 5.0 | |
| 344.8 | 50 | 10.0 | |
| 344.8 | 50 | 20.0 | |
| 206.8 | 30 | 20.0 | One bubble about 3.2 mm (1/8-in.) dia that would disappear in approximately 2 min |
| 482.6 | 70 | 760 (ambient) | One bubble indicated during three consecutive tests |
| 413.7 | 60 | 760 (ambient) | One bubble indicated during five consecutive tests |
| 193.1 | 28 | 760 (ambient) | One bubble about 4.8 mm (3/16-in.) dia occurred during every test |

of less than 500 microns (0.5 mm Hg abs) was obtained easily in less than 3 min from the laboratory portable vacuum pump, which was rated at 0.14 $m^3$/ 60s (5 cfm). An evacuation pressure of 500 microns reliably produced no visible air inclusion when the three-way valve was moved to the NORMAL position, thus allowing fluid to backfill the replaced transducer from the pressurized accumulator in the closed-loop system.

The breadboard development program for a three-way isolation valve was done to simplify the removal and replacement of pressure transducers used for monitoring the Shuttle water coolant and Freon-21 coolant loops. The Shuttle equipment will be designed to be capable of meeting specified performance for a minimum of 500 hr over a 10-yr period. This life includes operations such as test, checkout, prelaunch, and flight. The operating life of the equipment will be 100 missions. These goals will be achieved by periodic replacement and refurbishment of the hardware. It is recommended, therefore, that a three-way isolation valve be permanently installed between the liquid loop and each pressure transducer. This will expedite and simplify maintenance of the pressure transducers used to monitor and control the Shuttle liquid systems.

# SECTION 4

# TEMPERATURE

# SECTION 4
# TEMPERATURE

This section describes a development and verification test program for improving and evaluating the stability of surface-type temperature sensors made by Tylan Corporation, Torrance, California.

## Background

Preliminary studies made on Shuttle instrumentation showed a saving in weight and electrical power by utilizing separate sensors with a common power supply and signal conditioner. The separate sensors can withstand hostile environments in remote sections of the vehicle, while the electronics contained in a common power supply and signal conditioner can be installed in an environmentally conditioned compartment. In addition, redundancy and built-in-test provisions can be incorporated more simply. The transducer development plan, therefore, was patterned around the use of separate sensors with common power supply and signal conditioners.

The temperature sensors selected for this development program were off-the-shelf surface-type platinum resistance units that have been used on many major aerospace vehicles. They were designed for attachment to the outer surface of the tubing by means of aluminum foil tape for measurement of temperature on liquid loops, and installation inside perforated tubes for measurement of air temperature. The major requirement was to conduct cyclic tests to verify the stability of the units, including a determination of the error band caused by drift vs time, and the commonality of new sensor outputs, whether recently built or in stock for more than 5 years. Built-in-test (BITE) provisions were demonstrated by laminating a second 0.254-mm-(0.010-in.-) thick sensor over the primary sensor to act as a heater when the BITE circuit is energized by means of the power supply and signal conditioner. The increased temperature is sensed by the primary sensor to verify that it is functional.

## Development Program

Introduction. --The development program consisted of subjecting off-the-shelf surface type temperature sensors to cyclic temperatures between 195°K (-109°F) and 422°K (+300°F) for the purpose of determining the stability of the sensors. The surface-type temperature sensors were selected from the Tylan Corporation inventory on the basis of age (a span of approximately 2 months to over 5 years from the date of manufacture), to provide data relative to the repeatability (stability) of the sensors from their original calibration as a function of time. The development program produced test data and recommendations and a definition of built-in-test (BITE) provisions.

Tylan Corporation shared in the cost of the program by making the test articles available, conducting a BITE analysis, and conducting initial performance record tests on the test articles. AiResearch provided the cyclic test apparatus, conducted the cyclic temperature tests, performed periodic performance record tests on the test articles, reduced the test data, and prepared the monthly progress and final reports.

Temperature Sensor Description. --Tylan Corporation surface-type sensors (Model FG-100 series) were selected for the development test program because they are low-cost, lightweight (less than 12 gm/sensor), can be replaced in liquid coolant loops without flushing and refilling with every sensor failure, and do not pose the problems of pressure drop that can occur with an immersion-type or well-type sensor that can impede fluid flow.

The hermetically sealed temperature sensors were designed to measure the surface temperature of flat surfaces or circular ducts or tubing. The precision temperature-sensitive element is made from reference grade (99.999-percent-pure hard-drawn) platinum wire that undergoes a change in electrical resistance with respect to temperature. The sensor element is insulated with a multiple-layer coating of Pyre-ML synthetic varnish. The wire is noninductively wound on an epoxy-impregnated fiberglass card and terminated by welding to copper leads. The element and leads are sandwiched between two sheets of epoxy-impregnated fiberglass cloth and cured under heat and pressure. During this cure, the impregnated epoxy resin goes through a highly fluid phase, nearly like water, which results in intimate penetration and encapsulation of the fine wires and the lead wires. The resulting matrix is mechanically rugged and protective of the element while remaining thin for excellent heat transfer and low thermal mass.

The surface-type sensors provide a response time of less than 50 msec when immersed in agitated liquid. In actual use the response time will be considerably slower because of the thermal lag caused by the tube wall. Because the sensors are extremely thin (approximately 0.254 mm (0.010 in.)), their low thermal mass adds very little to the time constant.

Maintainability. --The simplest and lightest-weight installation method on external surfaces is bonding or taping; however, a variety of simple clamping methods can be used so that the sensor is held in place, protected from backside temperature effects or mechanical damage, and easily removable. Certain sensors are preshaped to conform to the outside diameter of 6.35-mm (1/4-in.), 9.53-mm (3/8-in.), 12.7-mm (1/2-in.), and 15.88-mm (5/8-in.) tubing. Preshaped surface sensors may be inserted in a perforated 6.35-mm-(1/4-in.-) dia tube for monitoring air temperatures. The sensor is shaped so that it will bear against the inside diameter of the tube for restraint while being exposed to the flow of air. Each of the surface sensors is supplied with 1.22-m (48-in.) leads consisting of No. 30 AWG stranded tin-plated copper wire with Teflon insulation. It is recommended the wires be terminated at a subsystem electrical connector for interfacing with the common power supply and signal conditioner. The use of insert pins on the subsystem electrical connector will permit easy replacement of a failed surface sensor.

Wire sensors have superior long-term stability (within 0.05°C per year) and often are used as temperature standards against which other temperature sensors are calibrated.

Wire sensors can be furnished with tolerances from 1 to 0.1 percent, or better. Sensors thus can be interchanged, often without the need for calibration, and therefore represent an important aspect for maintenance on Shuttle.

Test Article Configuration. --Table 4-1 provides a chronological summary of all the temperature sensors used in the development test program. The low-test temperature was selected on the basis of using dry ice for the cold 195°K (-109°F) bath; the high-test temperature of 422°K (+300°F) was selected to be substantially below the limited life rating of 478°K (400°F) for the epoxy used in the fiberglass laminate. More importantly, these temperature extremes encompass all of the temperature measurement applications in the Shuttle ECS. The test articles used initially conformed to the flat-shaped sensor shown in Figure 4-1. Later test articles were molded with a curvature to conform to the inside wall of a 9.53-mm- (3/8-in.-) dia tube. An example of this configuration is shown in Figure 4-1. The curved and the flat-shaped sensors are identical except for shape. The reason for changing the flat shape of the test articles to curved was to permit the use of thin-walled metal test tubes for containing the test article, so that the sensor would not be wetted by the high-temperature (422°K) (+300°F) fluid. Sensor failures experienced with the first two batches of 5 sensors were attributed to the solvent action of the 422°K (+300°F) Coolanol acting on the bond between the Teflon-insulated lead wire and the fiberglass laminate. One of the test articles in Figure 4-2 is shown with the Teflon lead wire broken away from the fiberglass.

During the selection and test of the first three batches of 5 test articles each, great care was given to finding test articles that were over 5 years old and still representative of current production configurations. Considerable care also was given to conducting performance record tests at Tylan and AiResearch so that the data would be useful for showing the repeatability of these sensors over a 5-year (or longer) time period. Electrical continuity tests were substituted for performance record tests in the latter part of the development test program to maximize the cycle time. The early part of the program verified that the sensors were stable over a 5-year program (see Figure 4-3). The latter part of the program was more concerned with the longevity of the various configurations tested. The electrical continuity check was made each day at the cyclic test apparatus with minimal effect on cycle time.

Thermal Shock. --The three temperature sensors (Serial Nos. 014, 015, and 023), on which cycle testing was begun March 28, 1974 (see Table 4-1), were connected to an oscilloscope to determine their response to the 195°K (-109°F) and 422°K (+300°F), (227°K temperature excursion) (409°F) fluid baths. The response time to achieve a 63-percent change (143°K) (258°F) for Serial No. 014 is approximately 2 sec for increasing temperature and approximately 3 sec for decreasing temperature (see Figure 4-4). During this test the curved fiberglass sensor was in contact with the inside wall of a 9.53-mm- (3/8-in.-) dia stainless steel tube with a wall thickness of 0.254 mm (0.010 in.). A heat-sink compound (Dow Corning 340 silicon) was used between the sensor and the tube to promote a fast thermal response between the temperature of the fluid bath and the temperature sensor. The response times of Serial Nos. 015 and 023 also were measured and found to be 2 sec and 1 sec, respectively, to reach 63 percent of the 227°K temperature excursion (409°F) (see Figures 4-5 and 4-6).

# TABLE 4-1

## SUMMARY OF CYCLIC TEMPERATURE TEST LOG

| Date | Task | Configuration | Test Article: Serial No. | Test Article: Date Manufactured | Test Article: Age at Test Date | Cycle Testing at AiResearch: Dates: Start | Cycle Testing at AiResearch: Dates: Stop | Cycle Testing at AiResearch: Total Cycles Applied | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 8-73 | Fabricate cyclic test apparatus. | Electric timer, 3-way solenoids pneumatically actuated arm over hot and cold baths (see Figure 4-1). | | | | | | | | 0 |
| 8-73 | Performance record tests at the Tylan Corporation (see Tylan test report, Appendix E). | Fiberglass epoxy platinum resistance surface temperature sensors; flat shape for bonding to flat or semiflat surfaces. | 036 | 12-67 | 5-3/4 yr | 10-11-73 | 11-12-73 | 11,600 | Cyclic test was stopped after 11,600 cycles for repeat of performance record test. Two of five sensors were found to be failed open. A microscopic examination of the failed units revealed that the bond between the fiberglass and the etched Teflon jacket that covers the copper lead wires was failed. Failure of this bond transfers the interface loads to the 1-mil platinum wire. The small diameter platinum wire is unable to withstand the cyclic loads occurring during alternate immersion in the hot and cold Coolanol baths. Examination of the other three temperature sensors indicated partial loss of the bond between the Teflon and fiberglass. This was evidenced by the inclusion of Coolanol fluid in a portion of the bonded area. The cause of failure was concluded to be the result of softening (solvent action) of the bond between the fiberglass and the etched Teflon by the high temperature 422°K (+300°F) Coolanol fluid. Preliminary cycle testing to 422°K (+300°F) in an oven with air as the ambient media has not indicated a weakening of the bond. Ten of these cycles between 219°K (-65°F) and 422.K (+300°F) were conducted between the initial performance record tests. | |
| | | | 196 | 4-69 | 4-1/2 yr | 10-11-73 | 11-12-73 | 11,600 | | |
| 9-73 | Fabricate an immersion fixture for mounting five temperature sensors. | Five-sided fixture with a temperature sensor bonded to each side. | 172 | 3-70 | 3-1/2 yr | 10-11-73 | 11-12-73 | 11,600 | | 11,600 |
| | | | 087 | 6-72 | 1-1/2 yr | 10-11-73 | 11-12-73 | 11,600 | | |
| 10-73 | Performance record tests at the AiResearch Mfg. Co. of California (see Figure 1, 73-9404(5), p. 2-2). Repeat Tylan test for correlation of test setups. | | 209 | 5-73 | 1/2 yr | 10-11-73 | 11-12-73 | 11,600 | | |
| 11-73 | AiResearch cyclic testing. Immerse the sensors in 195°K (-109°F) Coolanol (product of Monsanto, St. Louis, Missouri) for approximately 60 sec followed by approximately 60 sec of immersion in 422°K (+300°F) Coolanol fluid. | | | | | | | | | |

## TABLE 4-1 (Continued)

| Date | Task | Configuration | Test Article: Serial No. | Test Article: Date Manufactured | Test Article: Age at Test Date | Cycle Testing at AiResearch: Dates: Start | Cycle Testing at AiResearch: Dates: Stop | Cycle Testing at AiResearch: Total Cycles Applied | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 11-73 | Redesign and fabricate new holding fixture at Tylan. | | | | | | | | | |
| 11-73 | Install new test articles. | | | | | | | | | |
| 11-28-73 | Tylan performance record tests. Test each of the test articles for ice point (273°K, 32°F) resistance before mounting. Mount the units to the tabular test fixture and sequentially measure the resistance of each article at 273°K (32°F), 195°K (-109°F), 273°K (32°F), 373°K (212°F), 422°K (300°F), and 273°K (32°F). Place the test articles in the AiResearch cyclic test setup without a repeat of the performance record tests to maximize the number of cycles in the time available (see Figure 1, 73-9404(7), p. 2-2). | Flat shaped as described above. These sensors were bonded and taped to the outside diameter of a segment (approximately 76.2 mm (3 in.) long) of aluminum tubing. The aluminum tube measures 76.2 mm (3.00 in.) OD by 1.52 mm (0.060 in.) wall and serves as a holder for the temperature sensors during the cyclic immersion of the sensors in the 195°K (-109°F) and 422°K (300°F) Coolanol fluid. The sensors are completely covered over with aluminum foil tape including a portion of the Teflon-insulated lead wires. The previous test articles were only partially covered with tape in their holding fixture and consequently were wetted by the Coolanol fluid. | 110 | 9-67 | 6 yr | 11-30-73 | 12-18-73 | 5,975 | Test was stopped to conduct a performance record test. During the performance record test of December 18, 1973, SN 135 was found to be failed open. Further examination of the fixture indicated that the adhesive on the aluminum foil tape was dissolved which resulted in a loss of bond. As a consequence the temperature sensors were wetted by the Coolanol fluid, resulting in failure of the bond between the fiberglass and the etched Teflon jacket that covers the copper lead wires. The failure of this temperature sensor (SN 135) was identical to the failure previously experienced. The aluminum foil tape did not afford the required protection from the solvent action of the 422°K (300°F) Coolanol fluid. | |
| | | | 199 | 4-69 | 4-1/2 | 11-30-73 | 12-18-73 | 5,975 | | |
| | | | 135 | 5-69 | 4-1/2 yr | 11-30-73 | 12-18-73 | 5,975 | | 17,575 |
| | | | 187 | 3-70 | 3-1/2 yr | 11-30-73 | 12-18-73 | 5,975 | | |
| | | | 088 | 6-72 | 1-1/2 yr | 11-30-73 | 12-18-73 | 5,975 | | |

## TABLE 4-1 (Continued)

| Date | Task | Configuration | Test Article: Serial No. | Test Article: Date Manufactured | Test Article: Age at Test Date | Cycle Testing at AiResearch: Dates: Start | Cycle Testing at AiResearch: Dates: Stop | Cycle Testing at AiResearch: Total Cycles Applied | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-74 | Obtain a new group of temperature | A new batch of five surface-type temperature sensors were made available to AiResearch for continuation of the stability test program. The sensors were supplied by the Tylan Corporation, Torrance, California. These sensors were equivalent to the previous test articles except that they were molded in a curved condition to conform to the inner wall of a 8.5-mm-(3/8-in.-) dia tube. The cyclic test fixture was modified to contain five thin-walled 0.25-mm-(0.010-in.-) thick stainless steel tubes with one end of each tube welded closed. A temperature sensor was installed in each of the five tubes near to the closed end. The fixture held the tubes vertically such that during cycling the closed ends of the tubes were immersed in the 195°K (-109°F) to 422°K (300°F) Coolanol. The tubes were long enough to preclude Coolanol fluid from being splashed into the open end. The fixture allowed the temperature sensors to be cycled from 195°K (-109°F) to 422°K (300°F) without becoming wetted by the Coolanol fluid. The freezing and drying of the moisture in the air adjacent to the sensor is typical of the ambient conditions the sensors are designed to meet. | 014 | 1967 | 6 yr | 1-15-74 | 2-15-74 | 13,464 | The test was stopped after 13,464 cycles for the purpose of conducting a performance record test. No performance data was recorded during the cyclic testing. Two of the five temperature sensors indicated an open circuit. An investigation of the failure revealed that the Teflon lead wire lost its bond between the Teflon and the fiberglass that surrounds the platinum temperature sensor in the form of a laminate, transferring all the load to a welded junction between the 0.025-mm-(0.001-in.-) diameter platinum wire and the copper lead wire. The cyclic thermal expansion and contraction soon causes failure of the platinum wire at the welded junction.<br><br>An examination of the failure shows that the bond between the Teflon insulation surrounding the lead wires and the fiberglass weakened causing breakage of the platinum wire. This failure was shown to be the same as the previous two failures that were attributed to the solvent action of the 422°K (300°F) Coolanol. The latest failure occurred on sensors that were protected from intimate contact with the Coolanol. The failed sensors were viewed under magnification, and it was determined that the Teflon-jacketed wire was not properly etched to effect a suitable bond during the heat cure of the fiberglass lamination. Discussions with Tylan Corp. personnel indicated that the entire roll of Teflon insulated wire is purchased in the etched condition; however, no specific inspection is conducted by the Tylan Corp. for whether or not the Teflon is adequately etched. | |
| 1-74 | Modify holding fixture. | | 015 | 1967 | 6 yr | 1-21-74 | 2-15-74 | 13,464 | | |
| 1-18-74 | Mount sensors in the fixture and conduct a performance record test. | | 017 | 1967 | 6 yr | 1-21-74 | 2-15-74 | 13,464 | | 31,039 |
| 1-21-74 | Alternately cycle the sensors from 195°K (-109°F) to 422°K (300°F) on a 24 hr/day basis. (The automatic cycle testing apparatus is not operated on weekends and holidays.) | | 023 | 1967 | 6 yr | 1-21-74 | 2-15-74 | 13,464 | | |
| | | | 016 | 1973 | <1 yr | 1-21-74 | 2-15-74 | 13,464 | | |

TABLE 4-1 (Continued)

| Date | Task | Configuration | Test Article: Serial No. | Test Article: Date Manufactured | Test Article: Age at Test Date | Cycle Testing at AiResearch: Dates: Start | Cycle Testing at AiResearch: Dates: Stop | Cycle Testing at AiResearch: Total Cycles Applied | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 2-74 | Fabricate three new sensors. (Three lengths of the Teflon insulated wire were etched by the AiResearch Materials and Process Engineering Laboratory and were furnished to the Tylan Corp. for fabrication and assembly of three complete temperature sensors. Each of the three sensors had varying lengths of etched Teflon sandwiched between the fiberglass laminate. The length varies from approximately 2.8 mm (1/8-in.) to 8.5 mm (3/8-in.). Two temperature sensors using MIL-W-81044/12 wire were made available by the Tylan Corp. for cyclic testing. These surface sensors contain a cross-linked polyalkene-insulated, tin-coated copper wire). | The test fixture was also modified by flattening one end of two metal test tubes to accept the flat shape of these sensors. The flattened end of the test tube was welded closed after insertion of the temperature sensor to ensure a good seal from the hot and cold Coolanol thermal fluid. The two flat-shaped temperature sensors incorporated a lead-wire constructed from a cross-linked polyalkene insulated, tin-coated copper wire conforming to military specification MIL-W-81044/12. It was decided to cycle these two sensors to compare the adhesive property of the polyalkene insulation to the etched Teflon insulation. All Tylan temperature sensors previously cycled during this development program incorporate Teflon-insulated silver-plated copper wire conforming to military specification MIL-W-16878 Type E. | 001 | 2-74 | <1 mo | 2-3-74 | 4-1-74 | 5,778 | SN 002 developed an intermittent condition. It had received 5778 temperature cycles. The metal test tube was cut open to remove the sensor. An examination of the sensor under a microscope did not identify the exact cause of failure. The other sensor SN 001 was returned to the cyclic test apparatus for a continuation of the temperature cycling. | |
| | | | 002 | 2-74 | <1 mo | 3-3-74 | 4-1-74 | 5,778 | | 36,817 |
| 3-1-74 | Conduct performance test on the two temperature sensors that incorporate the cross-linked polyalkene insulated wire. Check electrical continuity weekly to determine if breakdown of the sensors occurred. | | | | | | | | | |

TABLE 4-1 (Continued)

| Date | Task | Configuration | Test Article | | | Cycle Testing at AiResearch | | | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Serial No. | Date Manufactured | Age at Test Date | Dates Start | Dates Stop | Total Cycles Applied | | |
| 3-74 | Fabricate three new sensors. (Three new surface-type temperature sensors were fabricated by the Tylan Corp. for AiResearch.) | The sensors incorporated Teflon-insulated lead wire that was etched by the AiResearch Materials and Process Engineering Laboratory. Each of the three sensors had varying lengths of the etched Teflon sandwiched between the fiberglass laminate. The lengths varied from 2.8 mm (1/8-in.) to 8.5 mm (3/8-in.). The sensors were molded with a curvature to conform to the inner walls of the 8.5-mm- (3/8-in.) dia metal test tubes contained in the cyclic test apparatus. | 014 | 3-74 | <1 mo | 3-28-74 | 4-12-74 | 6,674 | The sensors were checked for electrical continuity once each week to determine if and when failure occurs. One of the three sensors (SN 015) was reported to be failed open on April 12, 1974 after 6674 temperature cycles. The other two sensors continued cyclic testing.<br><br>Because of the failure during this development program, Tylan Corporation reviewed the materials of construction and processing of the fiberglass surface sensors; all sensor failures were associated with a softening of the fiberglass. This transfers the load to the weld junction of the copper lead wire and the 0.025-mm- (0.001-in.) dia platinum sensing element. Thermal contraction and expansion during the cyclic temperature tests causes fracture at this junction.<br><br>Tylan Corporation personnel obtained updated processing instructions for the fiberglass resin from their supplier. A new batch of sensors were fabricated in accordance with these procedures, and an extra layer of glass fiber was placed on either side of the weld junction for additional strength and insulation. Three of these sensors were furnished to AiResearch for the cyclic test program. These three sensors were molded in a curved shape to conform to the 8.5-mm- (3/8-in.) ID of the metal test tubes attached to the cyclic temperature test apparatus. | |
| | | | 015 | 3-74 | <1 mo | 3-28-74 | 4-12-74 | 6,674 | | 43,485 |
| 3-74 | Conduct performance record test at AiResearch on these three sensors at 273°K (32°F), 195°K (-109°F), 373°K (212°F), and 422°K (300°F) prior to cyclic testing. | | | | | | | | | |

## TABLE 4-1 (Continued)

| Date | Task | Configuration | Test Article | | | Cycle Testing at AiResearch | | | Reason for Stopping Test | Counter Reading No. of Cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Serial No. | Date Manufactured | Age at Test Date | Dates | | Total Cycles Applied | | |
| | | | | | | Start | Stop | | | |
| 4-74 | Fabricate three new sensors with updated fiberglass processing instructions. | Molded with a curvature to conform to the inner walls of the 8.5-mm- (3/8-in.) dia metal test tubes contained in the cyclic test apparatus. | | | | | | | | |
| 5-3-74 | Cycle test three new sensors. | These sensors shared space in the metal test tubes with Serial Nos. 014 and 023, which were installed on 3-27-74. | 1 | 4-74 | <1 mo | 5-3-74 | 5-20-74 | 5,571 | | |
| | | | 2 | 4-74 | <1 mo | 5-3-74 | 5-20-74 | 5,571 | SN 002 was found to be failed open on May 20, 1974. | 51,653 |
| | | | 3 | 4-74 | <1 mo | 5-3-74 | 5-20-74 | 5,571 | | |
| 5-20-74 | Conclude test. | | 001 | 2-74 | <1 mo | 3-3-74 | 5-20-74 | 24,713 | These sensors were in the test fixture at the time the test program was concluded. | |
| | | | 1 | 4-74 | <1 mo | 5-3-74 | 5-20-74 | 5,971 | | 57,624 |
| | | | 3 | 4-74 | <1 mo | 5-3-74 | 5-20-74 | 5,971 | | |
| | | | 014 | 3-74 | <1 mo | 5-28-74 | 5-20-74 | 17,802 | | |

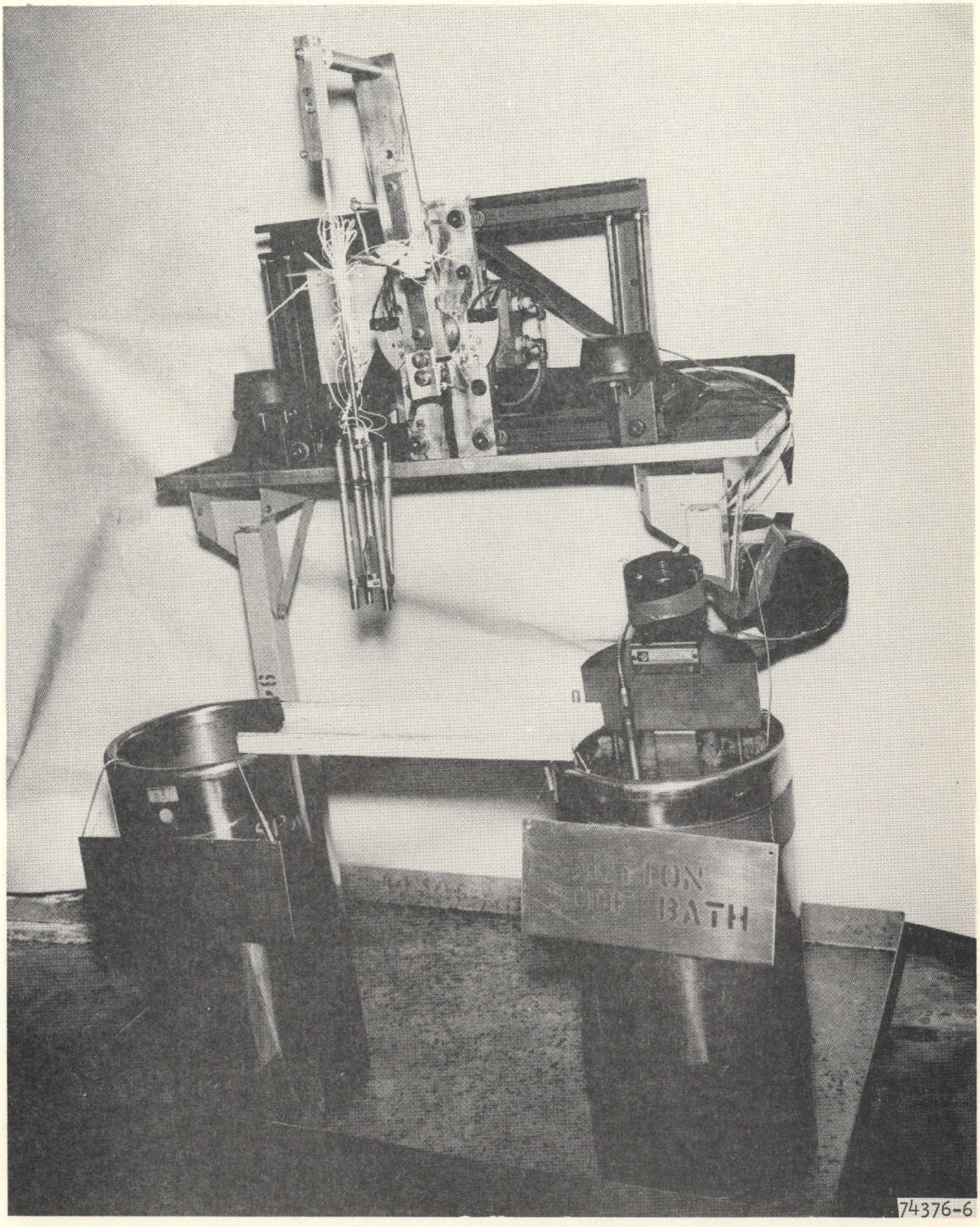



Figure 4-1. Temperature Sensor Cyclic Test Apparatus

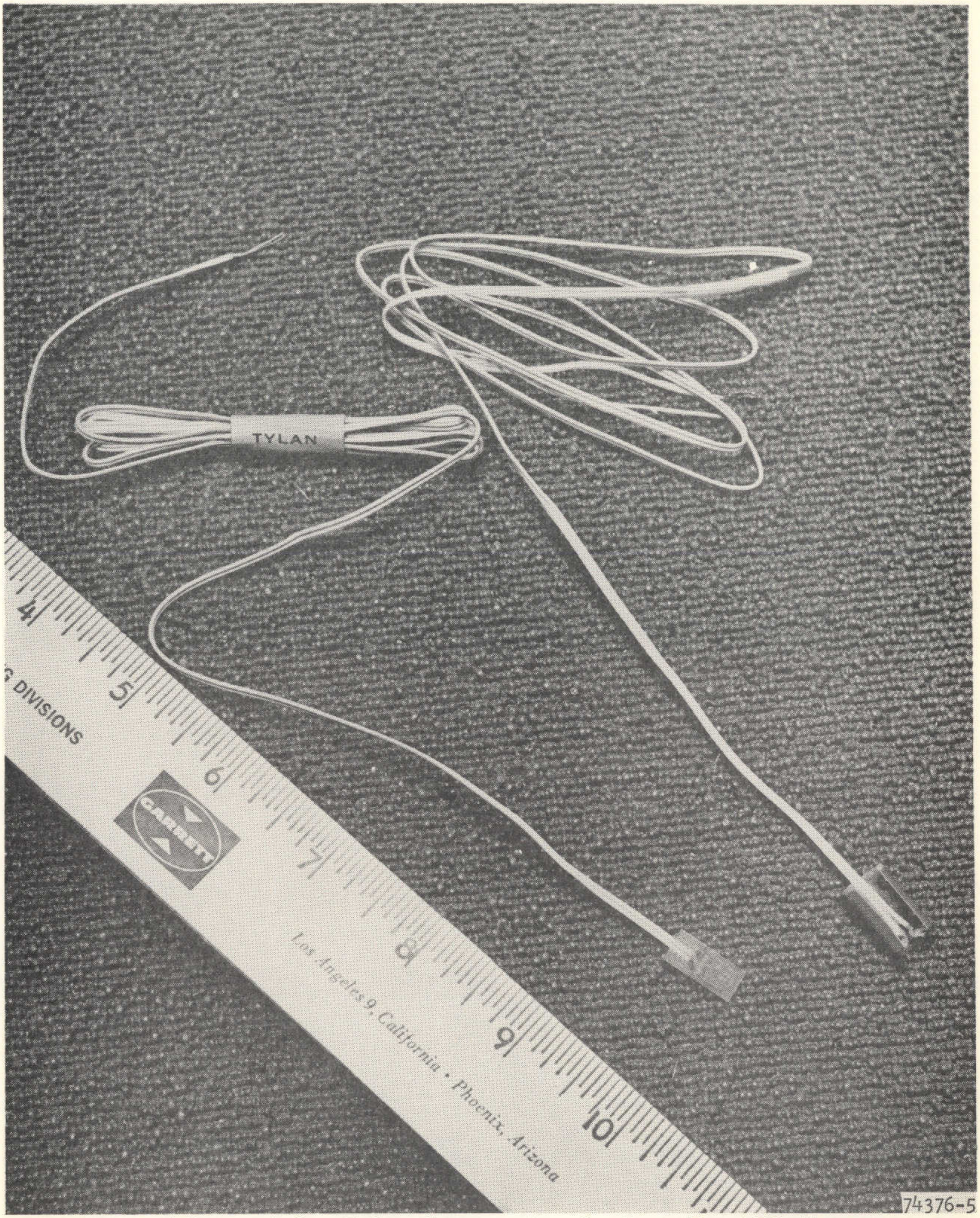



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Figure 4-2. Tylan Corporation Surface-Type Platinum Resistance Sensors, Series FG100P (6-in. ruler shown for comparison)

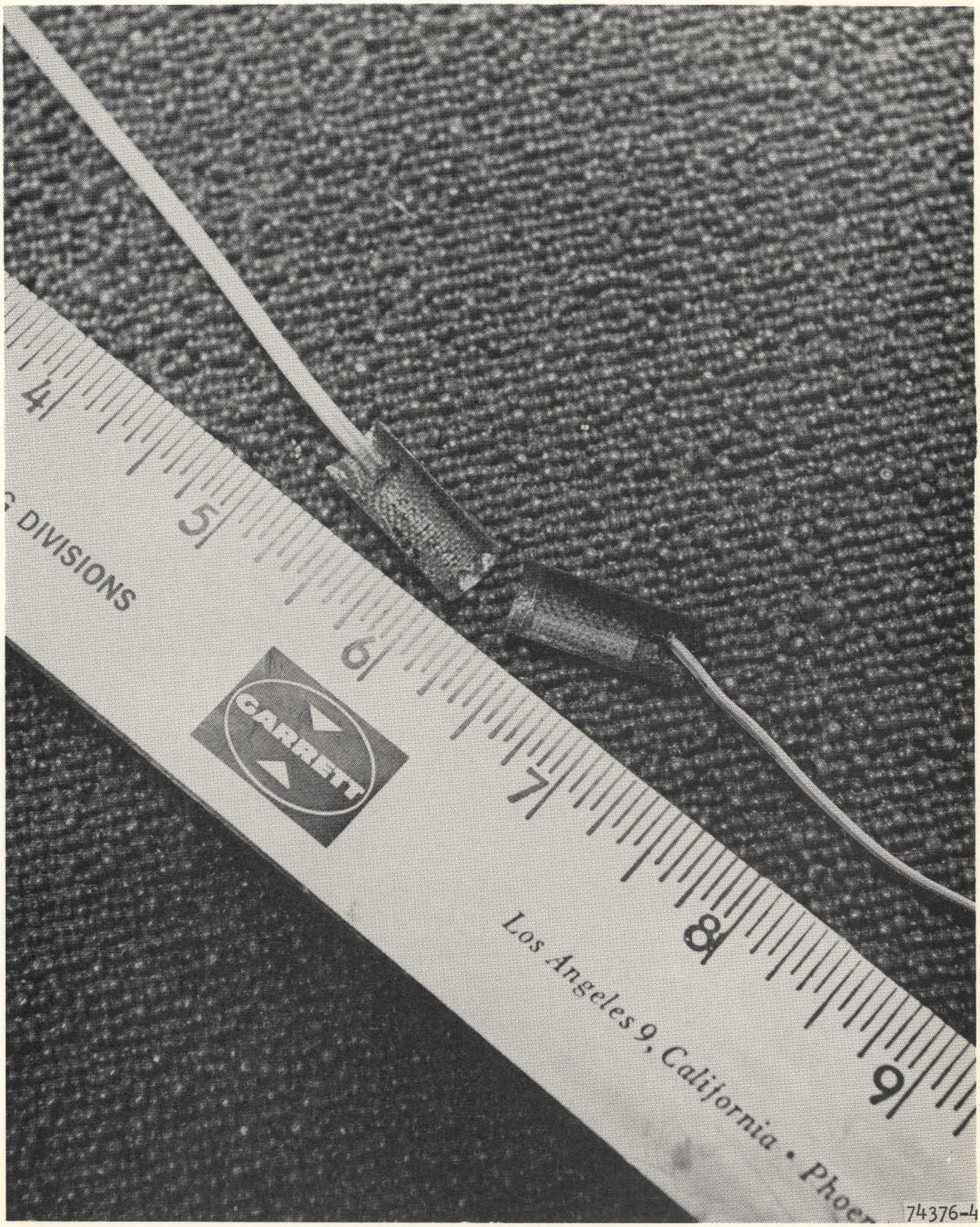
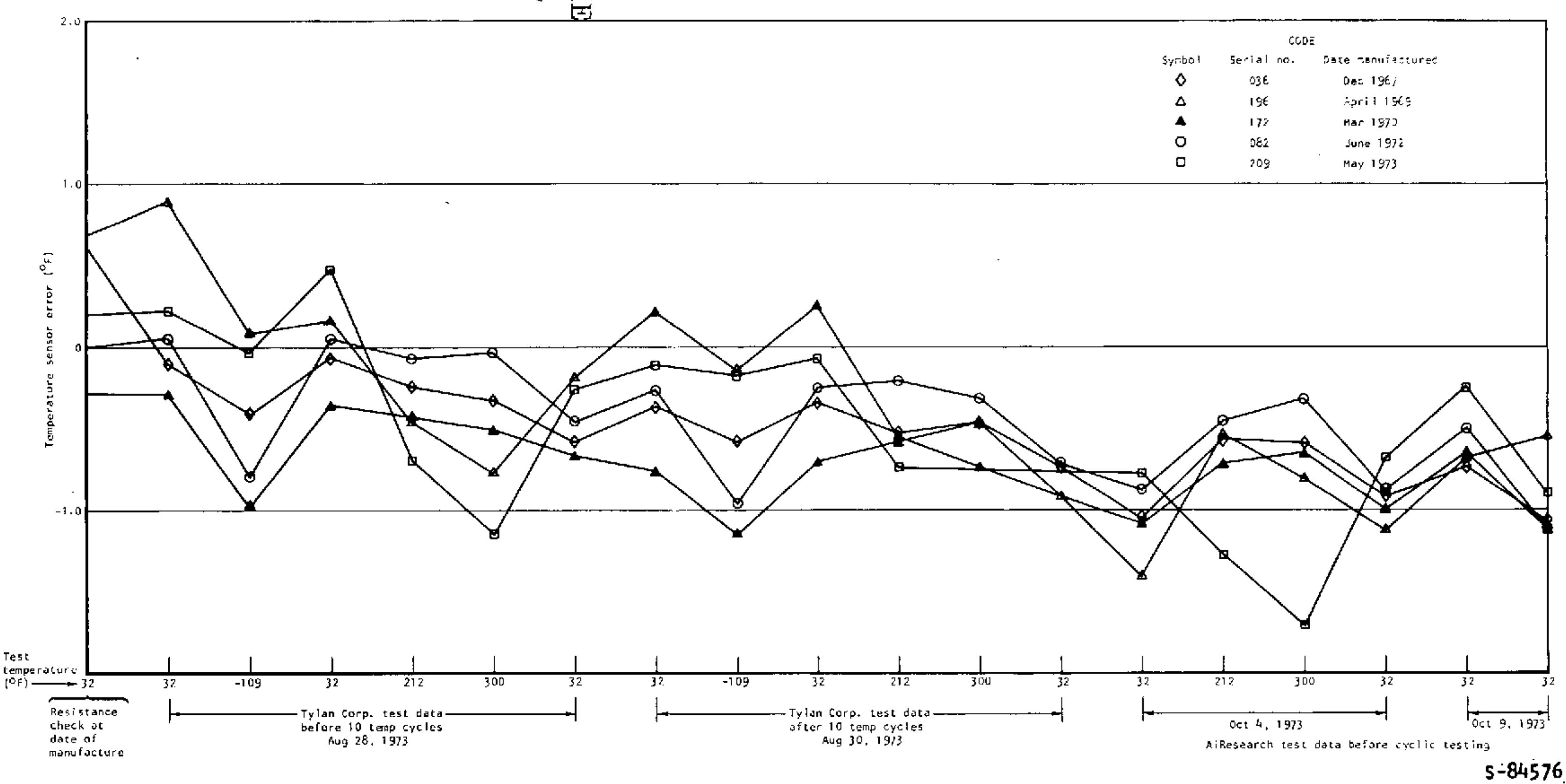



Figure 4-3. Loss of Bond Between Insulated Leadwire and Fiberglass Laminate Shown on Sensor on Right-Hand Side Only
(6-in. ruler shown for comparison)




$t_K = 5/9\ (t_F + 459.67)$

Figure 4-4. Temperature Sensor Stability vs Time

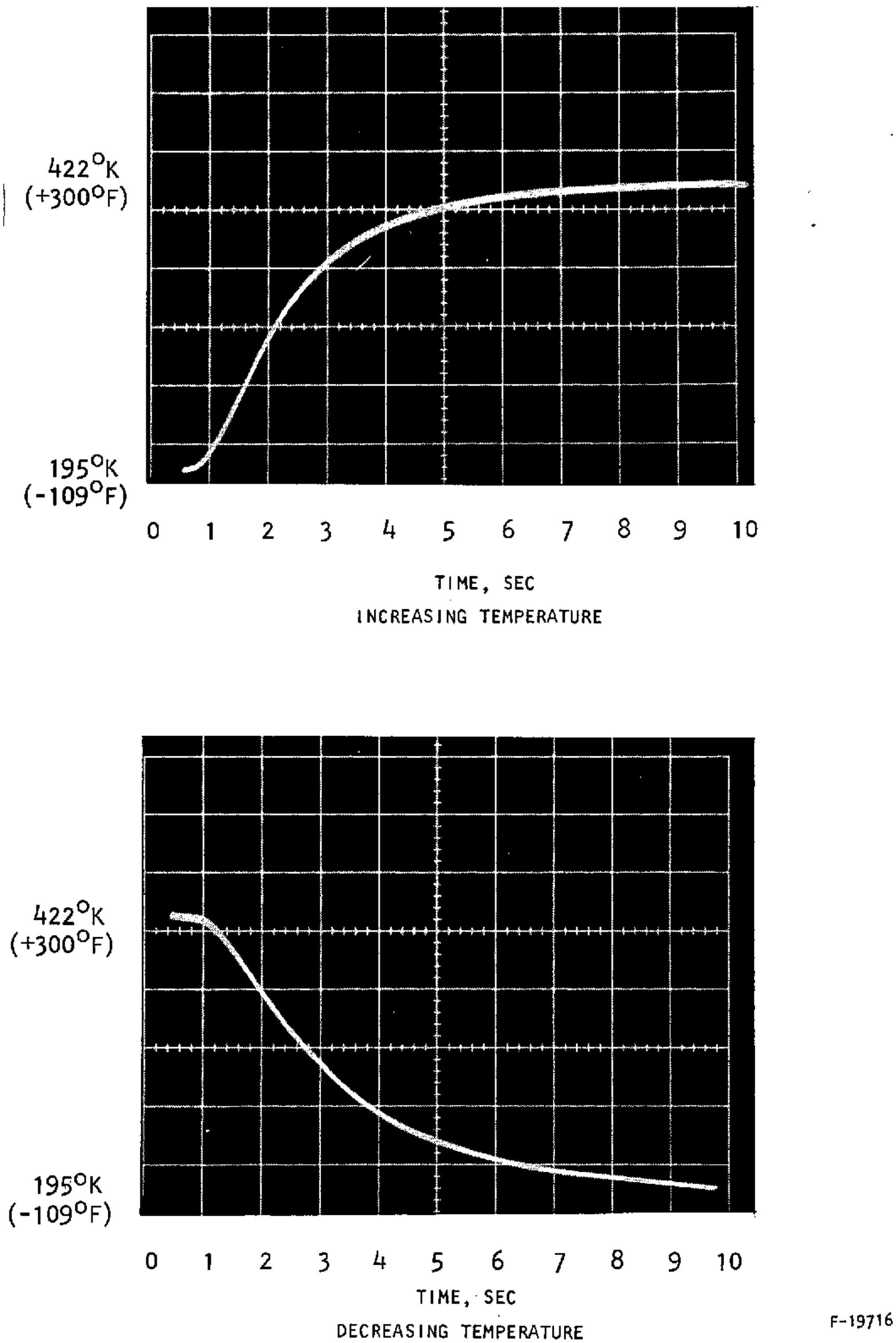



Figure 4-5. Response Time of Temperature Sensor SN 014

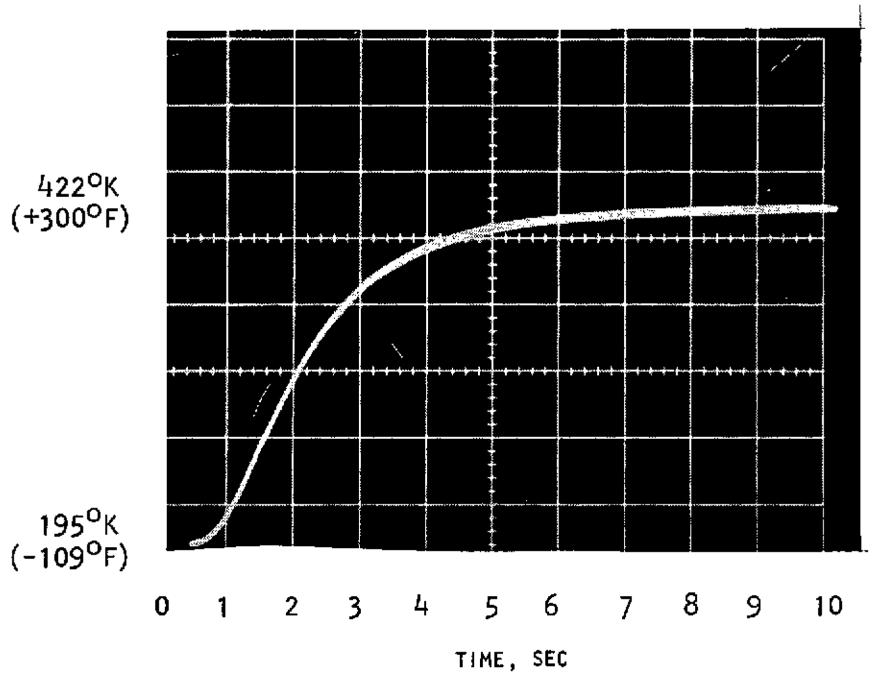



Figure 4-6. Response Time of Temperature Sensor SN 015

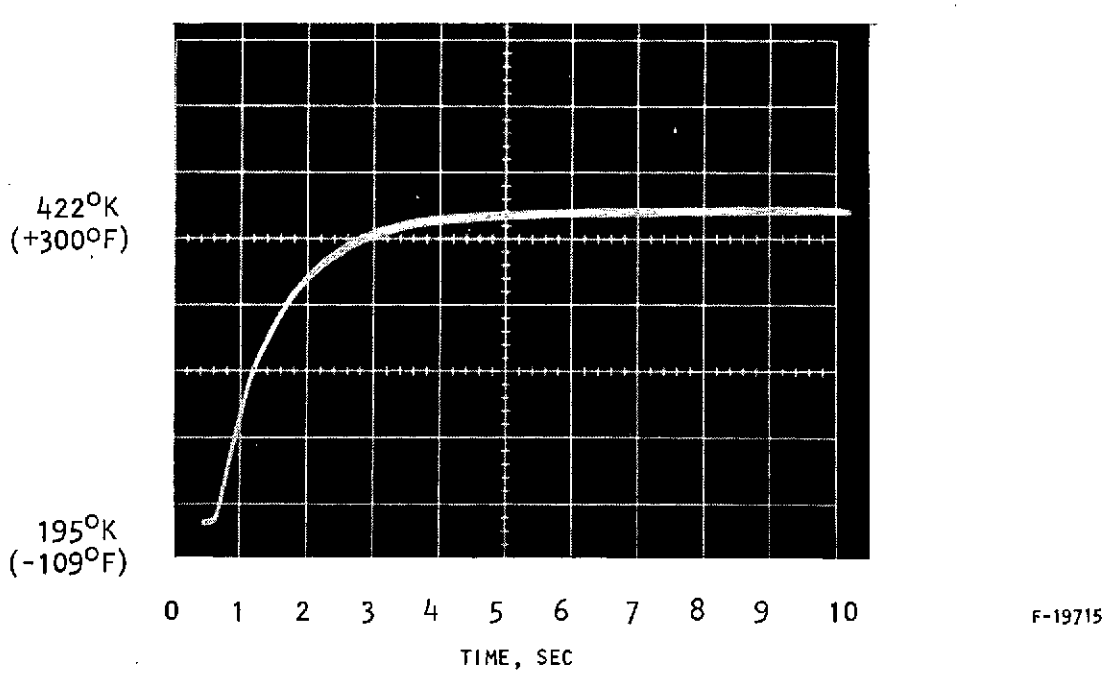



Figure 4-7. Response Time of Temperature Sensor SN 023

Built-In Test (BITE) Development. --A development program for defining and demonstrating built-in-test provisions in platinum resistance temperature sensors was subcontracted to Tylan Corporation of Torrance, California. The objective of incorporating BITE provisions in the temperature sensors was to provide a simple means of verifying the status of the temperature sensors installed in the Shuttle ECS during ground checkout. Many of these sensors are installed in insulated liquid loops and in relatively inaccessible areas; therefore, it would be extremely difficult and time-consuming to perform checkout of the sensor at the sensor interface.

The BITE development has been conducted on surface-type platinum resistance sensors; however, the results also are applicable to immersion-type and well-type platinum sensors.

Platinum has a fairly high temperature coefficient of resistance. In these sensors, a length of wire having the desired resistance is wound into a convenient physical form and is electrically connected as one arm of a Wheatstone bridge. The bridge completion circuitry, signal conditioning, and power supply are located in the centralized power supply and signal conditioner for data-type signals aboard the Shuttle. In the event the temperature signal is used for control, then the bridge completion circuitry, signal conditioning, and power supply are contained in the electronic control box for that particular system. Therefore, the end-item temperature sensor considered for the BITE development consists of a wire-wound platinum sensor representing one leg of the Wheatstone bridge. Wire sensors of this type are available with tolerances of 1 to 0.1 percent, or better, and thus can be interchanged without the need of recalibration.

The approaches considered for incorporation of BITE provisions in wire-wound resistance sensors are described below.

Special Temperature Sensor with Built-In Heater (Method A). --During this development, an electrical heater was incorporated by laminating a second 0.254-mm- (0.010-in.-) thick surface sensor over the primary temperature sensor to act as a heater ($R_H$) when the BITE circuit is energized. The increased temperature was sensed by the primary sensor ($R_T$) to verify that it is functional. The bridge completion circuitry and associated signal conditioning also are verified using this approach. The final configuration for this method may include the primary temperature sensor and heater element made integral in a single temperature sensor. This method is illustrated schematically in Figure 4-8.

Following are the design features of the special temperature sensor with built-in heater.

(a) Bridge design is independent of BITE.

(b) Reaction to BITE actuation depends upon dissipation coefficient of sensor mounting (results in possibility of overheating sensor).

BITE METHOD A

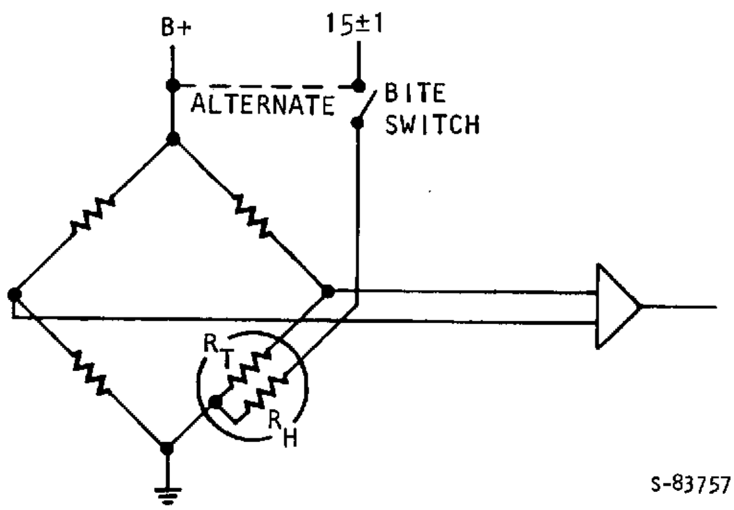



Figure 4-8. Special Temperature Sensor with Built-In Heater

(c) Special 2-element sensor required.

(d) Two power supply levels required. (Second supply might be taken from some bridge supply at much higher current if preferred.)

(e) Normal operation of bridge is not affected by any fail-open malfunctions of BITE circuit. (Other types of failures are far less likely.)

This method was demonstrated in the laboratory by cementing the laminated assembly of two surface sensors to a 2.4-kg copper block. The copper block represented an infinite heat sink for the extremely small, lightweight surface sensors. Each sensor weighed less than 12 grams. The large heat sink was used to simulate a liquid coolant loop typical of the Shuttle ECS and to determine whether or not the surface sensor would indicate an increase in temperature in the presence of the large heat sink and the small heater element. The temperature sensor ($R_T$) was sandwiched between the heater ($R_H$) and the copper block.

The data contained in Table 4-2 were recorded during the test.

The test data show that Temperature Sensor No. 1 increased in the presence of both the adjacent sensor that was used as an electrical heater and the large heat sink.

## TABLE 4-2

## TEST DATA OF TEMPERATURE SENSOR WITH BITE HEATER LAMINATED TO THE SENSOR

| FG-102P<br>Temperature Sensor No. 1<br><br>Ice Point Resistance<br>$R_o$ = 150.1 | | | FG-102P<br>Temperature Sensor No. 2<br>(Used as an Electrical Heater)<br><br>Ice Point Resistance<br>$R_o$ = 150.4<br>Power Supply = Spar Model 500 | | |
|---|---|---|---|---|---|
| $R_1$<br>Fluke 2117, ohm | $T_1$<br>From Platinum Table, °F | $E_2$<br>Weston 2304, v | $I_2$<br>Weston 2103, amp | $R_2$<br>(Calculated), ohm | $T_2$<br>From Platinum Table, °F |
| 163.5 | 73 | 0 | 0.0 | 163.8 | 73 |
| 177.0 | 115 | 28 | 0.125 | 224.0 | 260 |
| 174.2 | 109 | 24 | 0.114 | 210.2 | 217 |
| 171.3 | 97 | 20 | 0.0985 | 203.0 | 194 |
| 168.5 | 88 | 15 | 0.0808 | 185.6 | 140 |
| 166.0 | 81 | 10 | 0.0580 | 172.4 | 99 |
| 164.4 | 76 | 5 | 0.0302 | 165.5 | 78 |
| 163.8 | 73 | 0 | 0.0 | 164.1 | 73 |

$t_K = \frac{5}{9}(t_F + 459.67)$

Special Sensor with Built-In Heater and Sensor Temperature Limiting (Method B). --Another approach to incorporating BITE in the temperature sensor also involved the use of an integral resistance heater laminated adjacent to the platinum resistance temperature sensor as described in the first BITE method above, except that the sensor is protected from accidental overheating. The power to the integral resistance heater is regulated in the temperature sensor power supply. Figure 4-9 schematically illustrates this approach.

BITE METHOD B

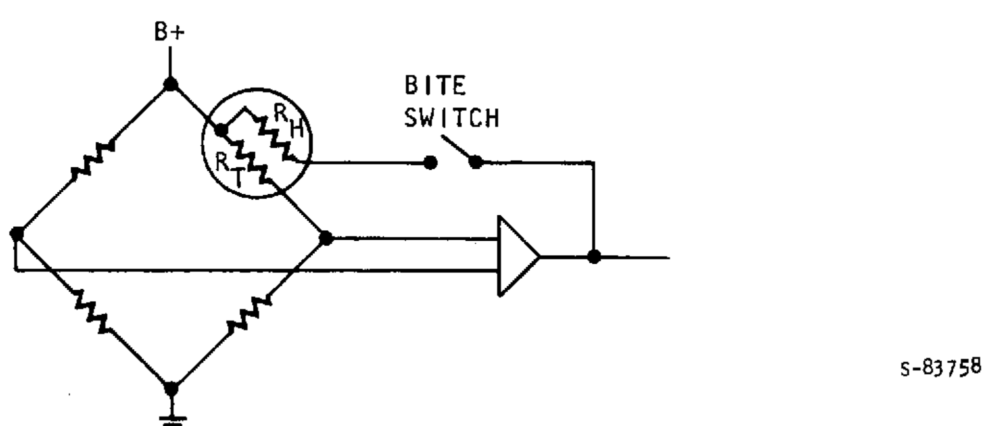



Figure 4-9. Special Sensor with Built-In Heater and Sensor Temperature Limiting

Following are the design features of the special sensor with built-in heater and sensor temperature limiting.

(a) Bridge design is somewhat interdependent with BITE.

(b) Reaction to BITE actuation is less dependent upon sensor-mounting dissipation coefficient than the first method, and sensor is protected from accidental overheating from BITE heater.

(c) Special 2-element sensor required.

(d) BITE heater power requirement must be provided by both bridge power supply and amplifier capacities.

(e) Normal operation of bridge is not affected by any fail-open malfunctions of BITE circuit.

Self-Heated Sensor (Method C). --In the approach shown in Figure 4-10, the platinum resistance temperature sensor is used alternately as a heater during system checkout via the BITE system. In the BITE mode, electrical power is applied to the sensor causing it to heat up as an electrical heater. The resistance simultaneously increases and is monitored by the output circuitry of the temperature sensor.

BITE METHOD C

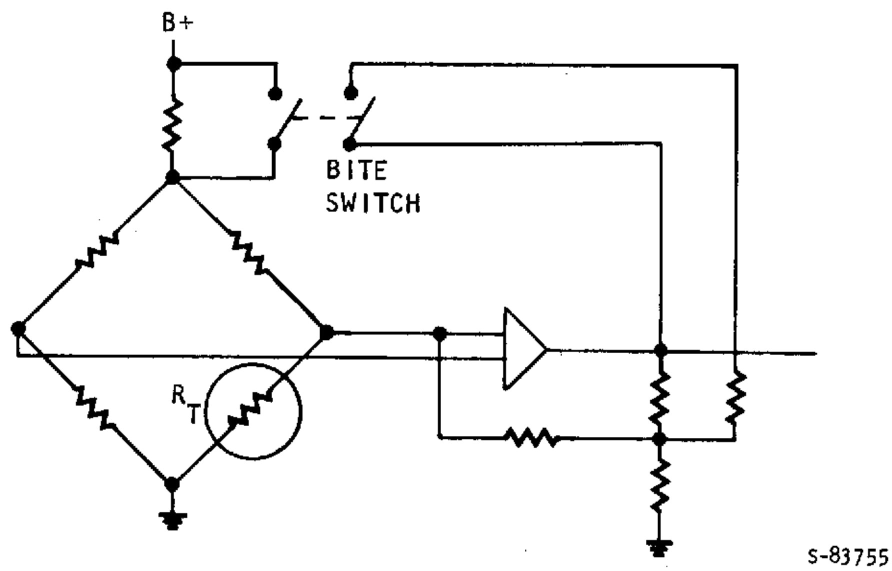



Figure 4-10. Self-Heated Sensor

Following are the design features of the self-heated sensor.

(a) Bridge design must be specifically optimized to permit BITE to function.

(b) BITE switch requires two poles, one to increase bridge excitation, the other to give compensating reduction in amplifier gain.

(c) There is some difficulty in getting adequate self-heating for BITE indication, but no danger of overheating the sensor.

(d) Sensor can be a standard single element.

(e) Power supply must be sized to accommodate higher current in BITE mode.

(f) The number of extra parts and connections indicates that reliability in normal operation may be lower.

Calibrated Bridge Offset (Method D).--In the approach shown in Figure 4-11, a resistor is installed in parallel to the platinum resistance temperature sensor. The BITE switch completes the circuit to the resistor when actuated so that the output indicates a known offset during checkout. The BITE switch also enables a check of the zero point of the amplifier in the second position.

BITE METHOD D

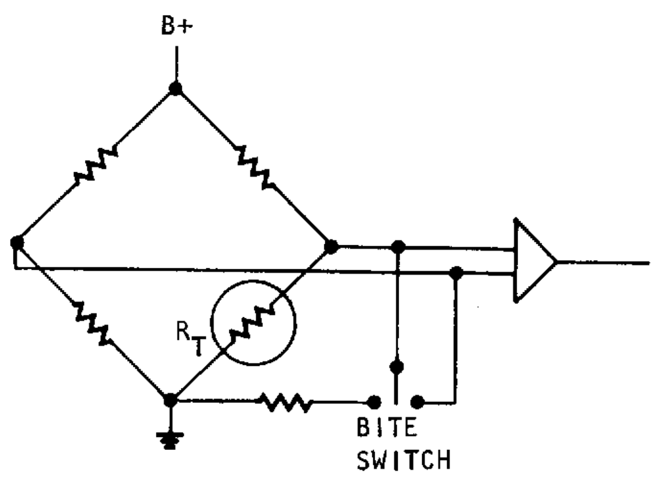



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Figure 4-11. Calibrated Bridge Offset

Following are the design features of the calibrated bridge offset.

(a) Bridge design is independent of BITE.

(b) Reaction to BITE actuation is quantitatively repeatable and independent of sensor mounting.

(c) Amplifier zero can be checked by same BITE switch with minimum added complexity.

(d) Sensor can be standard single element.

(e) Power supply design is not affected by BITE.

Summary of Built-In-Test BITE Methods.--The design features of each of the various methods for incorporating built-in-test provisions in resistance wire temperature sensors were evaluated and ranked against each other. Table 4-3 shows the results of the analysis.

TABLE 4-3

COMPARISON OF BITE METHODS

| Operational Features | Method | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Checks sensor calibration | 0 | 0 | 0 | 0 |
| Checks sensor continuity | 2 | 2 | 2 | 2 |
| Checks that sensor changes resistance as temperature changes | 2 | 2 | 2 | 0 |
| Checks amplifier zero | 0 | 0 | 0 | 2 |
| Checks amplifier gain quantitatively | 0 | 0 | 0 | 2 |
| Does not adversely affect sensor cost or reliability | 0 | 0 | 2 | 2 |
| Does not restrict bridge design parameters | 2 | 2 | 0 | 2 |
| Function of BITE is independent of sensor-mounting dissipation constant | 0 | 0 | 0 | 2 |
| Does not risk overheating sensor during BITE operation | 0 | 2 | 2 | 2 |
| Does not require extra power supply complexity or increased current rating | 0 | 0 | 0 | 2 |
| Does not add significant complexity or failure rate to normal operating function | 2 | 1 | 0 | 1 |
| Totals | 8 | 8 | 8 | 17 |

Scoring: 2 = good
1 = fair
0 = poor

## Results and Conclusions

A total of 23 surface-type platinum resistance temperature sensors were temperature-cycled between 195°K (-109°F) and 422°K (+300°F) for a total of 57,624 cycles. The sensors responded to the temperature change in less than 2 sec for a 63-percent change and were held at each temperature alternately for approximately 60 sec. One cycle included 60 sec of cold bath followed by 60 sec of hot bath. Eight of the sensors failed open as a result of breakage of the 0.0254-mm- (0.001-in.-) dia wire platinum resistance element. The cause of failure, however, was due to the loss of bond between the insulation covering the dual lead wire and the fiberglass laminate, which is molded over a portion of the insulated lead wire. The fewest number of cycles to failure was 5,571 and the greatest number of cycles logged was 24,713. The sensor with 24,713 cycles, and three other sensors with 17,802, 5,971, and 5,971 cycles, respectively, were still functional and were in the cyclic test apparatus at the time the test program was concluded.

The following conclusions are relevant to the use of the Tylan Corporation platinum resistance surface sensors:

- Cycle life may be increased substantially if the low- and high-temperature extremes are lowered to a range of 219°K (-65°F) to 347°K (+165°F). This temperature range encompasses most of the ECS control and monitoring temperature applications.

- Since all of the failures experienced with the temperature sensors are open failures, it is suggested that built-in-test provisions be included in the centralized signal conditioner and power supply, which (in the case of temperature sensors) includes the bridge completion circuitry. This method is illustrated by the fourth BITE method, Figure 4-11, which offers the advantage of simplicity and the capability of checking the zero calibration of the signal conditioner.

- The lightweight (less than 12 gr including 1.22 m (48 in.) of lead wire), low-cost features of the temperature sensors tested permit several (three for example) to be installed initially, especially in areas with little accessibility so that during maintenance, the second, and later, the third sensor can be connected in place of the failed unit(s) at the subsystem interface connector.

- Surface-type temperature sensors may be replaced readily without the necessity of breaking into the hard-fill of spacecraft liquid loops that have been evacuated and back-filled with deaerated thermal transport fluid.

- The test data show that sensors conforming to a particular part number may be replaced with new sensors of the same part number without the necessity of recalibrating the centralized signal conditioner.

- The test data show that the sensors are stable and repeatable even after being in storage for over five years.

- The test data show that the performance of the sensors does not degrade as a function of temperature cycles applied up to the time of failure, which is characterized by an open circuit. Thus, temperature-sensor failures are easy to diagnose by means of a computerized fault-detection system or by conventional maintenance schemes.

## Recommendations

The FG-100 series surface-type platinum resistance temperature sensors made by Tylan Corporation provide an accurate, low-cost, lightweight device for monitoring temperature. The results of this development program show that the minimum cycle life is between 5,700 and 13,500 temperature cycles, with a temperature cycle consisting of immersion of the sensor in 195°K (-109°F) thermal fluid for 60 sec, followed by immediate immersion of the sensor in 422°K (+300°F) thermal fluid for 60 sec. It is recommended that the sensor be used in applications where the temperature extremes are less than those used in this test program; preferably 219°K (-65°F) to 347°K (+165°F).

Since all failures experienced during this test program were initiated by the softening of the bond between the insulation on the lead wires and the fiberglass laminate, AiResearch recommends that Tylan continue the development program to provide improvements to the bonded joint by incorporating mechanical interlocking in addition to the adhesive bond. AiResearch also recommends continuation of the investigation of the selection, the compounding/processing, and the cure of the epoxy used in the fiberglass laminate to provide an ultimate bond that does not soften and lose strength at ambient temperatures up to 422°K (300°F).

# SECTION 5

# NUCLEONICS CONTENTS GAGING SYSTEM

# SECTION 5
# NUCLEONICS CONTENTS GAGING SYSTEM

This section describes a development and test program in which a nucleonics gaging system, produced by General Nucleonics, a division of TYCO Laboratories, Pomona, California, was interfaced with an Apollo bladder-type (zero-g) water storage tank.

## Background

A thorough review of the chronic problems associated with the quantity-measuring devices on the Apollo Environmental Control System (ECS) program was conducted during the transducer evaluation phase of this program. The objective was to identify problems and develop remedies to ensure that the quantity-measuring devices would be highly reliable for use on the Space Shuttle ECS. The Apollo Command Service Module (CSM) water tank gaging system suffered a total of 25 failures during the period December 1965 through January 1971. A review of the failure reports indicated that the contents gaging system was generally troublesome, sensitive to orientation of the tank, and unreliable for measurement of water quantity. Existing devices were considered unworthy of modification, because the concepts used were considered inappropriate for Shuttle use. A summary of the failures of the Apollo CSM water tank gaging system, effectively substantiating this decision, is presented in Appendix E. As a result of investigation of alternate devices, it was concluded that a nucleonics gaging system that could be interfaced with an existing CSM water tank and evaluated for future use in the Space Shuttle program should be developed.

## Review of Candidate Devices

Various approaches to quantity measuring were reviewed in an effort to find an alternate, reliable system. Some of these devices were:

> <u>CSM Water-Glycol Pump</u>--The accumulator in the CSM water-glycol pump consisted of a normally collapsed bellows that was designed with a known spring rate. With the water-glycol system filled to capacity (bellows elongated), the spring rate of the bellows caused an increase in pressure that was monitored by a pressure transducer. As the quantity in the accumulator decreased due to system leakage or temperature changes, the bellows approached a collapsed position and also applied less force on the liquid. The reduced pressure was monitored by the pressure transducer and thus the output signal of the pressure transducer was related to accumulator quantity. The Shuttle Freon pump requirements showed that a much larger bellows accumulator is required than was used in the CSM water-glycol pumps. The larger size makes it impractical to design the bellows as a spring or to apply force with an external spring because of the large forces that are required. A more efficient method is to apply

pressure pneumatically to the enclosure surrounding the external shape of the bellows. In this application the pneumatic pressure is held reasonably constant; therefore contents gaging with a pressure transducer is not possible. Other means must be used, e.g., attachment of the end of the bellows to a rotary potentiometer with a cable or the application of several reed switches that are actuated by a magnet attached to the upper edge of the bellows. As the magnet travels close to the respective reed switches, the appropriate switch closes to cause the indicator to give a readout of FULL, 3/4, 1/2, 1/4, or EMPTY.

Linear Variable Differential Transformer--Linear variable differential transformer (LVDT) transducers are sometimes used for measuring quantity. Figure 5-1 shows the diaphragm or bellows attached to a magnetic core that is moved inside a differential transformer as the quantity varies. The length of the LVDT housing must be at least as great as the stroke of the bellows or diaphragm, and thus may present a problem for some aerospace applications. The LVDT, however, does offer the advantages of continuous resolution, high output signal, and low hysteresis.

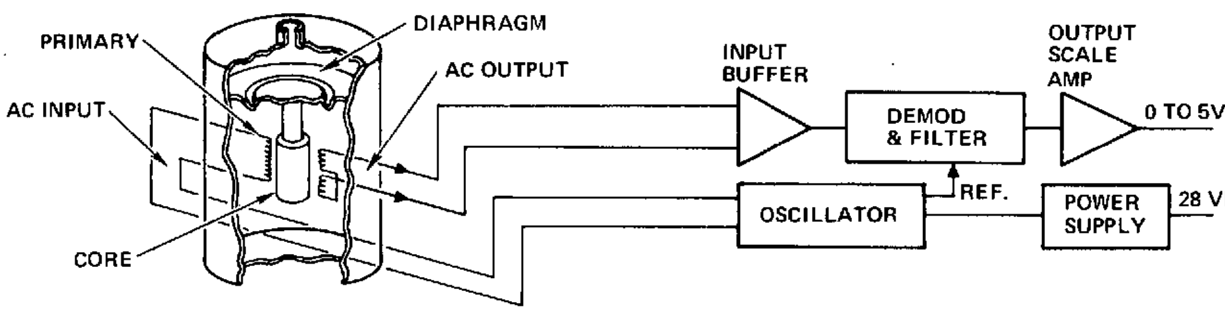



Figure 5-1. LVDT Transducer

Measurement of Fixed Charge of Ullage Gas--Another means of measuring the contents is to measure the pressure and temperature of the fixed charge of ullage gas contained on one side of the bladder or bellows. Both the lunar module (LM) and the portable life support system (PLSS) used a water quantity measuring device (WQMD) that relied on a pressure signal of the ullage compartment. This method is not recommended because of the large pressure excursions between empty and full. Other problems associated with this method include the difficulty of maintaining a suitable hermetic seal of the ullage gas and the complexity of integrating a temperature and pressure signal (both of which are subject to respective inherent inaccuracies) to establish fluid contents.

Capacitance Probes--Capacitance probes are not applicable to bladder-type tanks or bellows accumulators and therefore were not evaluated during this development program.

Nucleonics Gaging System--This system measures mass directly, and therefore is unaffected by error due to changes in temperature or pressure that occur with conventional systems, which are based on level or volume measurements. Since the system measures total mass in the tank, it is unaffected by the position of fluid in the tank, and therefore provides a true, continuous, highly accurate reading at all times. This device was considered the most appropriate of all systems evaluated, and was selected for development.

## Safety Assurance

The first consideration in the nucleonics gaging system was that of personnel safety. A radiation source must provide the right gamma energy and sufficient source strength to accomplish the purpose for which it is being used; however, it is essential that it does not cause any significant radiation dosage to crew members, ground maintenance personnel, or anyone who might be required to handle it in transit or in storage.

The threat of leakage and resulting radioactive contamination has prevented use of many excellent gaging devices. Since the nucleonics device provided by General Nucleonics for this program utilizes Krypton, its safety features are enhanced, because Krypton is inert and is not retained by the human body even if it is inhaled. It is permissible to ship the Krypton-85 source can in a standard cardboard carton to all parts of the world via all types of common carriers. An emission strength of 2 milliroengten/hr at one foot from the source is generated by 400 millicuries of Krypton-85 in 1/4-in.-OD aluminum alloy tubes. By comparison, a luminous-dial wristwatch emits more than 2 milliroentgen/hr at the face; a faulty color television set as much as 900 milliroentgen/hr; dental X-ray as high as 15,000 milliroentgen/hr; and fluoroscopic examinations up to 50,000 milliroentgen/hr. The average background radiation on the ground from cosmic rays is 0.5 to 1.5 milliroentgen/day.

## Background Radiation

In space, background radiation is an error source caused by cosmic radiation, solar particles, and Van Allen particles detected by the gaging system. The gaging system may be provided with a separate background detector that monitors background radiation and electronically compensates the gage reading for changes in background. Considerable data have been gathered on space radiation rates over the last ten years from instrumented satellites and the Gemini and Apollo missions. Dose rate data extrapolated from space missions indicate a very low background count rate; increases will occur during solar events or passage through the Van Allen belts; however, solar events have very low probability and most spacecraft missions spend only a small portion of time in the Van Allen belts. The gaging system can be precalibrated for a nominal background rate so that only increases or decreases will constitute errors. Gaging system errors can reasonably be estimated at less than 1 percent.

A more detailed discussion of radiation is presented in Appendix F.

## Description of Device Selected

The nucleonics gaging system selected is highly developed for monitoring oil quantity on military aircraft, and is qualified to MIL-O-38338A.

The system is simple; the source tube and the detector are the only two functional units on the tank; they are very light, have no moving parts, and transmit quantity information to the master indicator or onboard computer through one coaxial cable. The only moving part in the entire system is the dial pointer. The source tube fits snugly around the tank and is held in place by a simple bridle assembly. The detector is held in position by brackets that fit under the tank. The system is entirely external to the tank, thus greatly simplifying maintenance and tank design.

Operation of the system is based on the properties of radiation emission from radioactive materials, and the ability of matter to absorb, decelerate, or pass these emissions to varying degrees. The radioactive gas (Krypton-85) sealed in the source tube emits beta and gamma radiation in all directions, but the beta rays are absorbed completely by the walls of the aluminum tube.

Krypton-85, chosen as the radiation source for both technical and safety reasons, is an inert gas that cannot be absorbed or retained by the body. Hermetically sealed in the aluminum source tube, only its gamma rays need be monitored. If the source tube should rupture for any reason, the gas dissipates harmlessly into the atmosphere and does not leave any radioactive residue. The major precaution is to avoid excessively prolonged direct contact with the source tube; it contains 400 millicuries of Krypton-85, which emits with a strength of 2 milliroentgen/hr at one foot from the source, a relatively low level of radiation.

The gamma rays pass out of the tube, through the metal tank wall and the water, to the detector, a simple Geiger-Mueller tube mounted on the top surface of the tank in such a position that most of the radiation reaching it has passed through the greater portion of the tank that normally holds water. As each photon penetrates the case of the detector, an internal electrical discharge occurs. Each event generates a negative pulse that passes through the coaxial cable to the master indicator. The pulses are of relatively constant amplitude; therefore the required information is found in the number of pulses generated in a given time period (pulses per second). This pulse rate is proportional to the number of photons received, and thus is always inversely proportional to the amount of water in the tank.

The master indicator is a completely self-contained unit enclosing four modules in one case--the power supply module, rate meter module, switch module, and meter module. All modules are solid-state, welded, potted designs suitable for man-rated space applications, completely interchangeable between shipsets. The meter module is a separate hermetically sealed unit. A 400-cycle, 115-vac power supply generates 700 vdc for detector use and various low voltages for internal electronics use.

The switch module is calibrated by adjusting the potentiometer marked EMPTY until the meter reads empty, nulling out the mass of the tank itself. The tank then is filled with any desired quantity of water and the potentiometer marked FULL is adjusted until the meter reads full. The detector receives varying amounts of radiation from different areas of the source tube, but the cumulative effect of the energy is transmitted as a given pulse rate for a given amount of water.

## Development Program

Introduction--The nucleonics quantity gaging system was selected for investigation, and a program plan was prepared and submitted to NASA, describing the proposed interface of the nucleonics gaging system to the Apollo ECS zero-g/bladder-type water tank. Approval was granted under NASA JSC contract NAS 9-13446, and AiResearch selected General Nucleonics, a division of TYCO Laboratories, Pomona, California, to perform the development program.

The development program was conducted on the Apollo waste water tank (AiResearch PN 812260-4-1, SN 46-103, which was transferred from NASA Contract NAS 9-150 to NAS 9-13446). The tank was an expended qualification test article that was fully functional except that most of the conventional gaging system was missing from the tank assembly. The performance characteristics of the tank are presented in Table 5-1.

TABLE 5-1

PERFORMANCE CHARACTERISTICS, APOLLO WASTE WATER TANK

| | |
|---|---|
| Waste water tank | AiResearch PN 812260-4 |
| Configuration | Cylindrical tank with pressurized bladder for water expulsion at zero gravity |
| | Water collection channels prevent trapping of water port by bladder (tank empty); flow passages through bladder supporting frame prevent trapping of oxygen by bladder (tank full) |
| Ports | |
| Oxygen, nitrogen, or air | Expulsion gas inlet-outlet |
| Water | Water inlet-outlet |
| GSE service | Water-side servicing |
| Oxygen vent | Overboard vent to prevent hydrogen accumulation in oxygen expulsion gas (uncombined hydrogen in fuel cell water permeates through bladder) |
| | Fitting has internal 50-micron abs filter and internal 0.1016-mm (0.004-in.) orifice to control bleed |
| Storage capacity | 25.4 + 1.36 -0 kg (56 + 3 - 0 lb) $H_2O$ at 339°K (150°F) |
| Expulsion gas pressure | 225.5 kPa to 287.5 kPa (18 to 27 psig) |
| Water-side pressure | |
| Capability | 0 to 432 kPa (0 to 48 psig) |
| Normal range | Equal to expulsion gas pressure (tank neither full nor empty) |
| Water temperature | 278°K to 339°K (40° to 150°F) |
| Water delivery rate | 5.0 kg/hr minimum (11 lb/hr) at 225.5 kPa (18 psig) expulsion pressure |
| External leakage | 7.2 standard cc/hr $N_2$ (test fluid) max. at 377 kPa (40 psig) water side and 287.5 kPa (27 psig) gas side |
| Bladder leakage | 1.25 cc/hr $N_2$ (test fluid) max. at 172.4 kPa (25 psi) expulsion-to-water side $\Delta P$ |

The main area of development for this program involved the shaping of the radioisotope source to the water tank to achieve a highly reliable, lightweight quantity gaging system that accurately indicates the amount of water remaining during all flight attitudes and zero-g operation for space application. The Apollo CSM water tank was selected because it is a qualified zero-g bladder tank and because it imparts a complex shape to the water contained within the tank. The shape of the bladder and bladder restraints causes a configuration of water that is difficult to measure; consequently the development of a successful nucleonics gaging system for this particular tank demonstrates that virtually any tankage system can be monitored accurately using this system. The Apollo CSM water tank contains an elongated bladder that is mechanically restrained at either end. Oxygen or nitrogen gas is plumbed to the inside cavity formed by the bladder for maintaining the water in the liquid phase and for expelling it out of the water collection channels located around the periphery of the tank. The bladder forces the water in a partially full tank into a toroidal shape at each end of the tank; however, the inside diameter of each torus remains elongated because of the shape of the bladder restraints. Also, when the tank is nearly empty, a thin film of water is located about the periphery, representing a substantial volume of water for very small thicknesses.

Design Program--A nucleonics gaging system was designed using off-the-shelf hardware from existing nucleonics gaging systems, and interfaced with the Apollo CSM tank. Primary design effort was to optimize the location of the gaging elements on the tank to provide best gaging system accuracy. Two basic gaging system configurations were utilized, and variations of these two configurations were tested to determine the optimum configuration.

Nucleonic gages utilize the property of matter that results in the attenuation of radiation flux incident to it. The nucleonics gage employs a radioactive source of gamma rays positioned so that the material to be gaged is located between the source and the detection devices. The radioactive source emits gamma rays, a certain percentage of which are emitted in the direction of the gaging system detector and penetrate both the material to be gaged and the walls of the container holding the material, and reach the detector.

In penetrating the container walls and the material to be gaged, the gamma rays are attenuated according to the general relationship

$$I/_{Io} = e^{\mu d}$$

where $I/_{Io}$ is the fraction of the radiation flux photons remaining after passage through a thickness of material, d, with an attenuation coefficient, $\mu$. The attenuation coefficient, $\mu$, is a function of the energy of incident gamma ray photons and of the atomic number of the material being measured. For a given radioactive isotope, the energy of the gamma ray photons is constant; in the case of Krypton-85, (which was used in the Apollo CSM water tank gage), the gamma energy is 514 kev.

The equation above is the expression applicable for narrow beams of radiation and geometries in which an approximate point source of radiation is used in conjunction with a collimated detector. It results in an exponential curve when detected gamma ray photons (counts per unit time) are plotted versus material quantity; (in this case, the liquid contained in the water tank). If the source is distributed and no detector collimation is employed, then not only the broad-beam direct photons, but also photons scattered by the tank and liquid contained within the tank, are counted when they are scattered toward the uncollimated detector. In the Apollo CSM water tank, a distributed source and an uncollimated detector were used to maximize the detection of both the broad-beam direct and the scattered photons. When the source is properly distributed, the exponential plot of the equation can be changed into an approximately linear relationship of counts per unit time versus liquid quantity. The distribution of the source and the location of the detector on the tank to accomplish the linearization of gage output with liquid quantity is called mapping.

Mapping is primarily an empirical process. An attempt is made not only to provide a linear gage output with liquid quantity, but also to provide the same output irrespective of the location of the liquid in the tank. This includes tank orientation in a gravity field, where the liquid will respond to the gravity vector, as well as in a zero-gravity situation where the liquid location within the tank would be determined by smaller forces such as surface tension, etc.

In certain applications, it may be unnecessary to provide a linear output as long as the gage output remains constant for a given liquid quantity over the various tank attitudes and the random or zero-gravity situation. In these applications, the gage output can be compared to a calibration curve and the quantity information extracted from the curve. This can be accomplished manually, by curve fitting electronics that can be made part of the gaging system, or by simple computer "table look-up" data processing.

The output function for the Apollo CSM water tank is of the latter type, i.e. nonlinear; however, the output is linear over a large portion of the curve.

The gaging system used to gage the quantity of water contained in the Apollo CSM water tank comprised three major component assemblies: radioactive sources, radiation detectors, and a processing electronic unit. Since the primary objective of the program was to establish the feasibility of nucleonic gaging for this application, the program emphasis was placed upon mapping of the radioactive sources and collecting experimental data. As a result, existing detector assemblies and standard instrumentation electronics were used in the gaging system.

The detector assembly used was a nucleonic oil quantity indicating system (NOQIS) Geiger-Muller tube. Instrumentation electronics consisted of a NOQIS master indicator packaged into a test box to permit access to various test points, and a standard scaler/timer to measure the counts from the radiation detector. Aluminum tubes filled with radioactive Krypton-85 gas at a pressure of approximately 0.5 atm provided the radiation source.

In the Apollo CSM water tank, the water distribution within the tank is constrained by the pressurized bladder inside the tank. This is the predominant force acting on the water in the zero-g condition, and as a result, the location of the water for any given fill level is fairly constant. Under the influence of gravity the water location within the tank is a function of both the magnitude and direction of the gravity field and of the force exerted by the bladder.

Test Program. --The tank was mounted on a tumbling fixture, which permitted the tank to be oriented in any position with respect to the earth's gravity. Six positions were utilized for each of the tank fill levels. The tank was filled using city water pressure, and the bladder was pressurized with a constant 273.7 kPa (25 psig) air supply.

The test was conducted by applying a 1-g force in six different directions. Data were taken in each of the positions and then compared. Excellent results were obtained, ranging from -1.0- to +0.8-percent error with a full tank, to -0.5- to 0.8-percent error with an empty tank.

Although it is not a true source of error in the gaging system, the system sensitivity or resolution does impose restrictions on the ability of the gaging system to measure the quantity of water in the tank. The system sensitivity is a function of the water quantity and of the tank mapping.

In the single-detector system, the system has excellent sensitivity from full 26.1 kg (57.5 lb) to 9.1 kg (20 lb) remaining; fair sensitivity from 9.1 kg to 4.5 kg (20 to 10 lb) remaining; and poor sensitivity from 4.5 kg (10 lb) remaining to empty. In the double-detector system, the sensitivity is fair from full to 18.1 kg (40 lb) remaining and excellent from 18.1 kg (40 lb) remaining to empty. The steeper the slope of the sensitivity curve, the better the system sensitivity. The double-detector system provided much better sensitivity than the single-detector system.

After some initial measurements to determine the approximate location of the water in the tank at various fill levels and in various attitudes, a trial source and detector location (mapping) was determined in order to gage the tank.

The gaging system uses a single detector and a single Z-shaped source with the two ends bent to conform to the tank. The source was mapped in this manner, since it was discovered that, as the water quantity reached approximately half, the water remaining in the tank was forced near the ends of the tank, leaving the middle section with little or no water.

In order to improve the gage sensitivity from 11.34 kg (25 lb) to empty, a second mapping using a single detector was configured. Six small mapping sources were used instead of the continuous source used in the first mapping. Each of the mapping sources had a source strength of 50 millicuries (mci), so the total strength used in the second mapping was 300 mci. This is slightly less source strength than was used in the first mapping (364 mci). The mapping sources were used to simplify the mapping procedure; once a source map was completed, a single (or in certain cases, a double) source was designed from a continuous tube that approximated the location of the multiple mapping sources. Where source was not required in the continuous tube, the tube was flattened in that area to reduce the gas volume and thereby the source in that area.

The slope near empty was greatly improved over the original mapping; however, slope (sensitivity) at the full end was lost to improve the sensitivity at the empty end, as predicted. The curve for the second mapping could be improved somewhat by "fine tuning" the source locations, particularly to reduce the position errors in a gravity field; however, the sensitivity was nearly the best that could be expected using a single-detector configuration.

The reduction in total counts (area under the curves) from the first mapping to the second was due primarily to the reduction in source strength from 364 to 300 mci in the second map. By increasing the source strength in the mapping sources so that the total would equal the 364 mci, the total counts would be restored to approximately the previous value.

The next attempt at mapping the tank involved the use of two detectors instead of the single detector used in the previous maps. In the two-detector configuration, the detectors were mapped on the tank with their outputs feeding a single set of electronics. The detector outputs were fed in parallel to the same rate integrator within the electronics, and used a common high-voltage power supply. Six different double-detector maps were tried, with only minor differences detected.

In reviewing the data from earlier mappings, it was discovered that the F-106 detector with a 15.2-cm (6-in.) active length provided better gaging resolution near full tank than did the shorter 7.6-cm (3-in.) active length A-7D detector. As a result, the F-106 detector was used for the next four maps in an attempt to improve this full-end resolution. The data showed an improvement in resolution at the full end and an even more dramatic improvement at the empty end. The countrates were much higher than in the previous maps. The increased countrate in this mapping resulted from the use of twice as much detector area as was used in the previous two detector mappings, which employed the shorter detectors. Source strength also was reduced from Mapping No. 4 (300 mci) to Mapping No. 8 (240 mci). This source strength should be halved to approximately 120 mci for best test results, however, no sources with this source strength were available. The advantage of using a lower system source strength was twofold; it reduced the system dead time, which can be as much as 10 percent at 1000 cps, and drops to approximately 1 percent at 100 cps. This dead time resulted from the duration of a detected gamma ray output pulse from the detector (approximately 100 μsec in duration). During this time, the detector does not respond to additional gamma rays and is therefore "dead" to them. The more pulses experienced, the longer the integrated "dead" time. The overall effect on the gaging system is to introduce an increasing loss in system resolution as the countrate increases (near the empty end). Part of the decrease in the countrate near empty is the result of the increasing dead time at these countrates. If the source strength were halved, the countrate also would be approximately halved, and the dead time reduced to less than 5 percent.

The second advantage in reducing source strength was to reduce the radiation exposure to personnel working near the gage. There is very little radiation exposure from this gage even at the 300-mci level; however, the source strength should be reduced as much as possible without sacrificing system performance.

Test Result. --It was concluded that Mapping No. 8 is adequate for the intended gaging requirement. Resolution near the full end was not excellent, but it had an almost linear response from empty to 15.9 kg (35 lb), and the sensitivity was excellent from empty to 15.9 kg (35 lb) and adequate from 15.9 kg (35 lb) to full tank.

The gaging system error profile for representative points (using data from Mapping No. 8 and adding worst-case system errors) was:

| Fill Level, percent | Gaging Accuracy, percent |
|---|---|
| 100 | 1.2 |
| 73 | 1.9 |
| 45 | 3.7 |
| 18 | 3.0 |
| 0 | 0.9 |

These accuracy numbers represent the worst-case zero-g errors as determined by the six positions in an earth-gravity field; they should be considerably reduced in the zero-gravity field. Neither do the errors include the effect in the loss of system sensitivity. If the statistical error changes at the fill levels and realistic zero-g errors ($\pm 1$ percent) indicated are used to determine the effect on system sensitivity, the error profile would be as follows:

| Fill Level, percent | Gaging Accuracy, percent |
|---|---|
| 100 | 5 |
| 73 | 1.6 |
| 45 | 1.3 |
| 18 | 1.3 |
| 0 | 1.3 |

The error envelope seems to be adequate for the gaging requirement under investigation. The error experienced near full may be somewhat excessive and could be improved with additional refinement in the mapping; however, the additional effort involved to refine the mapping did not seem warranted for this program.

A complete, detailed report on the design and test program undertaken by General Nucleonics is presented in Appendix G.

Conclusions

The design, development, and test program demonstrated:

(a) The nucleonics device provided for the program by General Nucleonics interfaced successfully with an existing CSM tank.

(b) The nucleonics gaging device provides the most efficient, reliable, and safe performance available from known quantity-measuring devices.

(c) It was unnecessary to modify the water tank to accept the gaging system, i.e. the gaging system is completely external to the water tank assembly.

(d) Good accuracy can be achieved where needed. For example, the initial mapping shown in Figure 5-2 produced good accuracy and sensitivity when the water quantity measured over half full, whereas the eighth mapping, shown in Figure 5-3, produced good accuracy and sensitivity when the water quantity measured less than half full. By combining the techniques used in the first and eighth mappings, a location of the radioactive source tube and detector can be found to produce good accuracy and sensitivity between empty and full. The main area of development was concerned with the monitoring of water quantity at near full and near empty because of the unique shape of the water as confined by the internal bladder. The configuration of the water at these extremes is fully described earlier in this section in the introduction to the Development Program.

(e) The safety aspects of using a nucleonics gaging system of this type have been proven on the F-104 aircraft. The Air Force has determined by actual measurement that maintenance personnel do not need to wear film badges while servicing the nucleonics gaging system. Proof of this is contained in the Air Force letter dated 16 January 1968, attached to Appendix F.

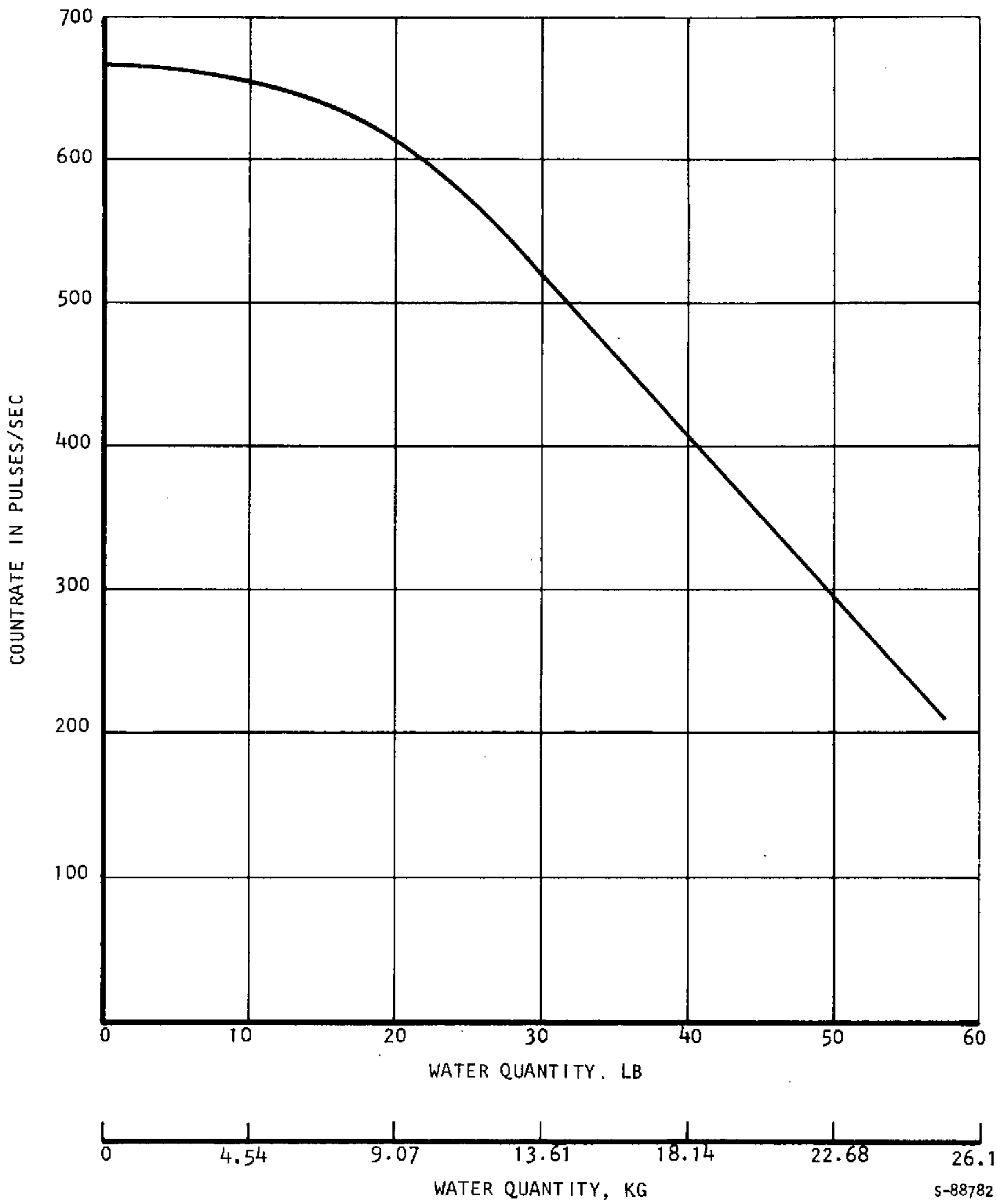



Figure 5-2. Apollo CSM Water Tank Nucleonic Gaging System Output vs Quantity (Initial Mapping)

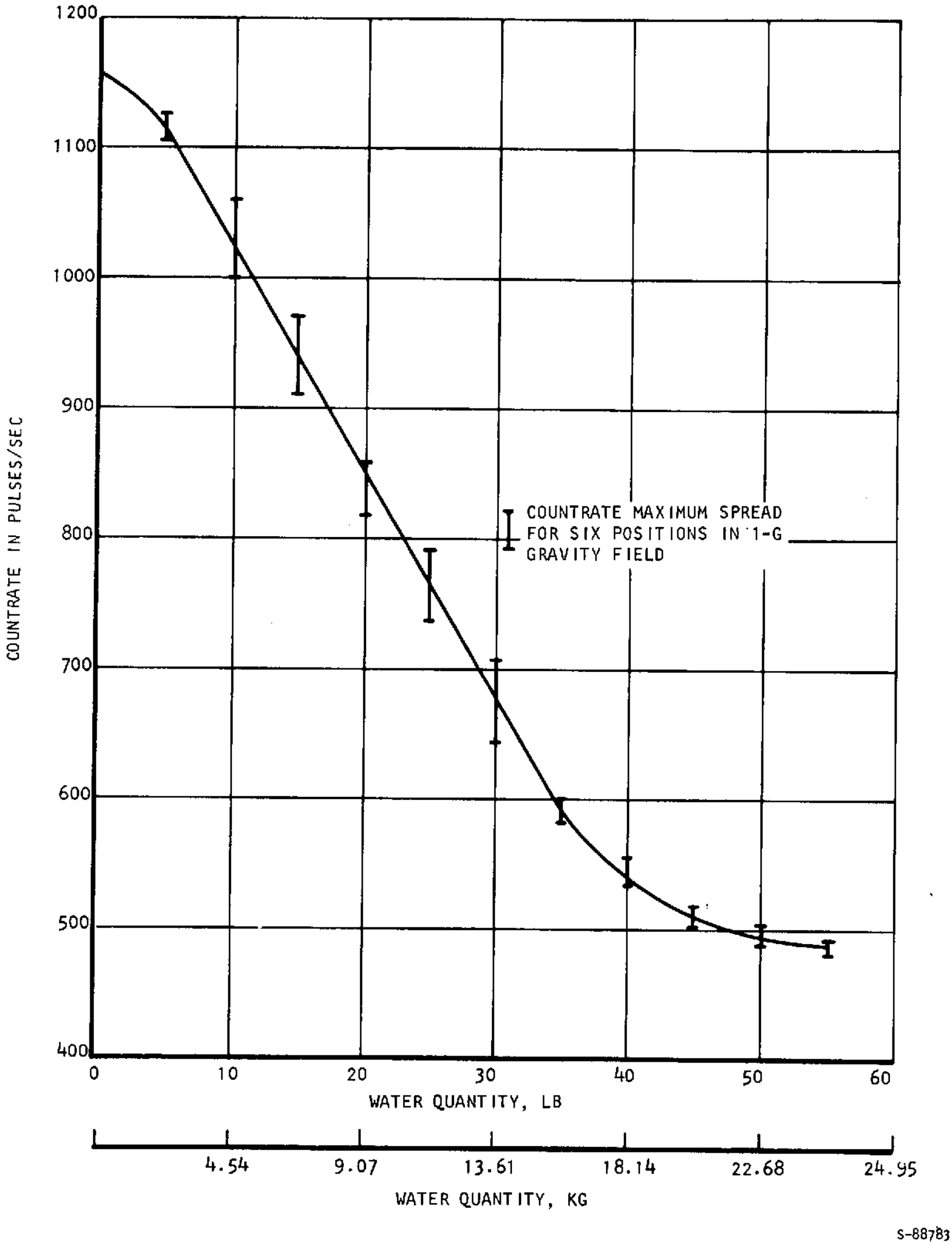



Figure 5-3. Apollo CSM Water Tank Gage Quantity vs Countrate (Eighth Mapping)

# APPENDIXES

# APPENDIX A

## STATHAM INSTRUMENTS, INC. TEST REPORT AND AIRESEARCH STATEMENT OF WORK TO STATHAM

# STATEMENT OF WORK

# STRAIN GAGE PRESSURE SENSORS

## 1. PURPOSE

The purpose of this SOW is to describe the development test work required to demonstrate drift versus time of strain gage pressure transducers.

### 1.1 OBJECTIVE

The objective of this development work is to define highly reliable, low cost, lightweight pressure sensors for the Shuttle ECS that are easy to check out and may be replaced without the need for recalibration of the common power supply and signal conditioner.

### 1.2 END PRODUCT

The end product of this effort will be informal monthly progress reports and an informal final report consisting of test data, conclusions, photographs and a summary of the overall test program.

### 1.3 BACKGROUND

The effort described in this SOW is in support of an environmental control system (ECS) transducer development study for NASA JSC under Contract No. NAS 9-13446.

Tradeoff studies made on the Shuttle ECS instrumentation indicate a savings in weight and electrical power are realized in the configuration of separate sensors with a common power supply and signal conditioner unit. It is desirable to be able to replace pressure sensors without having to recalibrate the common P/S and S/C; therefore, it is of interest to conduct stability testing on several pressure sensors to provide:

a. An indication that the pressure sensors are compatible with the 100 mission/10 year life requirement of Shuttle.

b. Information on the performance shift that is experienced from sensor to sensor when new.

c. The degradation in performance as a result of cyclic testing and age.

## 2. SCOPE

### 2.1 GENERAL

The subcontractor will provide the necessary resources and test articles to perform the required tests and analyses per the technical requirements of this SOW. The test articles shall be subjected to periodic record-type tests and the test results shall be compared to the original ATP test data taken at the time the sensors were manufactured.

## 2.2 PROGRAM SCHEDULE

The subcontractor will comply with the schedule presented in Figure 1.

# 3. TECHNICAL REQUIREMENTS

## 3.1 CONFIGURATION

The subcontractor shall fabricate four (4) strain gage pressure sensors for this development program. ATP type data shall be taken at the time of manufacture and retained so that subsequent test data can be related to the original data to determine the repeatability (stability) of the sensors as a function of time.

The test articles shall generally conform to the following specifications:

Full scale range: 2 each at 0 - 50 psia and 2 each at 0 - 150 psia

Proof pressure: 1.5 times full scale

Burst pressure: 2.5 times full scale

Case material: 17-4 PH SST

Pressure port: Per MS 33656-4

Input voltage: 10 ±0.1% vdc

Output voltage: 20 to 50 mv at full scale

Input power: 350 mwatts max

Nonlinearity and hysteresis: ±0.3% full scale

Long-term stability: < ±0.5% of full scale after 1000 hrs operation

Compensated temperature range: -65°F to +250°F

Thermal zero shift: within 0.005% of full scale per °F

Thermal span shift: within 0.005% of full scale per °F

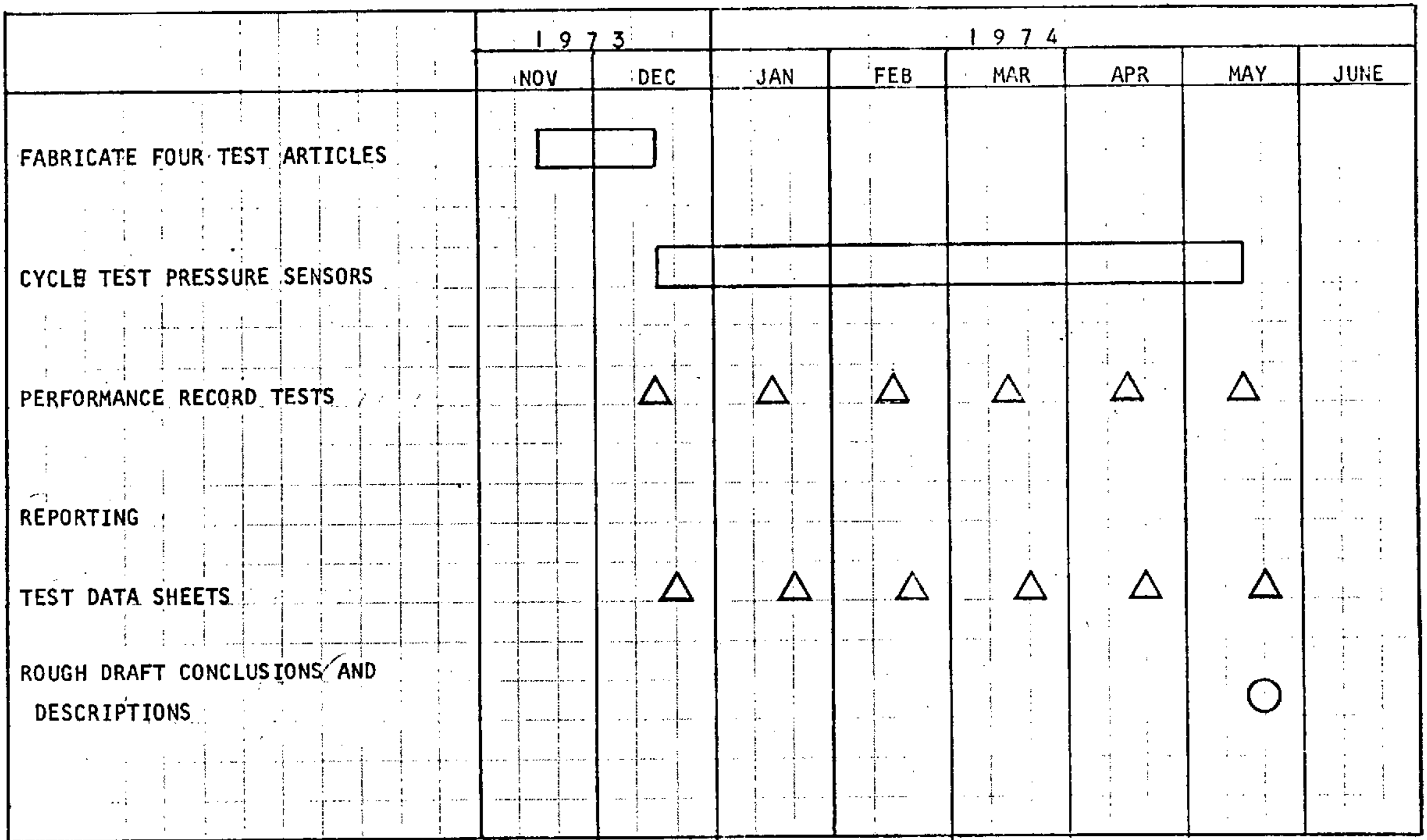
Operable temperature range: *-320°F to +350°F

Environmental: per AiResearch Document No. SC633502

Electrical connector: Bendix PT1H-10-6P, or equivalent

* Materials are compatible with a temperature range of -320°F to +350°F. Units are available at a compensated temperature range of -320°F to +400°F.

FIGURE 1. PROGRAM SCHEDULE






FORM 3148

PAGES A-4 thru A-23 ARE MISSING FROM THE ORIGINAL DOCUMENT.

**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 02-04-74
MODEL: PA822-50
S/N: 15159
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : B4JB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 200,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | -0.028 | -0.036 | -0.255 | -0.052 |
| 10 | 5.873 | 5.863 | 5.638 | 5.860 |
| 20 | 11.785 | 11.773 | 11.544 | 11.770 |
| 30 | 17.700 | 17.690 | 17.450 | 17.695 |
| 40 | 23.625 | 23.613 | 23.357 | 23.620 |
| 50 | 29.545 | 29.530 | 29.253 | 29.540 |
| 40 | 23.630 | 23.617 | 23.352 | 23.625 |
| 30 | 17.702 | 17.695 | 17.438 | 17.692 |
| 20 | 11.787 | 11.780 | 11.535 | 11.775 |
| 10 | 5.883 | 5.875 | 5.642 | 5.865 |
| 0 | -0.028 | -0.038 | -0.255 | -0.050 |
| FULL SCALE | 29.573 mV | 29.566 mV | 29.508 mV | 29.592 mV |
| NONLINEARITY & HYSTERESIS | 0.055 %FS | 0.059 %FS | 0.045 %FS | 0.050 %FS |
| THERMAL ZERO SHIFT | | 0.0002 %FS/°F | 0.0044 %FS/°F | 0.081 %FS |
| THERMAL SPAN SHIFT | | 0.0002 %FS/°F | 0.0013 %FS/°F | 0.064 %FS |

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STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
Oxnard, California 93030

**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 03-04-74
MODEL: PA822-50
S/N: 15159
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB:3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 300,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | -0.048 | -0.090 | -0.257 | -0.077 |
| 10 | 5.863 | 5.820 | 5.640 | 5.833 |
| 20 | 11.775 | 11.728 | 11.548 | 11.742 |
| 30 | 17.695 | 17.648 | 17.455 | 17.662 |
| 40 | 23.615 | 23.570 | 23.368 | 23.583 |
| 50 | 29.530 | 29.482 | 29.270 | 29.496 |
| 40 | 23.617 | 23.570 | 23.365 | 23.585 |
| 30 | 17.690 | 17.645 | 17.450 | 17.662 |
| 20 | 11.775 | 11.731 | 11.542 | 11.744 |
| 10 | 5.865 | 5.826 | 5.642 | 5.842 |
| 0 | -0.053 | -0.090 | -0.257 | -0.077 |
| FULL SCALE | 29.578 mV | 29.572 mV | 29.527 mV | 29.573 mV |
| NONLINEARITY & HYSTERESIS | 0.030 %FS | 0.037 %FS | 0.040 %FS | 0.034 %FS |
| THERMAL ZERO SHIFT | | 0.0010 %FS/°F | 0.0040 %FS/°F | 0.098 %FS |
| THERMAL SPAN SHIFT | | 0.0001 %FS/°F | 0.0010 %FS/°F | 0.017 %FS |

ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 04-01-74
MODEL: PA822-50
S/N: 15159
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : EAJB: 3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 400,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | -0.030 | -0.095 | -0.242 | -0.088 |
| 10 | 5.857 | 5.787 | 5.642 | 5.805 |
| 20 | 11.775 | 11.698 | 11.546 | 11.716 |
| 30 | 17.698 | 17.618 | 17.450 | 17.640 |
| 40 | 23.622 | 23.542 | 23.351 | 23.565 |
| 50 | 29.517 | 29.460 | 29.240 | 29.482 |
| 40 | 23.603 | 23.552 | 23.337 | 23.572 |
| 30 | 17.675 | 17.623 | 17.427 | 17.638 |
| 20 | 11.755 | 11.710 | 11.523 | 11.722 |
| 10 | 5.846 | 5.800 | 5.625 | 5.812 |
| 0 | -0.037 | -0.095 | -0.264 | -0.085 |
| FULL SCALE | 29.547 mV | 29.555 mV | 29.482 mV | 29.570 mV |
| NONLINEARITY & HYSTERESIS | 0.114 %FS | 0.098 %FS | 0.100 %FS | 0.081 %FS |
| THERMAL ZERO SHIFT | | 0.0016 %FS/°F | 0.0041 %FS/°F | 0.196 %FS |
| THERMAL SPAN SHIFT | | 0.0002 %FS/°F | 0.0013 %FS/°F | 0.078 %FS |

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**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 05-06-74
MODEL: PA822-50
S/N: 15159
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : B4JB:3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 500,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | -0.047 | -0.062 | -0.290 | -0.075 |
| 10 | 5.852 | 5.780 | 5.598 | 5.824 |
| 20 | 11.755 | 11.675 | 11.494 | 11.733 |
| 30 | 17.667 | 17.583 | 17.398 | 17.646 |
| 40 | 23.585 | 23.497 | 23.303 | 23.567 |
| 50 | 29.497 | 29.393 | 29.193 | 29.476 |
| 40 | 23.592 | 23.502 | 23.298 | 23.565 |
| 30 | 17.645 | 17.586 | 17.388 | 17.643 |
| 20 | 11.745 | 11.684 | 11.491 | 11.731 |
| 10 | 5.845 | 5.794 | 5.603 | 5.830 |
| 0 | -0.044 | -0.090 | -0.289 | -0.078 |
| FULL SCALE | 29.544 mV | 29.455 mV | 29.483 mV | 29.551 mV |
| NONLINEARITY & HYSTERESIS | 0.116 %FS | 0.166 %FS | 0.041 %FS | 0.049 %FS |
| THERMAL ZERO SHIFT | | 0.0004 %FS/°F | 0.0047 %FS/°F | 0.095 %FS |
| THERMAL SPAN SHIFT | | 0.0022 %FS/°F | 0.0012 %FS/°F | 0.024 %FS |

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ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 12-12-73
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 0

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.398 | 0.500 | 0.390 | 0.406 |
| 10 | 7.049 | 7.145 | 7.024 | 7.061 |
| 20 | 13.687 | 13.779 | 13.653 | 13.685 |
| 30 | 20.333 | 20.420 | 20.286 | 20.344 |
| 40 | 26.981 | 27.060 | 26.925 | 26.996 |
| 50 | 33.612 | 33.680 | 33.546 | 33.626 |
| 40 | 26.962 | 27.040 | 26.903 | 26.980 |
| 30 | 20.318 | 20.402 | 20.267 | 20.333 |
| 20 | 13.684 | 13.780 | 13.640 | 13.695 |
| 10 | 7.049 | 7.149 | 7.026 | 7.063 |
| 0 | 0.400 | 0.501 | 0.394 | 0.411 |
| FULL SCALE | 33.214 mV | 33.180 mV | 33.156 mV | 33.220 mV |
| NONLINEARITY & HYSTERESIS | 0.058 %FS | 0.060 %FS | 0.066 %FS | 0.048 %FS |
| THERMAL ZERO SHIFT | | 0.0022 %FS/°F | 0.0001 %FS/°F | 0.024 %FS |
| THERMAL SPAN SHIFT | | 0.0007 %FS/°F | 0.0010 %FS/°F | -0.018 %FS |

**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 01-14-74
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : EAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 100,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.355 | 0.522 | 0.408 | 0.305 |
| 10 | 6.978 | 7.145 | 7.077 | 6.930 |
| 20 | 13.617 | 13.777 | 13.740 | 13.567 |
| 30 | 20.260 | 20.412 | 20.405 | 20.210 |
| 40 | 26.900 | 27.052 | 27.070 | 26.845 |
| 50 | 33.535 | 33.685 | 33.730 | 33.480 |
| 40 | 26.895 | 27.055 | 27.064 | 26.840 |
| 30 | 20.250 | 20.412 | 20.386 | 20.198 |
| 20 | 13.620 | 13.780 | 13.723 | 13.567 |
| 10 | 6.990 | 7.160 | 7.072 | 6.935 |
| 0 | 0.355 | 0.523 | 0.382 | 0.308 |
| FULL SCALE | 33.180 mV | 33.163 mV | 33.322 mV | 33.175 mV |
| NONLINEARITY & HYSTERESIS | 0.039 %FS | 0.045 %FS | 0.078 %FS | 0.036 %FS |
| THERMAL ZERO SHIFT | | 0.0036 %FS/°F | 0.0009 %FS/°F | 0.151 %FS |
| THERMAL SPAN SHIFT | | 0.0004 %FS/°F | 0.0024 %FS/°F | 0.015 %FS |

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ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 02-04-74
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 200,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.391 | 0.547 | 0.466 | 0.348 |
| 10 | 7.013 | 7.162 | 7.122 | 6.971 |
| 20 | 13.645 | 13.795 | 13.785 | 13.608 |
| 30 | 20.285 | 20.430 | 20.455 | 20.250 |
| 40 | 26.920 | 27.067 | 27.120 | 26.888 |
| 50 | 33.555 | 33.687 | 33.780 | 33.520 |
| 40 | 26.915 | 27.063 | 27.118 | 26.880 |
| 30 | 20.275 | 20.425 | 20.445 | 20.250 |
| 20 | 13.642 | 13.800 | 13.785 | 13.608 |
| 10 | 7.020 | 7.175 | 7.128 | 6.980 |
| 0 | 0.391 | 0.548 | 0.463 | 0.348 |
| FULL SCALE | 33.164 mV | 33.140 mV | 33.314 mV | 33.172 mV |
| NONLINEARITY & HYSTERESIS | 0.044 %FS | 0.039 %FS | 0.030 %FS | 0.034 %FS |
| THERMAL ZERO SHIFT | | 0.0034 %FS/°F | 0.0013 %FS/°F | 0.130 %FS |
| THERMAL SPAN SHIFT | | 0.0005 %FS/°F | 0.0026 %FS/°F | 0.024 %FS |

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ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 03-04-74
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : B4JB:3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 300,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.382 | 0.537 | 0.412 | 0.311 |
| 10 | 7.018 | 7.170 | 7.082 | 6.948 |
| 20 | 13.657 | 13.802 | 13.750 | 13.588 |
| 30 | 20.300 | 20.438 | 20.415 | 20.230 |
| 40 | 26.938 | 27.075 | 27.085 | 26.868 |
| 50 | 33.575 | 33.695 | 33.745 | 33.508 |
| 40 | 26.938 | 27.075 | 27.085 | 26.868 |
| 30 | 20.293 | 20.429 | 20.407 | 20.225 |
| 20 | 13.655 | 13.798 | 13.741 | 13.592 |
| 10 | 7.022 | 7.180 | 7.087 | 6.958 |
| 0 | 0.381 | 0.535 | 0.412 | 0.313 |
| FULL SCALE | 33.193 mV | 33.158 mV | 33.333 mV | 33.197 mV |
| NONLINEARITY & HYSTERESIS | 0.021 %FS | 0.035 %FS | 0.027 %FS | 0.030 %FS |
| THERMAL ZERO SHIFT | | 0.0033 %FS/°F | 0.0005 %FS/°F | 0.214 %FS |
| THERMAL SPAN SHIFT | | 0.0008 %FS/°F | 0.0024 %FS/°F | 0.012 %FS |

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**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 04-01-74
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 400,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75°F | -65°F | +250°F | +75°F |
|---|---|---|---|---|
| 0 | 0.378 | 0.467 | 0.352 | 0.290 |
| 10 | 6.978 | 7.069 | 6.998 | 6.903 |
| 20 | 13.673 | 13.705 | 13.671 | 13.545 |
| 30 | 20.268 | 20.353 | 20.342 | 20.180 |
| 40 | 26.895 | 26.985 | 27.003 | 26.815 |
| 50 | 33.525 | 33.630 | 33.670 | 33.453 |
| 40 | 26.880 | 26.988 | 27.003 | 26.815 |
| 30 | 20.255 | 20.353 | 20.330 | 20.172 |
| 20 | 13.616 | 13.708 | 13.667 | 13.548 |
| 10 | 6.980 | 7.076 | 7.002 | 6.907 |
| 0 | 0.378 | 0.470 | 0.352 | 0.290 |
| FULL SCALE | 33.147 mV | 33.163 mV | 33.318 mV | 33.163 mV |
| NONLINEARITY & HYSTERESIS | 0.172 %FS | 0.092 %FS | 0.053 %FS | 0.059 %FS |
| THERMAL ZERO SHIFT | | 0.0019 %FS/°F | 0.0004 %FS/°F | 0.265 %FS |
| THERMAL SPAN SHIFT | | 0.0003 %FS/°F | 0.0030 %FS/°F | 0.048 %FS |

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

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**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 05-06-74
MODEL: PA822-50
S/N: 15160
PRESSURE RANGE: 0-50 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : E4JB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 500,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.390 | 0.619 | 0.473 | 0.351 |
| 10 | 6.998 | 7.233 | 7.130 | 6.974 |
| 20 | 13.633 | 13.864 | 13.798 | 13.608 |
| 30 | 20.262 | 20.500 | 20.455 | 20.250 |
| 40 | 26.892 | 27.142 | 27.125 | 26.888 |
| 50 | 33.522 | 33.765 | 33.780 | 33.515 |
| 40 | 26.853 | 27.141 | 27.115 | 26.886 |
| 30 | 20.200 | 20.500 | 20.440 | 20.245 |
| 20 | 13.600 | 13.871 | 13.781 | 13.613 |
| 10 | 6.995 | 7.250 | 7.129 | 6.986 |
| 0 | 0.388 | 0.620 | 0.460 | 0.355 |
| FULL SCALE | 33.132 mV | 33.146 mV | 33.307 mV | 33.164 mV |
| NONLINEARITY & HYSTERESIS | 0.209 %FS | 0.051 %FS | 0.052 %FS | 0.036 %FS |
| THERMAL ZERO SHIFT | | 0.0049 %FS/°F | 0.0014 %FS/°F | 0.118 %FS |
| THERMAL SPAN SHIFT | | 0.0003 %FS/°F | 0.0030 %FS/°F | 0.097 %FS |

**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 12-12-73
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 0

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.020 | -0.155 | -0.015 | 0.008 |
| 30 | 6.815 | 6.646 | 6.764 | 6.802 |
| 60 | 13.605 | 13.440 | 13.532 | 13.594 |
| 90 | 20.405 | 20.246 | 20.306 | 20.395 |
| 120 | 27.214 | 27.064 | 27.099 | 27.209 |
| 150 | 34.053 | 33.908 | 33.925 | 34.047 |
| 120 | 27.233 | 27.086 | 27.118 | 27.225 |
| 90 | 20.432 | 20.280 | 20.331 | 20.418 |
| 60 | 13.633 | 13.475 | 13.547 | 13.624 |
| 30 | 6.843 | 6.679 | 6.775 | 6.832 |
| 0 | 0.023 | -0.157 | -0.021 | 0.008 |
| FULL SCALE | 34.033 mV | 34.068 mV | 33.940 mV | 34.039 mV |
| NONLINEARITY & HYSTERESIS | 0.102 %FS | 0.108 %FS | 0.127 %FS | 0.107 %FS |
| THERMAL ZERO SHIFT | | 0.0037 %FS/°F | 0.0006 %FS/°F | 0.035 %FS |
| THERMAL SPAN SHIFT | | 0.0006 %FS/°F | 0.0016 %FS/°F | 0.018 %FS |

STATHAM INSTRUMENTS, INC.
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ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 01-14-74
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SO# # : DAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 100,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.114 | -0.087 | 0.072 | 0.093 |
| 30 | 6.902 | 6.700 | 6.843 | 6.880 |
| 60 | 13.707 | 13.506 | 13.628 | 13.682 |
| 90 | 20.512 | 20.317 | 20.405 | 20.485 |
| 120 | 27.310 | 27.125 | 27.190 | 27.288 |
| 150 | 34.125 | 33.932 | 33.975 | 34.088 |
| 120 | 27.320 | 27.125 | 27.188 | 27.285 |
| 90 | 20.523 | 20.320 | 20.410 | 20.492 |
| 60 | 13.710 | 13.507 | 13.633 | 13.687 |
| 30 | 6.912 | 6.702 | 6.845 | 6.887 |
| 0 | 0.114 | -0.098 | 0.075 | 0.093 |
| FULL SCALE | 34.011 mV | 34.019 mV | 33.903 mV | 33.995 mV |
| NONLINEARITY & HYSTERESIS | 0.042 %FS | 0.049 %FS | 0.028 %FS | 0.035 %FS |
| THERMAL ZERO SHIFT | | 0.0042 %FS/°F | 0.0007 %FS/°F | 0.062 %FS |
| THERMAL SPAN SHIFT | | 0.0002 %FS/°F | 0.0018 %FS/°F | 0.047 %FS |

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**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 02-04-74
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : EAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 200,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.169 | 0.038 | 0.108 | 0.165 |
| 30 | 6.957 | 6.830 | 6.878 | 6.957 |
| 60 | 13.758 | 13.639 | 13.663 | 13.757 |
| 90 | 20.562 | 20.450 | 20.448 | 20.560 |
| 120 | 27.363 | 27.275 | 27.228 | 27.360 |
| 150 | 34.172 | 34.075 | 34.023 | 34.159 |
| 120 | 27.370 | 27.275 | 27.235 | 27.365 |
| 90 | 20.572 | 20.460 | 20.460 | 20.567 |
| 60 | 13.767 | 13.656 | 13.670 | 13.765 |
| 30 | 6.966 | 6.840 | 6.887 | 6.960 |
| 0 | 0.170 | 0.039 | 0.112 | 0.165 |
| FULL SCALE | 34.003 mV | 34.037 mV | 33.915 mV | 33.994 mV |
| NONLINEARITY & HYSTERESIS | 0.037 %FS | 0.050 %FS | 0.038 %FS | 0.024 %FS |
| THERMAL ZERO SHIFT | | 0.0028 %FS/°F | 0.0010 %FS/°F | 0.012 %FS |
| THERMAL SPAN SHIFT | | 0.0007 %FS/°F | 0.0015 %FS/°F | 0.026 %FS |

ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 03-04-74
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : DAJB:3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 300,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.216 | 0.068 | 0.157 | 0.190 |
| 30 | 7.013 | 6.867 | 6.936 | 6.986 |
| 60 | 13.813 | 13.675 | 13.722 | 13.785 |
| 90 | 20.616 | 20.483 | 20.512 | 20.590 |
| 120 | 27.419 | 27.292 | 27.296 | 27.396 |
| 150 | 34.228 | 34.103 | 34.092 | 34.199 |
| 120 | 27.425 | 27.295 | 27.303 | 27.404 |
| 90 | 20.633 | 20.495 | 20.525 | 20.607 |
| 60 | 13.822 | 13.685 | 13.725 | 13.807 |
| 30 | 7.018 | 6.875 | 6.944 | 6.996 |
| 0 | 0.217 | 0.068 | 0.158 | 0.193 |
| FULL SCALE | 34.012 mV | 34.035 mV | 33.935 mV | 34.009 mV |
| NONLINEARITY & HYSTERESIS | 0.050 %FS | 0.035 %FS | 0.038 %FS | 0.065 %FS |
| THERMAL ZERO SHIFT | | 0.0031 %FS/°F | 0.0010 %FS/°F | 0.076 %FS |
| THERMAL SPAN SHIFT | | 0.0005 %FS/°F | 0.0013 %FS/°F | 0.009 %FS |

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## ENGINEERING TEST
## CALIBRATION DATA SHEET

DATE: 04-01-74
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : EDJB: 3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 400,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75°F | -65°F | +250°F | +75°F |
|---|---|---|---|---|
| 0 | 0.232 | 0.105 | 0.180 | 0.205 |
| 30 | 7.010 | 6.872 | 6.944 | 6.990 |
| 60 | 13.815 | 13.677 | 13.727 | 13.790 |
| 90 | 20.613 | 20.495 | 20.515 | 20.598 |
| 120 | 27.410 | 27.292 | 27.288 | 27.400 |
| 150 | 34.201 | 34.098 | 34.070 | 34.195 |
| 120 | 27.407 | 27.296 | 27.288 | 27.403 |
| 90 | 20.618 | 20.506 | 20.523 | 20.610 |
| 60 | 13.818 | 13.693 | 13.730 | 13.805 |
| 30 | 7.017 | 6.878 | 6.953 | 6.998 |
| 0 | 0.230 | 0.102 | 0.180 | 0.207 |
| FULL SCALE | 33.969 mV | 33.993 mV | 33.890 mV | 33.990 mV |
| NONLINEARITY & HYSTERESIS | 0.047 %FS | 0.093 %FS | 0.041 %FS | 0.044 %FS |
| THERMAL ZERO SHIFT | | 0.0027 %FS/°F | 0.0009 %FS/°F | 0.079 %FS |
| THERMAL SPAN SHIFT | | 0.0005 %FS/°F | 0.0013 %FS/°F | 0.062 %FS |

STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
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## ENGINEERING TEST
## CALIBRATION DATA SHEET

DATE: 05-06-74
MODEL: PA822-150
S/N: 15163
PRESSURE RANGE: 0-150psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB:3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 500,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.232 | -0.028 | 0.154 | 0.208 |
| 30 | 7.017 | 6.758 | 6.923 | 6.996 |
| 60 | 13.816 | 13.560 | 13.706 | 13.798 |
| 90 | 20.617 | 20.362 | 20.484 | 20.599 |
| 120 | 27.417 | 27.165 | 27.265 | 27.392 |
| 150 | 34.213 | 33.972 | 34.046 | 34.191 |
| 120 | 27.416 | 27.162 | 27.260 | 27.399 |
| 90 | 20.627 | 20.372 | 20.490 | 20.610 |
| 60 | 13.827 | 13.570 | 13.710 | 13.809 |
| 30 | 7.027 | 6.765 | 6.928 | 7.004 |
| 0 | 0.232 | -0.034 | 0.155 | 0.208 |
| FULL SCALE | 33.981 mV | 34.000 mV | 33.892 mV | 33.983 mV |
| NONLINEARITY & HYSTERESIS | 0.033 %FS | 0.041 %FS | 0.028 %FS | 0.036 %FS |
| THERMAL ZERO SHIFT | | 0.0055 %FS/°F | 0.0013 %FS/°F | 0.071 %FS |
| THERMAL SPAN SHIFT | | 0.0004 %FS/°F | 0.0015 %FS/°F | 0.006 %FS |

## ENGINEERING TEST
## CALIBRATION DATA SHEET

DATE: 12-12-73
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 0

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.124 | 0.085 | -0.026 | 0.116 |
| 30 | 7.246 | 7.214 | 7.077 | 7.238 |
| 60 | 14.376 | 14.350 | 14.194 | 14.366 |
| 90 | 21.504 | 21.489 | 21.311 | 21.496 |
| 120 | 28.629 | 28.622 | 28.428 | 28.625 |
| 150 | 35.765 | 35.775 | 35.557 | 35.766 |
| 120 | 28.638 | 28.625 | 28.432 | 28.625 |
| 90 | 21.508 | 21.495 | 21.322 | 21.505 |
| 60 | 14.382 | 14.350 | 14.206 | 14.375 |
| 30 | 7.247 | 7.216 | 7.085 | 7.240 |
| 0 | 0.123 | 0.085 | -0.020 | 0.116 |
| FULL SCALE | 35.641 mV | 35.690 mV | 35.583 mV | 35.650 mV |
| NONLINEARITY & HYSTERESIS | 0.022 %FS | 0.042 %FS | 0.038 %FS | 0.031 %FS |
| THERMAL ZERO SHIFT | | 0.0008 %FS/°F | 0.0024 %FS/°F | 0.022 %FS |
| THERMAL SPAN SHIFT | | 0.0010 %FS/°F | 0.0009 %FS/°F | 0.025 %FS |

STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
Oxnard, California 93030

## ENGINEERING TEST
## CALIBRATION DATA SHEET

DATE: 01-14-74
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : DAJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 100,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.183 | 0.187 | 0.000 | 0.160 |
| 30 | 7.293 | 7.300 | 7.102 | 7.275 |
| 60 | 14.420 | 14.432 | 14.215 | 14.402 |
| 90 | 21.547 | 21.563 | 21.325 | 21.530 |
| 120 | 28.670 | 28.690 | 28.440 | 28.655 |
| 150 | 35.810 | 35.840 | 35.570 | 35.797 |
| 120 | 28.680 | 28.700 | 28.442 | 28.660 |
| 90 | 21.560 | 21.580 | 21.337 | 21.540 |
| 60 | 14.435 | 14.447 | 14.225 | 14.420 |
| 30 | 7.303 | 7.312 | 7.110 | 7.283 |
| 0 | 0.183 | 0.187 | 0.000 | 0.162 |
| FULL SCALE | 35.627 mV | 35.653 mV | 35.570 mV | 35.637 mV |
| NONLINEARITY & HYSTERESIS | 0.043 %FS | 0.054 %FS | 0.048 %FS | 0.051 %FS |
| THERMAL ZERO SHIFT | | 0.0001 %FS/°F | 0.0029 %FS/°F | 0.065 %FS |
| THERMAL SPAN SHIFT | | 0.0005 %FS/°F | 0.0009 %FS/°F | 0.028 %FS |



GARRETT AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

**ENGINEERING TEST**
**CALIBRATION DATA SHEET**

DATE: 02-04-74
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : BAJB: 3011:1106

NUMBER OF PRESSURE CYCLES COMPLETED 200,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.350 | 0.420 | 0.165 | 0.327 |
| 30 | 7.460 | 7.538 | 7.265 | 7.440 |
| 60 | 14.583 | 14.668 | 14.375 | 14.565 |
| 90 | 21.705 | 21.800 | 21.490 | 21.690 |
| 120 | 28.838 | 28.935 | 28.605 | 28.820 |
| 150 | 35.977 | 36.080 | 35.727 | 35.960 |
| 120 | 28.837 | 28.948 | 28.618 | 28.825 |
| 90 | 21.720 | 21.817 | 21.513 | 21.702 |
| 60 | 14.597 | 14.680 | 14.396 | 14.580 |
| 30 | 7.463 | 7.548 | 7.280 | 7.450 |
| 0 | 0.341 | 0.420 | 0.172 | 0.327 |
| FULL SCALE | 35.627 mV | 35.660 mV | 35.562 mV | 35.633 mV |
| NONLINEARITY & HYSTERESIS | 0.060 %FS | 0.048 %FS | 0.059 %FS | 0.043 %FS |
| THERMAL ZERO SHIFT | | 0.0014 %FS/°F | 0.0030 %FS/°F | 0.065 %FS |
| THERMAL SPAN SHIFT | | 0.0007 %FS/°F | 0.0010 %FS/°F | 0.017 %FS |

STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
Oxnard, California 93030

ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 03-04-74
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : EMJB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 300,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.383 | 0.437 | 0.239 | 0.372 |
| 30 | 7.498 | 7.557 | 7.341 | 7.487 |
| 60 | 14.617 | 14.683 | 14.451 | 14.605 |
| 90 | 21.730 | 21.813 | 21.561 | 21.728 |
| 120 | 28.855 | 28.951 | 28.676 | 28.857 |
| 150 | 35.988 | 36.096 | 35.795 | 35.990 |
| 120 | 28.865 | 28.960 | 28.682 | 28.862 |
| 90 | 21.745 | 21.833 | 21.578 | 21.745 |
| 60 | 14.620 | 14.701 | 14.467 | 14.622 |
| 30 | 7.497 | 7.564 | 7.352 | 7.492 |
| 0 | 0.380 | 0.431 | 0.242 | 0.370 |
| FULL SCALE | 35.605 mV | 35.659 mV | 35.556 mV | 35.618 mV |
| NONLINEARITY & HYSTERESIS | 0.045 %FS | 0.056 %FS | 0.048 %FS | 0.048 %FS |
| THERMAL ZERO SHIFT | | 0.0011 %FS/°F | 0.0023 %FS/°F | 0.031 %FS |
| THERMAL SPAN SHIFT | | 0.0011 %FS/°F | 0.0008 %FS/°F | 0.037 %FS |

STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
Oxnard, California 93030

ENGINEERING TEST
CALIBRATION DATA SHEET

DATE: 04-01-74
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150 psia
EXCITATION VOLTAGE: 10 VDC

STATHAM S/O# : 51842
AIRESEARCH SOW # : B4JB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 400,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75°F | -65°F | +250°F | +75°F |
|---|---|---|---|---|
| 0 | 0.343 | 0.053 | 0.228 | 0.319 |
| 30 | 7.458 | 7.152 | 7.320 | 7.430 |
| 60 | 14.580 | 14.267 | 14.432 | 14.545 |
| 90 | 21.686 | 21.398 | 21.545 | 21.662 |
| 120 | 28.810 | 28.540 | 28.647 | 28.775 |
| 150 | 35.935 | 35.678 | 35.757 | 35.920 |
| 120 | 28.808 | 28.550 | 28.647 | 28.785 |
| 90 | 21.688 | 21.417 | 21.548 | 21.670 |
| 60 | 14.560 | 14.278 | 14.440 | 14.552 |
| 30 | 7.437 | 7.150 | 7.326 | 7.430 |
| 0 | 0.343 | 0.052 | 0.232 | 0.315 |
| FULL SCALE | 35.592 mV | 35.625 mV | 35.529 mV | 35.601 mV |
| NONLINEARITY & HYSTERESIS | 0.069 %FS | 0.101 %FS | 0.039 %FS | 0.070 %FS |
| THERMAL ZERO SHIFT | | 0.0058 %FS/°F | 0.0018 %FS/°F | 0.067 %FS |
| THERMAL SPAN SHIFT | | 0.0007 %FS/°F | 0.0010 %FS/°F | 0.025 %FS |

STATHAM INSTRUMENTS, INC.
2230 Statham Boulevard
Oxnard, California 93030

## ENGINEERING TEST
## CALIBRATION DATA SHEET

DATE: 05-06-74
MODEL: PA822-150
S/N: 15164
PRESSURE RANGE: 0-150psia
EXCITATION VOLTAGE: 10 VDC

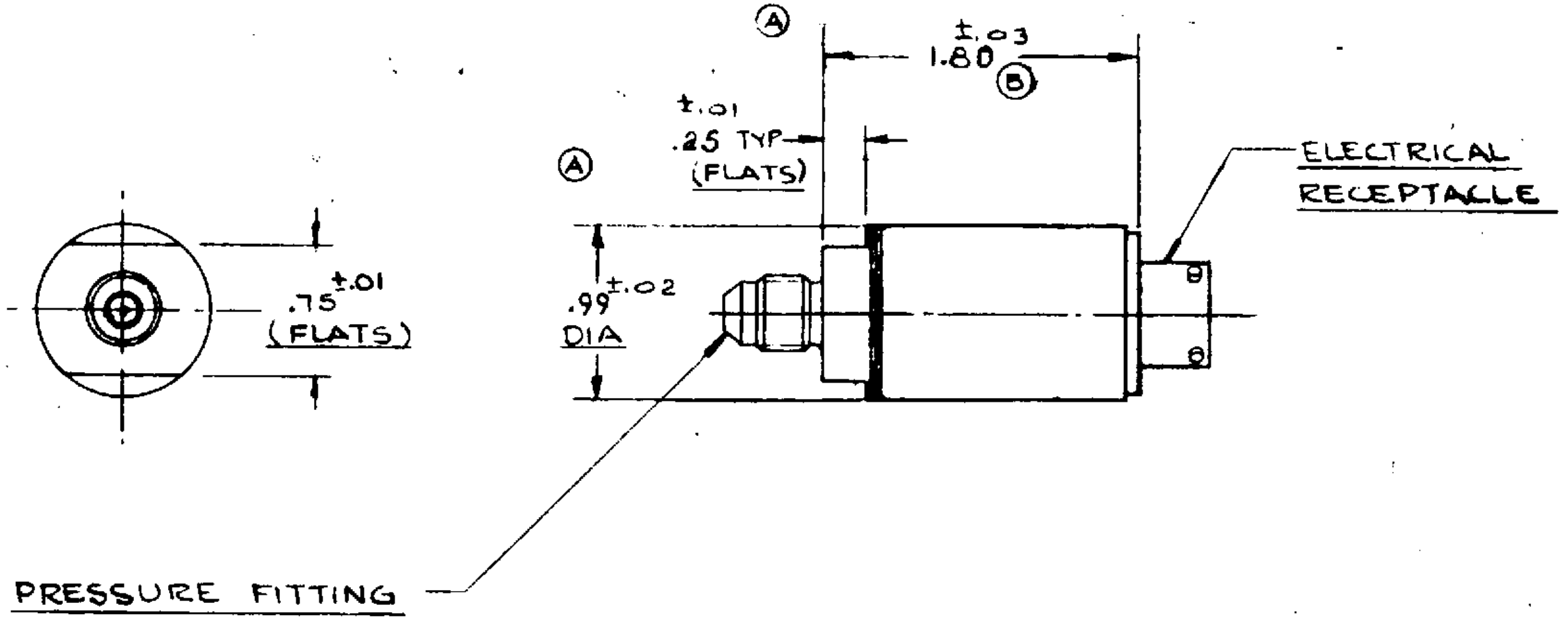
STATHAM S/O# : 51842
AIRESEARCH SOW # : B4JB: 3011: 1106

NUMBER OF PRESSURE CYCLES COMPLETED 500,000

OUTPUT IN MILLIVOLTS (open circuit)

| PRESSURE psia | +75 °F | -65 °F | +250 °F | +75 °F |
|---|---|---|---|---|
| 0 | 0.320 | 0.294 | 0.230 | 0.322 |
| 30 | 7.420 | 7.384 | 7.315 | 7.428 |
| 60 | 14.555 | 14.476 | 14.414 | 14.550 |
| 90 | 21.678 | 21.571 | 21.518 | 21.660 |
| 120 | 28.810 | 28.683 | 28.638 | 28.772 |
| 150 | 35.923 | 35.810 | 35.756 | 35.897 |
| 120 | 28.808 | 28.683 | 28.640 | 28.770 |
| 90 | 21.702 | 21.569 | 21.528 | 21.668 |
| 60 | 14.572 | 14.454 | 14.427 | 14.568 |
| 30 | 7.449 | 7.365 | 7.323 | 7.440 |
| 0 | 0.326 | 0.291 | 0.242 | 0.323 |
| FULL SCALE | 35.603 mV | 35.516 mV | 35.526 mV | 35.575 mV |
| NONLINEARITY & HYSTERESIS | 0.081 %FS | 0.131 %FS | 0.077 %FS | 0.051 %FS |
| THERMAL ZERO SHIFT | | 0.0005 %FS/°F | 0.0014 %FS/°F | 0.006 %FS |
| THERMAL SPAN SHIFT | | 0.0018 %FS/°F | 0.0012 %FS/°F | 0.079 %FS |

27106




| LET. | REVISION | BY | DATE | CHK. | APP. |
|---|---|---|---|---|---|
| B | 1.80 WAS 1.60, ADD 27723 N/A | Ve | 2-23-66 | F.T. | 2-25-66 |
| A | .99±.02 DIA. WAS .99±.01, 1.60±.03 WAS 1.53±.03 FLATS .25±.01 WAS .19±.01 | BC | 1-4-66 | CRA | 1-5-66 |

TOLERANCE UNLESS NOTED:
FILLET MAX. .010
BREAK EDGE .005 - .010
MACH. FINISH RMS

**STATHAM INSTRUMENTS, INC.**
LOS ANGELES 64, CALIFORNIA

| | | |
|---|---|---|
| SCALE | FULL | |
| STOCK | | |
| MATERIAL | | |
| HEAT TREAT | | |
| FINISH | | |
| DRAWN | C. KOOTZ | 8/24/65 |
| CHECKED | D. G. | 8/26/65 |
| PROJECT ENGINEER | R. HELIN | 8/26/65 |
| APPROVED | | 8/26/65 |

| MODEL | NEXT ASSEMBLY |
|---|---|
| P8080 | 27725 |
| P8068 | 27725 |
| P822a | 27723 |

OUTLINE - PRESSURE TRANSDUCER P822
CODE IDENT. NO. 57167
27106

G

K•E ALBANENE® TRACING PAPER

GARRETT
AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

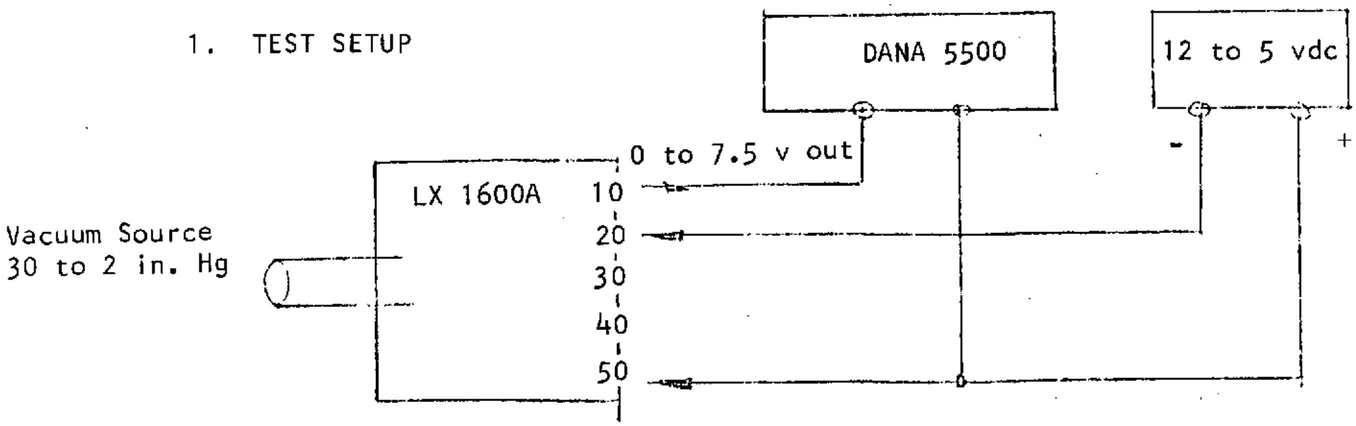
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

# APPENDIX B

# NATIONAL SEMICONDUCTOR CORPORATION TEST PROCEDURE AND TEST DATA

TEST REQUIREMENTS FOR LX 1600A PRESSURE TRANSDUCER

1. TEST SETUP




2. TEST SCHEDULE

2.1 Calibration over temperature

2.2 Temperature Cycle

2.3 Calibration at Lab Ambient

2.4 Pressure Cycle

2.5 Calibration at Lab Ambient

3. TEST EQUIPMENT ACCURACY

Pressure Measurement to within ± .002 in. Hg

Temperature Measurement ± 5°F

Voltage Ratio (Use DANA 5500) ± .004% 10-V Range

4. CALIBRATION OVER TEMPERATURE

4.1 Lab Ambient

Measure output voltage rates at 2 in. Hg intervals between 30 and 2 in. Hg abs.
In order to be able to measure hysteresis, conduct 5 sweeps at this temperature.

4.2 + 180°F - as in 4.1 only one sweep

4.3 + 240°F - as in 4.1 only one sweep

4.4 - 40°F - as in 4.1 only one sweep

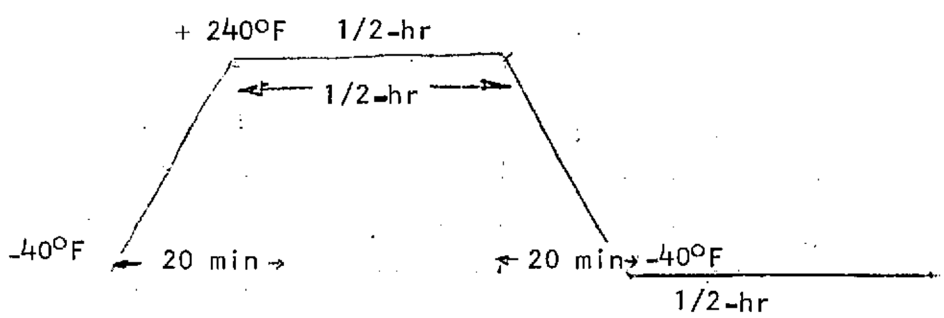
Note: allow 1/2-hour soak at temperature with power off before testing.

5. PRESSURE CYCLE

500 pressure cycles from 30 to 2 in. Hg. Abs. at approximately 2 min per full cycle

Repeat test 4.1 with only one sweep before and after test.

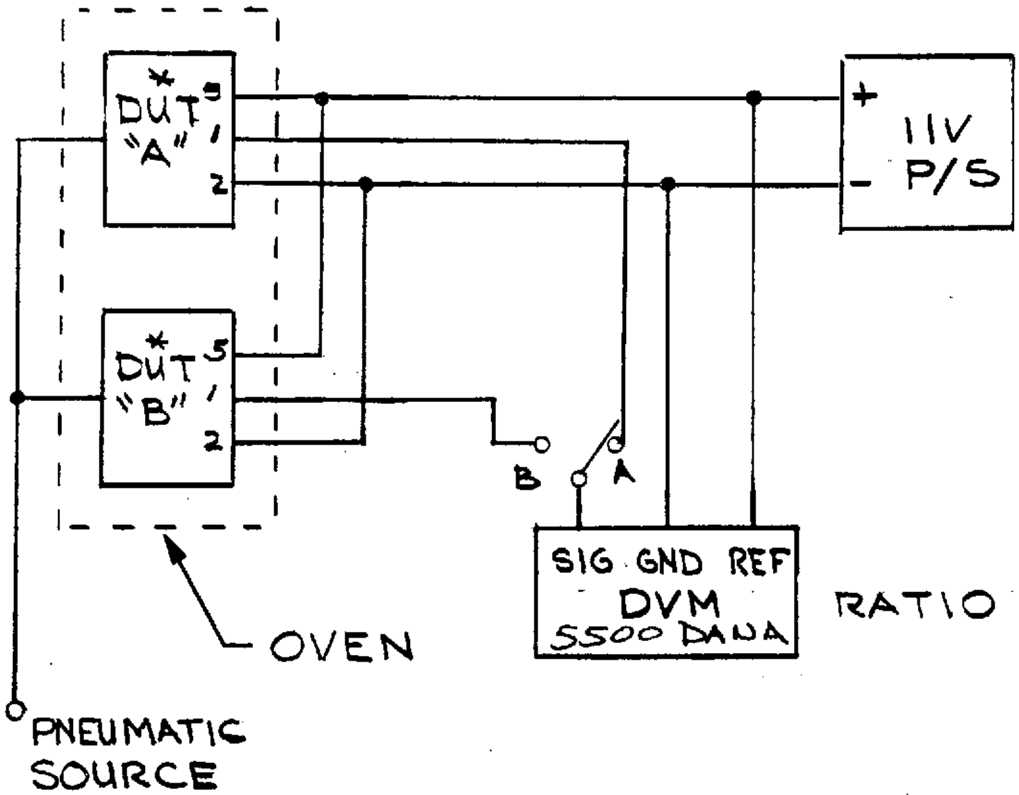
6. TEMPERATURE CYCLE




Perform 20 temperature cycles to above requirement.

Repeat Test 4.1 before and after.

J. Simmons 12/1/72 LX1600 A
Pres. Trans.




TEST SET UP

*DUT - DEVICE UNDER TEST

Development and Design Engineer's Record

SIMMONS 12/12/72 LX 1600 A LEAK TEST

Nº

DATE WANTED

LEAK RATE IN Hg

2.5 THOUSANDS / MIN 1ST MIN

1.0 " " 2ND MIN

1.0 " " 3RD MIN

1.0 " " 4th "

1.0 " " 5th "

TEST STARTED AT 2.0000"

AFTER FIVE MIN PRES WAS

2.0065" HG

SIGNATURE

ROUTING

ACTION

FOR USE BY RECIPIENT ONLY

RET.

SIGN

DATE

J. SIMMONS 1/15/3  LX 1600A
ST. TIME 1010  TA 72 °F  FINISH TIME 1045

| PRESSURE IN. HG | V/R OUT SN 175 ↓ | V/R OUT SN 188 ↓ | V/R OUT SN 175 ↑ | V/R OUT SN 188 ↑ |
|---|---|---|---|---|
| 30 | .6366 | .6278 | .6357 | .6269 |
| 28 | .6092 | .6004 | .6082 | .5995 |
| 26 | .5815 | .5728 | .5805 | 5717 |
| 24 | .5534 | .5447 | .5524 | 5438 |
| 22 | .5250 | .5164 | .5241 | .5155 |
| 20 | .4964 | .4878 | 4955 | 4869 |
| 18 | .4676 | .4591 | .4667 | 4582 |
| 16 | .4386 | .4300 | .4376 | 4292 |
| 14 | .4092 | .4008 | .4085 | 4001 |
| 12 | .3798 | .3714 | .3791 | .3707 |
| 10 | .3502 | .3419 | .3496 | .3413 |
| 8 | .3205 | .3123 | .3200 | .3118 |
| 6 | .2907 | .2826 | .2903 | .2822 |
| 4 | .2610 | .2528 | .2607 | .2526 |
| 2 | .2311 | .2231 | | |

RUN # 1 OF 3 @ TA 72°F

J. SIMMONS 1/15/73 LX 1600A

START TIME 1055 TA 72°F FINISH TIME 1125

| PRESSURE IN HG | V/R OUT #175 ↓ | V/R OUT #188 ↓ | V/R OUT #175 ↑ | V/R OUT 188 ↑ |
|---|---|---|---|---|
| 30 | .6359 | .6270 | .6355 | .6266 |
| 28 | .6086 | .5997 | .6081 | .5992 |
| 26 | .5809 | .5720 | .5804 | .5715 |
| 24 | .5528 | .5441 | .5523 | .5435 |
| 22 | .5244 | .5157 | .5240 | .5152 |
| 20 | .4959 | .4872 | .4954 | .4867 |
| 18 | .4671 | .4584 | .4666 | .4579 |
| 16 | .4381 | .4294 | .4376 | .4289 |
| 14 | .4088 | .4002 | .4083 | .3997 |
| 12 | .3794 | .3709 | .3790 | .3704 |
| 10 | .3499 | .3414 | .3495 | .3410 |
| 8 | .3203 | .3118 | .3200 | .3115 |
| 6 | .2905 | .2822 | .2904 | 2819 |
| 4 | .2607 | .2525 | .2605 | .2523 |
| 2 | .2310 | .2228 | — | — |

RUN #2 OF 3 @ TA 72 °F

J. SIMMONS 1/15/3 LX1600A

START TIME 1130 TA 72°F FINISH TIME 1200

| PRESSURE IN. HG | V/R OUT 175 ↓ | V/R OUT 188 ↓ | V/R OUT 175 ↑ | V/R OUT 188 ↑ |
|---|---|---|---|---|
| 30 | .6357 | .6267 | .6355 | .6264 |
| 28 | .6085 | .5995 | .6081 | .5991 |
| 26 | .5808 | .5719 | .5803 | .5713 |
| 24 | .5528 | .5438 | .5522 | .5434 |
| 22 | .5244 | .5156 | .5239 | .5150 |
| 20 | .4958 | .4870 | .4963 | .4865 |
| 18 | .4670 | .4583 | .4666 | .4577 |
| 16 | .4380 | .4292 | .4375 | .4288 |
| 14 | .4088 | .4000 | .4083 | .3996 |
| 12 | .3793 | .3708 | .3789 | .3703 |
| 10 | .3498 | .3413 | .3494 | .3408 |
| 8 | .3202 | .3118 | .3198 | .3113 |
| 6 | .2904 | .2820 | .2902 | .2818 |
| 4 | .2607 | .2524 | .2605 | .2522 |
| 2 | .2309 | .2228 | — | — |

RUN 3 TA 72°F

J Simmons 1/4/3 LX/600 A
START 1530 TA - 40°F FINISH 1555

| PRESSURE IN. HG | V/R OUT #175 ↓ | V/R OUT #188 ↓ | V/R OUT #175 ↑ | V/R OUT #188 ↑ |
|---|---|---|---|---|
| 30 | .6953 | .6503 | .6932 | .6490 |
| 28 | .6664 | .6228 | .6633 | .6210 |
| 26 | .6360 | .5942 | .6335 | .5924 |
| 24 | .6062 | .5656 | .6030 | .5636 |
| 22 | .5754 | .5364 | .5722 | .5346 |
| 20 | .5446 | .5071 | .5413 | .5050 |
| 18 | .5132 | .4774 | .5101 | .4755 |
| 16 | .4818 | .4476 | .4787 | .4459 |
| 14 | .4500 | .4176 | .4472 | .4158 |
| 12 | .4182 | .3875 | .4153 | .3857 |
| 10 | .3867 | .3570 | .3835 | .3553 |
| 8 | .3535 | .3263 | .3514 | .3248 |
| 6 | .3207 | .2955 | .3192 | .2944 |
| 4 | .2880 | .2646 | .2871 | .2639 |
| 2 | .2551 | .2336 | — | — |

J SIMMONS 1/18/3 LX 1600 A

START TA 140°F FINISH

| PRESSURE IN HG | V/R OUT #175 ↓ | V/R OUT #188 ↓ | V/R OUT #175 ↑ | V/R OUT #188 ↑ |
|---|---|---|---|---|
| | .6083 | | .6067 | .6093 |
| 30 | ~~.6199~~ | .6107 | .5799 | 5823 |
| 28 | .5815 | .5838 | .5528 | 5551 |
| 26 | .5545 | .5566 | .5255 | 5276 |
| 24 | .5271 | .5291 | .4979 | 4999 |
| 22 | .4995 | .5013 | .4701 | 4719 |
| 20 | .4716 | .4732 | .4422 | 4438 |
| 18 | .4436 | .4449 | .4140 | .4154 |
| 16 | .4151 | .4166 | .3856 | .3869 |
| 14 | .3866 | .3878 | .3571 | .3582 |
| 12 | .3580 | .3591 | .3284 | .3294 |
| 10 | .3292 | .3301 | .2997 | .3005 |
| 8 | .3003 | .3012 | .2709 | .2716 |
| 6 | .2714 | .2721 | ~~.2709~~ | ~~.2716~~ |
| 4 | .2425 | .2431 | 2421 | 2427 |
| 2 | .2135 | .2140 | | |

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

SIMMONS 12/12/72 LX 1600A
1100 HRS TA 72°F RUN 1

| PRESSURE IN. Hg | 'A' OUT DECREASING | 'B' OUT DECREASING | 'A' OUT INCREASING | 'B' OUT INCREASING |
|---|---|---|---|---|
| 30 | .6593 | .6448 | .6594 | .6448 |
| 28 | 6318 | 6175 | 6316 | 6172 |
| 26 | 6038 | 5896 | 6036 | 5894 |
| 24 | 5756 | 5615 | 5753 | 5612 |
| 22 | 5470 | 5331 | 5468 | 5328 |
| 20 | 5181 | 5044 | 5178 | 5041 |
| 18 | 4891 | 4755 | 4888 | 4752 |
| 16 | 4599 | 4464 | 4595 | 4461 |
| 14 | 4304 | 4171 | 4300 | 4168 |
| 12 | 4007 | 3876 | 4004 | 3873 |
| 10 | 3709 | 3580 | 3706 | 3577 |
| 8 | 3410 | 3283 | 3407 | 3280 |
| 6 | 3110 | 2985 | 3108 | 2982 |
| 4 | 2810 | 2686 | 2808 | 2685 |
| 2 | 2509 | 2388 | 2509 | 2388 |

OUTPUTS IN VOLTAGE RATIO

SIMMONS 12/12/72 LX1600A

1520 HeTA 72°F RUN 2

| PRESSURE IN. HG | 'A' OUT DECR | 'B' OUT DECR | 'A' OUT INCR | 'B' OUT INCR |
|---|---|---|---|---|
| 30 | .6599 | .6455 | .6599 | .6453 |
| 28 | 6324 | 6181 | 6322 | 6177 |
| 26 | 6045 | 5903 | 6042 | 5899 |
| 24 | 5762 | 5622 | 5758 | 5617 |
| 22 | 5477 | 5337 | 5473 | 5333 |
| 20 | 5188 | 5050 | 5184 | 5046 |
| 18 | 4898 | 4761 | 4894 | 4757 |
| 16 | 4605 | 4470 | 4601 | 4654 |
| 14 | 4310 | 4177 | 4306 | 4172 |
| 12 | 4014 | 3882 | 4010 | 3878 |
| 10 | 3715 | 3586 | 3712 | 3581 |
| 8 | 3416 | 3288 | 3413 | 3285 |
| 6 | 3116 | 2990 | 3113 | 2987 |
| 4 | 2816 | 2691 | 2813 | 2689 |
| 2 | 2515 | 2393 | | |

SIMMONS 12/13/72 LX1600A
0830 TA 72°F RUN 3

| PRESSURE IN. HG. | 'A' OUT DECR | 'B' OUT DECR | 'A' OUT INCR | 'B' OUT INCR |
|---|---|---|---|---|
| 30 | .6645 | .6489 | .6641 | .6484 |
| 28 | 6368 | 6213 | 6364 | 6208 |
| 26 | 6087 | 5934 | 6083 | 5929 |
| 24 | 5803 | 5652 | 5799 | 5647 |
| 22 | 5516 | 5367 | 5512 | 5362 |
| 20 | 5227 | 5079 | 5223 | 5074 |
| 18 | 4935 | 4789 | 4931 | 4784 |
| 16 | 4641 | 4497 | 4638 | 4492 |
| 14 | 4345 | 4202 | 4342 | 4198 |
| 12 | 4048 | 3906 | 4044 | 3903 |
| 10 | 3748 | 3609 | 3746 | 3606 |
| 8 | 3448 | 3311 | 3446 | 3308 |
| 6 | 3147 | 3011 | 3145 | 3009 |
| 4 | 2846 | 2712 | 2844 | 2710 |
| 2 | 2544 | 2412 | | |

SIMMONS 12/13/72 LX 1600A
0905 TA 72°F RUN 4

| PRESSURE IN. HG | 'A' OUT DECR. | 'B' OUT DECR | 'A' OUT INCR. | 'B' OUT INCR |
|---|---|---|---|---|
| 30 | .6642 | .6485 | .6643 | .6485 |
| 28 | 6365 | 6210 | 6365 | 6209 |
| 26 | 6086 | 5932 | 6084 | 5929 |
| 24 | 5802 | 5650 | 5800 | 5647 |
| 22 | 5516 | 5365 | 5513 | 5362 |
| 20 | 5227 | 5078 | 5224 | 5074 |
| 18 | 4935 | 4788 | 4932 | 4784 |
| 16 | 4642 | 4496 | 4638 | 4492 |
| 14 | 4346 | 4202 | 4342 | 4198 |
| 12 | 4049 | 3906 | 4045 | 3902 |
| 10 | 3750 | 3609 | 3746 | 3605 |
| 8 | 3450 | 3311 | 3446 | 3307 |
| 6 | 3148 | 3011 | 3146 | 3009 |
| 4 | 2847 | 2712 | 2845 | 2710 |
| 2 | 2544 | 2412 | | |

SIMMONS 12/3/72 LX 1600 A
0945 TA 72°F RUN 5

| PRESSURE IN. HG. | 'A' OUT DECR. | 'B' OUT DECR | 'A' OUT INCR. | 'B' OUT INCR. |
|---|---|---|---|---|
| 30 | .6644 | .6487 | .6645 | .6488 |
| 28 | 6369 | 6212 | 6368 | 6211 |
| 26 | 6088 | 5934 | 6087 | 5932 |
| 24 | 5805 | 5652 | 5802 | 5649 |
| 22 | 5518 | 5367 | 5516 | 5364 |
| 20 | 5229 | 5079 | 5226 | 5076 |
| 18 | 4938 | 4790 | 4935 | 4787 |
| 16 | 4645 | 4498 | 4641 | 4495 |
| 14 | 4349 | 4204 | 4345 | 4200 |
| 12 | 4051 | 3908 | 4048 | 3905 |
| 10 | 3752 | 3611 | 3749 | 3608 |
| 8 | 3452 | 3313 | 3449 | 3309 |
| 6 | 3151 | 3014 | 3148 | 3011 |
| 4 | 2849 | 2714 | 2848 | 2712 |
| 2 | 2548 | 2414 | | |

SIMMONS 12/11/72 LX 1600 A
0900 TA-40°F

| PRESSURE IN. HG | 'A' OUT V/R DECR. PRES | 'B' OUT V/R DECR. PRES. | 'A' OUT V/R INCR. PRES. | 'B' OUT V/R INCR. PRES. |
|---|---|---|---|---|
| 30 | .6760 | .6430 | .6699 | .6369 |
| 28 | 6470 | 6152 | 6402 | 6088 |
| 26 | 6190 | 5875 | 6105 | 5805 |
| 24 | 5880 | 5585 | 5805 | 5521 |
| 22 | 5575 | 5295 | 5505 | 5233 |
| 20 | 5275 | 5003 | 5210 | 4945 |
| 18 | 4968 | 4705 | 4897 | 4654 |
| 16 | 4652 | 4407 | 4591 | 4359 |
| 14 | 4337 | 4105 | 4285 | 4062 |
| 12 | 4020 | 3803 | 3980 | 3767 |
| 10 | 3705 | 3497 | 3665 | 3467 |
| 8 | 3388 | 3193 | 3355 | 3168 |
| 6 | 3067 | 2888 | 3045 | 2869 |
| 4 | 2744 | 2580 | 2733 | 2570 |
| 2 | 2430 | 2277 | | |

# APPENDIX C

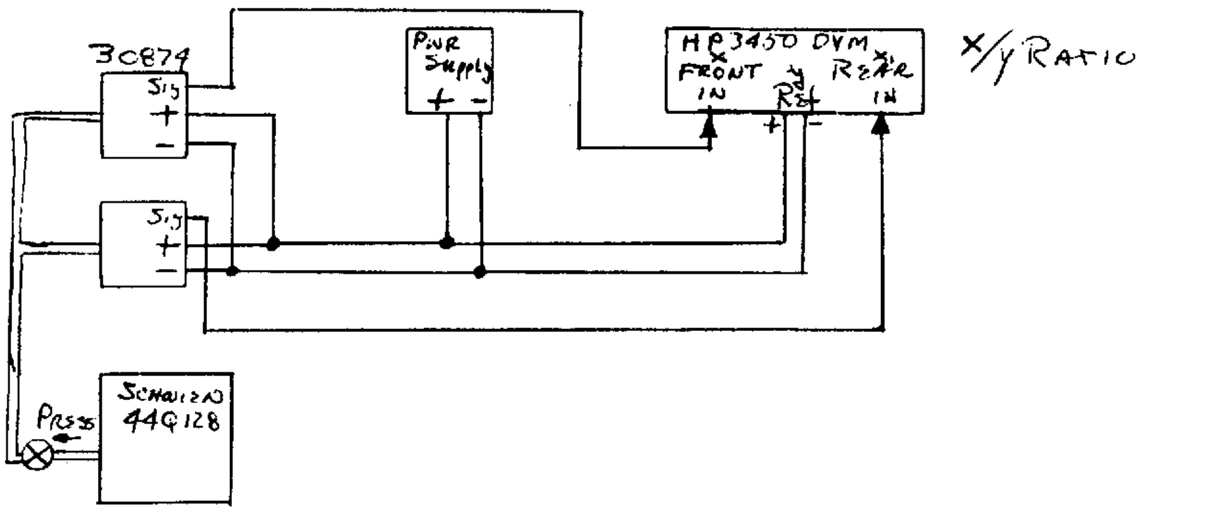
# FAIRCHILD SEMICONDUCTOR COMPONENTS GROUP TEST DATA

ABSOLUTE PRESS
XDUCERS SH4207 & SH4208

6-22-71

TRANSDUCERS S/N 30874 (SH4208) WT = 52 grams
S/N 31006 (SH4207) WT = 52 grams

BOTH UNITS ARE CONNECTED AS FOLLOWS




POWER SUPPLY = POWER DESIGNS MODEL 5015T
PNUEMATIC SOURCE = SCHWIEN MANOMETER 44Q128
READOUT DEVICE = HP 3450A D.V.M. RATIO MODE

Absolute Press

Xducers S/N 42071 & S/N 4208

6-22-74

All Data Taken Using A +12.00 V.D.C. Reference & Excitation. All Data Is In Voltage Ratio

Test # 4.1 Lab Ambient – Unit In Temp Chamber Temp Chamber Is Not 'On'.

| Press. In Hg | Temp °F T.C. | Decr. Press Unit 30874 | Decr. Press Unit 31006 | Incr. Press Unit 30874 | Incr. Press Unit 31006 | Decr. Press Unit 30874 | Decr. Press Unit 31006 | Incr. Press Unit 30874 | Incr. Press Unit 31006 |
|---|---|---|---|---|---|---|---|---|---|
| 30″ | 78° ~~.38063~~ | .38063 ~~.37654~~ | .37654 | .38089 | .37666 | .38093 | .37633 | 38105 | 37636 |
| 26″ | ~~.34704~~ | .34704 ~~.34247~~ | .34247 | .34742 | .34266 | .34734 | .34257 | 34754 | 34268 |
| 22″ | ~~.31355~~ | .31355 ~~.30891~~ | 30891 | .31388 | .30905 | 31382 | 30891 | 31396 | 30899 |
| 18″ | ~~.27996~~ | .27996 ~~.27561~~ | .27561 | .28034 | .27576 | 28024 | 27528 | 28042 | 27537 |
| 14″ | ~~.24647~~ | .24647 ~~.24116~~ | .24116 | .24677 | .24150 | 24667 | 24167 | 24684 | 24177 |
| 10″ | ~~.21290~~ | .21290 ~~.20833~~ | .20833 | .21322 | .20853 | 21321 | 20817 | 21334 | 20822 |
| 6″ | | .17942 | .17463 | .17972 | .17482 | 17977 | 17481 | 17982 | 17484 |
| 2″ | | .14601 | .14161 | .14618 | .14174 | 14630 | 14150 | 14639 | 14160 |

ABSOLUTE PRESS
XDUCERS SN 4207 / SN 4208

CONT. TEST #4.1 LAB AMBIENT 6-22-74

| PRESS IN Hg | TEMP °F TC | DECR PRESS 30874 | DECR PRESS 31006 | INCR PRESS 30874 | INCR PRESS 31006 | DECR PRESS 30874 | DECR PRESS 31006 | INCR PRESS 30874 | INCR PRESS 31006 |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 78°F | 38097 | 37628 | 38117 | 37639 | 38116 | 37638 | 38115 | 37633 |
| 26 | ↓ | 34756 | 34260 | 34763 | 34266 | 34752 | 34257 | 34769 | 34262 |
| 22 | | 31399 | 30894 | 31403 | 30901 | 31404 | 30892 | 31407 | 30897 |
| 18 | | 28045 | 27528 | 28054 | 27532 | 28050 | 27522 | 28054 | 27530 |
| 14 | | 24691 | 24169 | 24694 | 24172 | 24687 | 24162 | 24697 | 24169 |
| 10 | | 21334 | 20815 | 21341 | 20825 | 21336 | 20816 | 21341 | 20814 |
| 6 | ↓ | 17990 | 17481 | 17992 | 17483 | 17988 | 17472 | 17995 | 17481 |
| 2 | 78°F | 14648 | 14150 | 14652 | 14158 | 14649 | 14149 | 14652 | 14154 |

LEAK CK.

| | | | | | | Time | In Hg A | 30874 V.R.U. |
|---|---|---|---|---|---|---|---|---|
| 30 | 78°F | 38123 | 37633 | 38123 | 37634 | | | |
| 26 | ↓ | 34764 | 34257 | 34771 | 34263 | Min 0 | 2.0000 | 14646 |
| 22 | | 31409 | 30891 | 31417 | 30896 | Min 1 | 2.0000 | 14646 |
| 18 | | 28058 | 27524 | 28061 | 27528 | Min 2 | 2.0000 | 14646 |
| 14 | | 24697 | 24164 | 24702 | 24170 | Min 3 | 2.0000 | 14646 |
| 10 | | 21349 | 20815 | 21352 | 20815 | Min 4 | 2.0000 | 14646 |
| 6 | ↓ | 18003 | 17480 | 18001 | 17479 | Mins 5 | 2.0000 | 14646 |
| 2 | 78°F | 14652 | 14144 | 14654 | 14147 | | | |

ABSOLUTE PRESS

XDUCERS SH4207 & SH4208

TP4.2 +140°F 6-22-74 | TP4.4 −40°F 6-24-74

TEMP = −44 °F TC

| PRESS In Hg | TEMP °F TC | DECR. PRESS S/N 30874 | DECR. PRESS S/N 31006 | INCR. PRESS S/N 30874 | INCR. PRESS S/N 31006 | DECR. PRESS S/N 30874 | DECR. PRESS S/N 31006 | INCR. PRESS S/N 30874 | INCR. PRESS S/N 31006 |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 142°F TC | 38039 | 37617 | 37919 | 37528 | ~~37897~~ 37932 | 37737 | 37876 | 37651 |
| 26 | | 34657 | 34246 | 34584 | 34175 | 34574 | 34320 | 34516 | 34235 |
| 22 | | 31313 | 30889 | 31250 | 30828 | 31197 | 30896 | 31162 | 30831 |
| 18 | | 27968 | 27544 | 27911 | 27482 | 27839 | 27483 | 27805 | 27434 |
| 14 | | 24616 | 24192 | 24572 | 24144 | 24485 | 24081 | 24465 | 24042 |
| 10 | | 21259 | 20851 | 21231 | 20815 | 21141 | 20699 | 21125 | 20674 |
| 6 | | 17910 | 17511 | 17895 | 17497 | 17809 | 17333 | 17800 | 17316 |
| 2 | | 14564 | 14190 | 14555 | 14184 | 14492 | 13983 | 14490 | 13982 |

56 Reydes

Absolute Press
Xducers SN 41207 & SN 41208

| Inches In Hg | 6-25-74 #5 Pressure Cycle, Prior to Cycle: °F TC | Decr Press 3084A | Decr Press 31006 | Incr Press 3084A | Incr Press 31006 | 6-26-74 After Cycle: °F TC | Decr Press 3084A | Decr Press 31006 | Incr Press 3084A | Incr Press 31006 |
|---|---|---|---|---|---|---|---|---|---|---|
| | 75°F | 37981 | 37680 | | | 70° | | | | |
| 30 | | 37981 | 37680 | 37976 | 37672 | | 38002 | 37674 | 38001 | 37673 |
| [illegible] | | 34640 | 34319 | 34630 | 34307 | | 34653 | 34302 | 34657 | 34305 |
| [illegible] | | 31304 | 30965 | 31284 | 30943 | | 31301 | 30931 | 31302 | 30934 |
| 8 | | 27963 | 27608 | 27939 | 27579 | | 27945 | 27560 | 27950 | 27567 |
| 14 | | 24610 | 24241 | 24593 | 24223 | | 24590 | 24196 | 24601 | 24205 |
| 10 | | 21257 | 20889 | 21250 | 20872 | | 21241 | 20845 | 21256 | 20857 |
| 6 | | 17918 | 17545 | 17911 | 17536 | | 17895 | 17501 | 17913 | 17514 |
| 2 | | 14581 | 14220 | 14579 | 14214 | | 14561 | 14176 | 14573 | 14187 |

Start Press Cycle 1430 Hrs.
6-25-74

6-26-74
Unit Pressure Cycled 563 Times.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

# APPENDIX D

# TYLAN CORPORATION TEST REPORT

STABILITY AND CALIBRATION TEST RESULTS

PLATINUM RESISTANCE SURFACE THERMOMETERS

INTRODUCTION

This report describes work which was performed in response to Air Research Purchase Order No. 444-24004-3, and Statement of Work EMJB: 3006:0615 dated June 15, 1973. The first phase of testing under the statement of work Paragraph 3.2 (Stability Test Requirements) is covered by this report.

SUMMARY

The test articles are representative samples of Tylan fibreglass epoxy platinum surface resistance temperature sensors which were selected from stock with manufacturing dates from December 1967 through May 1973. Each unit had been stored at room temperature along with its original calibration certification specifying the ice point resistance as measured when it was built. Each unit was recalibrated at the ice point, then calibrated in sequence at -109$^{o}$ F., 32$^{o}$ F., 212$^{o}$ F., 300$^{o}$ F., and again at the ice point. Each sensor was then subjected to ten temperature cycles from -65$^{o}$ F. to +300$^{o}$ F. The sequential calibration from -109$^{o}$ F. to +300$^{o}$ F. was then repeated as before. The data was analyzed to show the stability at the ice point from the date of manufacture through storage, and then through subsequent temperature cycling. Repeatability at the temperature extremes was also analyzed, as was the degree of correspondence

with the Tylan platinum table characteristics.

Based on these five samples the ice point resistance showed a repeatability of ± 0.14% in the worst case. The average of all samples tested showed that the correspondence with the Tylan platinum table was within 0.06% from -20° F. to +300° F. The nature of the difference was in the direction of greater nonlinearity than shown by the table.

## DESCRIPTION OF TESTS

Tylan FG-100-series temperature gauges with platinum elements were selected for the stability testing. All transducers in the FG-100 series use an epoxy fibreglass carrier with a reference grade (99.999% pure) platinum element. The various gauges in this series differ from each other primarily in physical size and resistance at the ice point. Since the materials and method of construction are identical on all units in the series, their data can be compared on a nondimensional basis without regard to model number. The five test units are tabulated below:

| Part Number | Date Manufactured | Serial Number |
|---|---|---|
| FG-107P | 12-67 | 036 |
| FG-103P | 4-69 | 196 |
| FG-106P | 3-70 | 172 |
| FG-105P | 6-72 | 087 |
| FG-103P | 5-73 | 209 |

Each of the test units was accompanied by a calibration certificate listing the ice point resistance which was measured when the unit was manufactured. Each sensor was then subjected to the temperature calibration test in the sequence noted on the temperature calibration data sheet. The first reading was the 32° F., so that this reading gave a direct comparison with the previous ice point reading before the unit was placed in storage. Each sensor was subsequently tested at -109° F. in a $CO_2$ bath, the ice point was repeated, then 212° F. and 300° F. readings were taken in an oil bath, after which the ice point was again repeated.

Following the temperature calibration tests, the units were placed in a Statham oven which was stabilized at -65° F. After a 30 minute soak they were transferred immediately to a second oven which was stabilized at 300° F. This process constituted one temperature cycle; it was repeated for a total of ten temperature cycles. The previous calibration test procedure was then repeated, beginning and ending with ice point resistance checks. The later temperature calibration tests were run on the morning following the evening completion of the temperature cycling.

All data was reduced so that the resistance data corresponded to the nominal test temperatures. These resistances were divided by the nominal ice point resistance of the sensor, so that all data are presented in non-dimensional form. This permits the direct comparison of gauges of different resistances on a common scale.

## TEST RESULTS

Data are appended which show the actual test results, and the corrected parametric values. The data for each transducer is plotted on a separate data sheet which indicates the effect of the test sequence on the parameter values. A butterfly tolerance band is also drawn to show the envelope of all units tested, but with the original manufacturing tolerance (initial 32$^{o}$ F. reading) removed as a variable.

The data shows a slight negative hysteresis effect during temperature transients. In other words, when the resistance is going up the readings are somewhat higher, and when the resistance is going down the readings are somewhat lower than nominal. The reason for this is not known; however, it is presumed to be a strain effect caused by the differential thermal expansion between the fibreglass and the platinum. This same effect is probably responsible for the nonrepeatability of all readings at the ice point. It should further be noted that the repeatability at temperatures other than the ice point is certainly no better than at the ice point, but does not show up in the data because fewer readings were taken.

A comparison with the Tylan platinum resistance table shows the average values to be in relatively good agreement except at the -109$^{o}$ F. temperature. Since the readings appear to be low at both the cold and hot extremes, it indicates a discrepancy in the value of delta in the Callendar - VanDuzen relationship. A discrepancy in the value of alpha would cause a slope difference, whereas the difference in the value of delta shows up as a difference in nonlinearity.

# DATA SHEET

| | |
|---|---|
| Specimen: Temperature Sensor | Job No. 7039 |
| Date: 7-2?-72 | Report No. [illegible] |
| Part No. FG-107 P | Specimen Temp. |
| Serial No. 036 | Amb. Temp. |
| Mfg. Date 12-7-67 | Ice Point Res. on Mfg. Date 1502 Ω |
| | $R/R_{NOM}$ = 1.0013 |

Test Equipment

| | |
|---|---|
| 1 Wheatstone bridge, sensor, 3801 | 6 Oil Bath and stirrer |
| 2 Ref. therm. bridge, 3803 | 7 $CO_2$ bath, thermos |
| 3 Galvanometer 3604 | 8 |
| 4 Ref. thermometer 8052 | 9 |
| 5 Ice bath, thermos | 10 |

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ① | Nominal temperature | °F | 32 | −109 | 32 | 212 | 300 | 32 |
| ② | Reference therm. res. | Ohms | —— | 17.4426 | —— | 35.5005 | 40.3519 | —— |
| ③ | Bath temperature | °F | 32.0 | -109.24 | 32.0 | 211.07 | 300.17 | 32.0 |
| ④ | Measured sensor res. | Ohms | 1501.2 | 1030.6 | 1501.3 | 2080.1 | 2361.1 | 1499.6 |
| ⑤ | Correction rate, ohms/°F | | —— | 3.35 | —— | 3.17 | 3.12 | —— |
| ⑥ | Correction ΔR = ⑤×(③−①) | | —— | | —— | | | —— |
| ⑦ | Corrected R = ④−⑥ ohms at nominal temperature | | 1501.2 | 1031.4 | 1501.3 | 2083.0 | 2360.0 | 1499.6 |
| ⑧ | $R_{NOM}$ | | 1500.0 | 1031.7 | 1500.0 | 2081.7 | 2359.3 | 1500.0 |
| ⑨ | $R/R_{NOM}$ = ⑦/⑧ | | 1.0008 | .9997 | 1.0009 | 1.0006 | 1.0006 | .9997 |

| | |
|---|---|
| Specimen Failed | Tested By A.Y. Date: 8-28-73 |
| Specimen Passed | Witness Date: |
| NOD Written | Sheet No. 5 of |
| | Approved |

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

ivlan

# DATA SHEET

Specimen: Temperature Sensor
Date: 8-28-73
Part No.: EG-103 P
Serial No.: 196
Mfg. Date: 4-69

Job No.: 7039
Report No.: R-7039-1
Specimen Temp.:
Amb. Temp.:
Ice Point Res. on Mfg. Date: 250.38
R/RNOM = 1.0015

Test Equipment

1. Wheatstone bridge, sensor, 3801
2. Ref. therm. bridge, 3803
3. Galvanometer 3604
4. Ref. thermometer 8052
5. Ice bath, thermos
6. Oil Bath and stirrer
7. $CO_2$ bath, thermos
8.
9.
10.

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Nominal temperature °F | 32 | −109 | 32 | 212 | 300 | 32 |
| 2 | Reference therm. res. Ohms | —— | 17.4417 | —— | 35.3631 | 40.3700 | —— |
| 3 | Bath temperature °F | 32.0 | -109.26 | 32.0 | 212.22 | 300.50 | 32.0 |
| 4 | Measured sensor res. Ohms | 250.07 | 171.86 | 250.09 | 346.83 | 393.07 | 249.90 |
| 5 | Correction rate, ohms/°F | —— | 0.558 | —— | 0.528 | 0.520 | —— |
| 6 | Correction ΔR = (5)x((3)-(1)) | —— | | —— | | | —— |
| 7 | Corrected R = (4)-(6) ohms at nominal temperature | 250.07 | 172.00 | 250.09 | 346.71 | 392.81 | 249.90 |
| 8 | RNOM | 250.00 | 171.96 | 250.00 | 346.95 | 393.21 | 250.00 |
| 9 | R/RNOM = (7)/(8) | 1.0003 | 1.0002 | 1.0004 | .9993 | .9990 | .9996 |

Specimen Failed
Specimen Passed
NOD Written

Tested By: A.V  Date: 8-28-73
Witness:  Date:
Sheet No.: 6  of
Approved

Sylan

# DATA SHEET

Specimen Temperature Sensor
Date 8-28-73
Part No. FG-106 P
Serial No. 172
Mfg. Date 3-70

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 999.40
$R/R_{NOM}$ = .9994

**Test Equipment**

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

**Test Title:** Temperature Calibration

**Description of Test:** Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ① | Nominal temperature °F | 32 | −109 | 32 | 212 | 300 | 32 |
| ② | Reference therm. res. Ohms | — | 17.4417 | — | 35.5266 | 40.3599 | — |
| ③ | Bath temperature °F | 32.0 | -109.26 | 32.0 | 211.55 | 300.32 | 32.0 |
| ④ | Measured sensor res. Ohms | 999.35 | 685.03 | 999.21 | 1386.0 | 1572.5 | 998.54 |
| ⑤ | Correction rate, ohms/°F | — | 2.23 | — | 2.11 | 2.08 | — |
| ⑥ | Correction ΔR = ⑤x(③-①) | — | | — | | | — |
| ⑦ | Corrected R = ④-⑥ ohms at nominal temperature | 999.35 | 675.61 | 999.21 | 1386.9 | 1571.8 | 998.54 |
| ⑧ | $R_{NOM}$ | 1000.00 | 687.83 | 1000.00 | 1387.8 | 1572.8 | 1000.00 |
| ⑨ | $R/R_{NOM}$ = ⑦/⑧ | .9994 | .9968 | .9992 | .9994 | .9994 | .9985 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A.V. Date: 8-28-73
Witness Date:
Sheet No. 7 of
Approved

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

# DATA SHEET

| | |
|---|---|
| Specimen: Temperature Sensor | Job No. 7039 |
| Date: 2-28-73 | Report No. R-7039-1 |
| Part No. FG-105P | Specimen Temp. |
| Serial No. 087 | Amb. Temp. |
| Mfg. Date 6-72 | Ice Point Res. on Mfg. Date 500.0 |
| | $R/R_{NOM}$ = 1.0001 |

**Test Equipment**

1. Wheatstone bridge, sensor, 3801
2. Ref. therm. bridge, 3803
3. Galvanometer 3604
4. Ref. thermometer 8052
5. Ice bath, thermos
6. Oil Bath and stirrer
7. $CO_2$ bath, thermos
8. 
9. 
10. 

**Test Title:** Temperature Calibration

**Description of Test:** Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (1) | Nominal temperature °F | 32 | −109 | 32 | 212 | 300 | 32 |
| (2) | Reference therm. res. Ohms | —— | 17.4436 | —— | 35.5445 | 43.3606 | —— |
| (3) | Bath temperature °F | 32.0 | -109.24 | 32.0 | 211.88 | 300.37 | 32.0 |
| (4) | Measured sensor res. Ohms | 500.05 | 342.74 | 500.05 | 693.73 | 786.77 | 499.50 |
| (5) | Correction rate, ohms/°F | —— | 1.12 | —— | 1.06 | 1.04 | —— |
| (6) | Correction ΔR = (5)x((3)-(1)) | —— | | —— | | | —— |
| (7) | Corrected R = (4)-(6) ohms at nominal temperature | 500.05 | 343.01 | 500.05 | 693.83 | 786.34 | 499.50 |
| (8) | $R_{NOM}$ | 500.00 | 343.92 | 500.00 | 693.90 | 786.42 | 500.00 |
| (9) | $R/R_{NOM}$ = (7)/(8) | 1.0001 | .9974 | 1.0001 | .9999 | 1.0000 | .9990 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A. V Date: 8-28-73
Witness Date:
Sheet No. 8 of
Approved

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

Wyle

# DATA SHEET

Specimen Temperature Sensor
Date 8-28-73
Part No. FG-103 P
Serial No. 209
Mfg. Date 5-73

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 250.11
R/RNOM = 1.0004

Test Equipment

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (1) | Nominal temperature °F | 32 | −109 | 32 | 212 | 300 | 32 |
| (2) | Reference therm. res. Ohms | — | 17.4417 | — | 35.5115 | 40.3539 | — |
| (3) | Bath temperature °F | 32.0 | -109.26 | 32.0 | 211.38 | 300.20 | 32.0 |
| (4) | Measured sensor res. Ohms | 250.12 | 171.80 | 250.18 | 346.20 | 392.71 | 249.86 |
| (5) | Correction rate, ohms/°F | — | 0.558 | — | 0.528 | 0.520 | — |
| (6) | Correction ΔR = (5)x((3)-(1)) | — | | — | | | — |
| (7) | Corrected R = (4)-(6) ohms at nominal temperature | 250.12 | 171.94 | 250.18 | 346.58 | 392.60 | 249.86 |
| (8) | RNOM | 250.00 | 171.96 | 250.00 | 346.95 | 393.21 | 250.00 |
| (9) | R/RNOM = (7)/(8) | 1.0005 | .9999 | 1.0007 | .9989 | .9984 | .9994 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A.V. Date: 8-28-73
Witness Date:
Sheet No. 9 of
Approved

# DATA SHEET

tylan

Specimen Temperature Sensor
Date 8-29-73
Part No. FG-10XP
Serial No. 036, 196, 172, 087, 209

Job No. 7039
Report No. R-7039-1
Specimen Temp. noted
Amb. Temp.

Test Equipment

1 Temperature chamber 5609/5610
2 Thermometer (300°F) 839265
3 Thermometer (-65°F) 2019
4
5
6
7
8
9
10

Test Title: Temperature cycling

Description of Test: Soak parts at -65 + 10°F for 30 minutes (min.), then +300°F for 30 minutes (min.). Repeat for 10 cycles total.

| | COLD | | | | HOT | | | |
|---|---|---|---|---|---|---|---|---|
| Cycle No. | Start Time | Temp. °F | Stop Time | Duration Min. | Start Time | Temp. °F | Stop Time | Duration Min. |
| 1 | 7:30 | -64 | 8:00 | 30 | 8:00 | 300 | 8:30 | 30 |
| 2 | 8:30 | -64 | 9:00 | 30 | 9:00 | 300 | 9:30 | 30 |
| 3 | 9:30 | -64 | 10:00 | 30 | 10:00 | 300 | 10:30 | 30 |
| 4 | 10:30 | -64 | 11:00 | 30 | 11:00 | 300 | 11:30 | 30 |
| 5 | 11:30 | -64 | 12:00 | 30 | 12:00 | 300 | 12:30 | 30 |
| 6 | 12:30 | -64 | 1:00 | 30 | 1:00 | 300 | 1:30 | 30 |
| 7 | 1:30 | -64 | 2:00 | 30 | 2:00 | 300 | 2:30 | 30 |
| 8 | 2:30 | -64 | 3:00 | 30 | 3:00 | 300 | 3:30 | 30 |
| 9 | 3:30 | -64 | 4:00 | 30 | 4:00 | 300 | 4:30 | 30 |
| 10 | 4:30 | -64 | 500 | 30 | 5:00 | 300 | 530 | 30 |
| | | | | | | | | |

Specimen Failed
Specimen Passed
NOD Written

Tested By A.V Date: 8-29-73
Witness Date:
Sheet No. 10 of
Approved

# DATA SHEET

Lylan Corporation

Specimen: Temperature Sensor
Date: 8-30-73
Part No.: FG-107 P
Serial No.: 036
Mfg. Date: 12-7-67

Job No.: 7039
Report No.: R-7039-1
Specimen Temp.:
Amb. Temp.:
Ice Point Res. on Mfg. Date: 1502 Ω

**Test Equipment**

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ① | Nominal temperature | °F | 32 | −109 | 32 | 212 | 300 | 32 |
| ② | Reference therm. res. | Ohms | —— | 17.4347 | —— | 35.5070 | 40.3192 | —— |
| ③ | Bath temperature | °F | 32.0 | -109.38 | 32.0 | 211.20 | 299.56 | 32.0 |
| ④ | Measured sensor res. | Ohms | 1500.3 | 1029.5 | 1500.4 | 2080.4 | 2358.8 | 1499.1 |
| ⑤ | Correction rate, ohms/°F | | —— | 3.35 | —— | 3.17 | 3.12 | —— |
| ⑥ | Correction ΔR = ⑤x(③-①) | | —— | | —— | | | —— |
| ⑦ | Corrected R = ④-⑥ ohms at nominal temperature | | 1500.3 | 1030.8 | 1500.4 | 2082.9 | 2360.2 | 1499.1 |
| ⑧ | $R_{NOM}$ | | 1500.0 | 1031.7 | 1500.0 | 2081.7 | 2359.3 | 1500.0 |
| ⑨ | $R/R_{NOM}$ = ⑦/⑧ | | 1.0002 | .9991 | 1.0003 | 1.0006 | 1.0004 | .9994 |

Specimen Failed
Specimen Passed
NOD Written

Tested By: A. V  Date: 8-30-73
Witness:  Date:
Sheet No.: 11 of
Approved:

(vlhn)

# DATA SHEET

Specimen Temperature Sensor
Date 8-30-73
Part No. FG-103 P
Serial No. 196
Mfg. Date 4-69

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 250.38

Test Equipment

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (1) | Nominal temperature °F | 32 | -109 | 32 | 212 | 300 | 32 |
| (2) | Reference therm. res. Ohms | — | 17.4347 | — | 35.5281 | 40.3938 | — |
| (3) | Bath temperature °F | 32.0 | -109.38 | 32.0 | 211.58 | 300.94 | 32.0 |
| (4) | Measured sensor res. Ohms | 250.13 | 171.66 | 250.14 | 346.44 | 393.32 | 249.70 |
| (5) | Correction rate, ohms/°F | — | 0.558 | — | 0.528 | 0.520 | — |
| (6) | Correction ΔR = (5)×((3)-(1)) | — | | — | | | — |
| (7) | Corrected R = (4)-(6) ohms at nominal temperature | 250.13 | 171.87 | 250.14 | 346.66 | 392.83 | 249.70 |
| (8) | $R_{NOM}$ | 250.00 | 171.96 | 250.00 | 346.95 | 393.21 | 250.00 |
| (9) | $R/R_{NOM}$ = (7)/(8) | 1.0005 | .9995 | 1.0006 | .9992 | .9990 | .9988 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A.V. Date: 8-30-73
Witness Date:
Sheet No. 12 of
Approved

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

tylan

# DATA SHEET

Specimen Temperature Sensor
Date 8-30-73
Part No. FG-106.P
Serial No. 172
Mfg. Date 3-70

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 999.40

Test Equipment

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ① | Nominal temperature °F | 32 | -109 | 32 | 212 | 300 | 32 |
| ② | Reference therm. res. Ohms | — | 17.4341 | — | 35.5427 | 40.3200 | — |
| ③ | Bath temperature °F | 32.0 | -109.39 | 32.0 | 211.85 | 299.58 | 32.0 |
| ④ | Measured sensor res. Ohms | 998.34 | 684.38 | 998.47 | 1386.3 | 1571.0 | 998.00 |
| ⑤ | Correction rate, ohms/°F | — | 2.23 | — | 2.11 | 2.08 | — |
| ⑥ | Correction ΔR = ⑤x(③-①) | — | | — | | | — |
| ⑦ | Corrected R = ④-⑥ ohms at nominal temperature | 998.34 | 685.25 | 998.47 | 1386.6 | 1571.9 | 998.00 |
| ⑧ | $R_{NOM}$ | 1000.00 | 687.83 | 1000.00 | 1387.8 | 1572.8 | 1000.00 |
| ⑨ | $R/R_{NOM}$ = ⑦/⑧ | .9983 | .9962 | .9985 | .9991 | .9994 | .9980 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A V Date: 8-30-73
Witness Date:
Sheet No. 13 of
Approved

lylan

# DATA SHEET

Specimen Temperature Sensor
Date 8-30-73
Part No. FG-105 P
Serial No. 087
Mfg. Date 6-72

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 500.0

**Test Equipment**

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

**Test Title:** Temperature Calibration

**Description of Test:** Stabilize and test at each temperature in sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Nominal temperature °F | 32 | −109 | 32 | 212 | 300 | 32 |
| 2 | Reference therm. res. Ohms | —— | 17.4347 | —— | 35.5313 | 40.3639 | —— |
| 3 | Bath temperature °F | 32.0 | -109.38 | 32.0 | 211.64 | 300.39 | 32.0 |
| 4 | Measured sensor res. Ohms | 499.71 | 342.42 | 499.73 | 693.30 | 786.50 | 499.22 |
| 5 | Correction rate, ohms/°F | —— | 1.12 | —— | 1.06 | 1.04 | —— |
| 6 | Correction ΔR = (5)×((3)−(1)) | —— | | —— | | | —— |
| 7 | Corrected R = (4)−(6) ohms at nominal temperature | 499.71 | 342.84 | 499.73 | 693.68 | 786.10 | 499.22 |
| 8 | $R_{NOM}$ | 500.00 | 343.92 | 500.00 | 693.90 | 786.42 | 500.00 |
| 9 | $R/R_{NOM}$ = (7)/(8) | .9994 | .9969 | .9995 | .9997 | .9996 | .9984 |

Specimen Failed
Specimen Passed
NOD Written

Tested By A.V. Date: 8-30-73
Witness Date:
Sheet No. 14 of
Approved

lylan

# DATA SHEET

Specimen Temperature Sensor
Date 8-30-73
Part No. FG-103 P
Serial No. 209
Mfg. Date 5-73

Job No. 7039
Report No. R-7039-1
Specimen Temp.
Amb. Temp.
Ice Point Res. on Mfg. Date 250.11

Test Equipment

1 Wheatstone bridge, sensor, 3801
2 Ref. therm. bridge, 3803
3 Galvanometer 3604
4 Ref. thermometer 8052
5 Ice bath, thermos
6 Oil Bath and stirrer
7 $CO_2$ bath, thermos
8
9
10

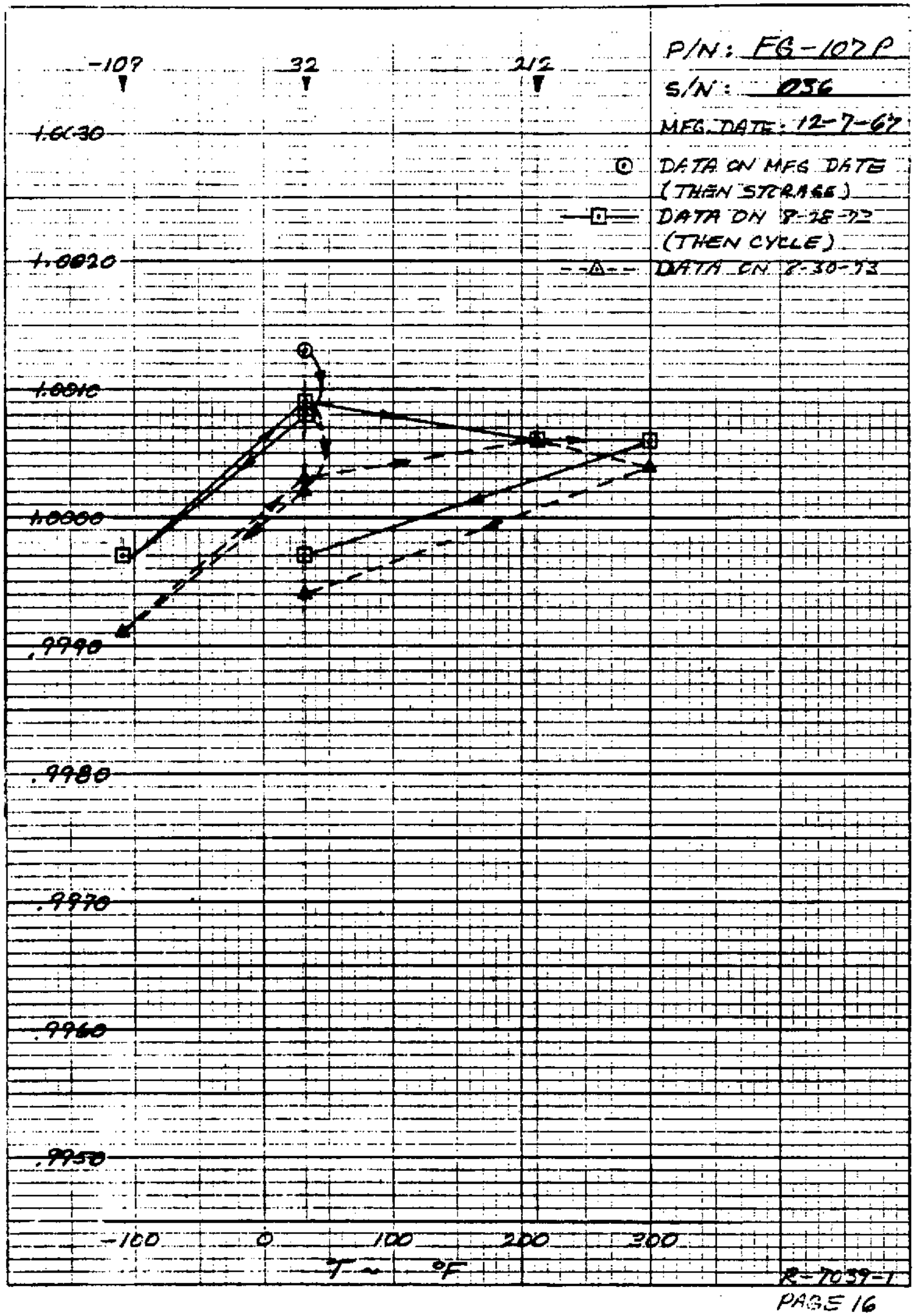
Test Title: Temperature Calibration

Description of Test: Stabilize and test at each temperature in sequence.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ① | Nominal temperature | °F | 32 | −109 | 32 | 212 | 300 | 32 |
| ② | Reference therm. res. | Ohms | —— | 17.4347 | —— | 35.5356 | 40.3698 | —— |
| ③ | Bath temperature | °F | 32.0 | -109.38 | 32.0 | 211.72 | 300.50 | 32.0 |
| ④ | Measured sensor res. | Ohms | 249.94 | 171.65 | 249.97 | 346.41 | 392.70 | |
| ⑤ | Correction rate, ohms/°F | | —— | 0.553 | —— | 0.528 | 0.520 | —— |
| ⑥ | Correction ΔR = ⑤x(③-①) | | —— | | —— | | | —— |
| ⑦ | Corrected R = ④-⑥ ohms at nominal temperature | | 249.94 | 171.86 | 249.97 | 346.56 | 392.44 | |
| ⑧ | $R_{NOM}$ | | 250.00 | 171.96 | 250.00 | 346.95 | 393.21 | |
| ⑨ | $R/R_{NOM}$ = ⑦/⑧ | | .9998 | .9994 | .9999 | .9989 | .9980 | |

Specimen Failed
Specimen Passed
NOD Written

Tested By A. V. Date: 8-30-73
Witness Date:
Sheet No. 15 of
Approved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32
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P/N: FG-102P
S/N: 036
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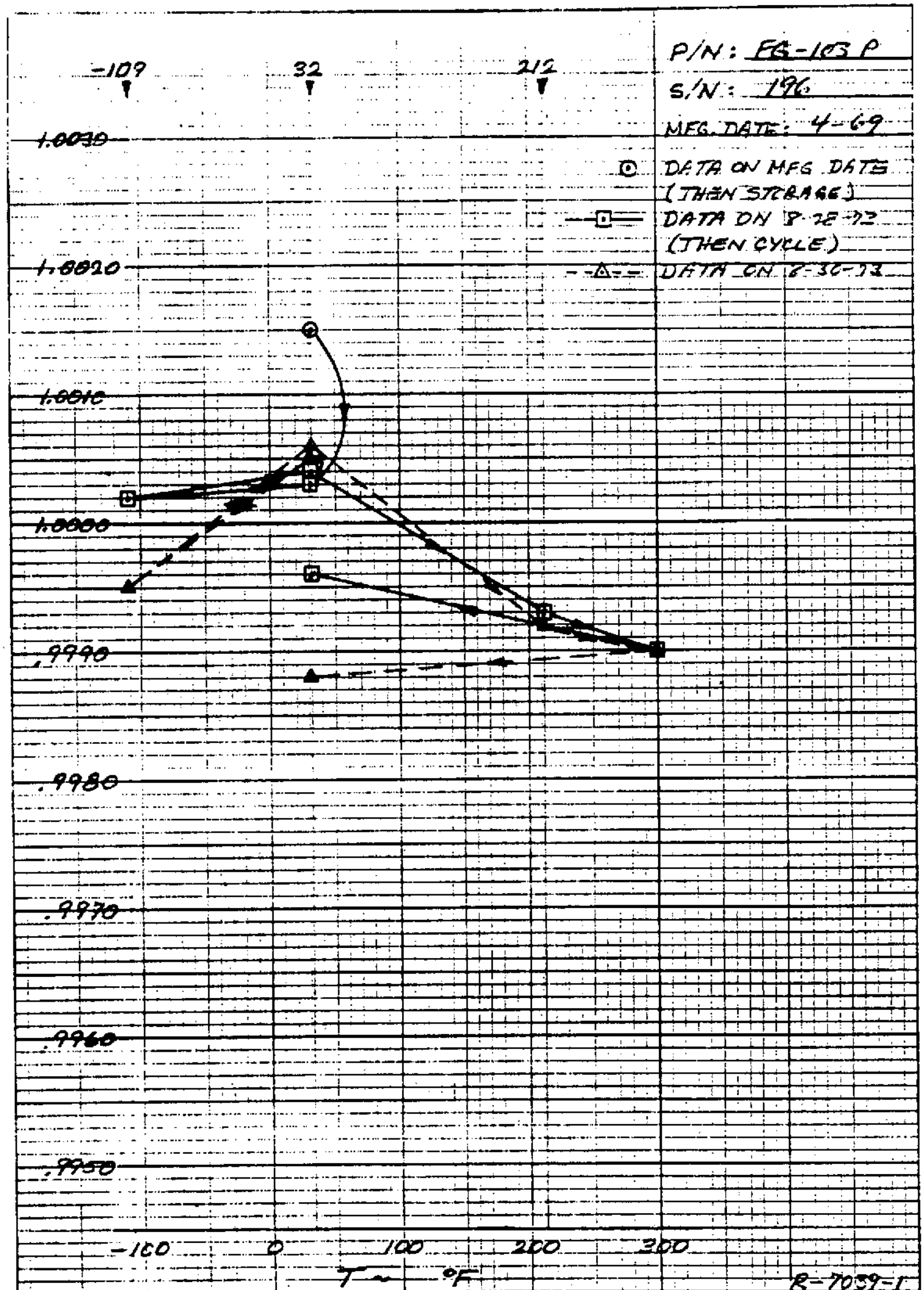
DATA ON 8-30-73
R-7039-1
PAGE 16

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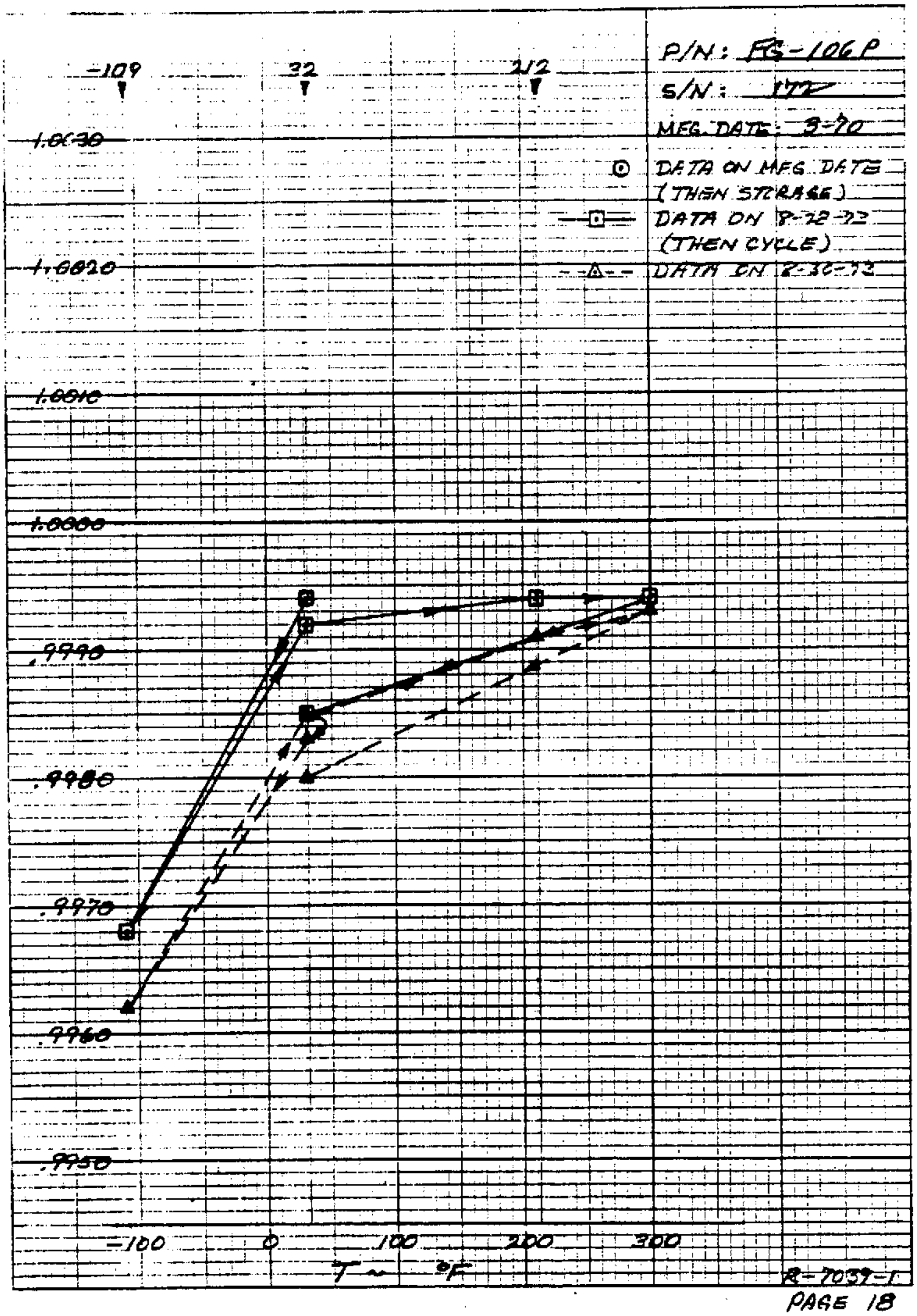
PAGE 17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MFG. DATE: 9-70
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DATA ON 8-22-73 (THEN CYCLE)
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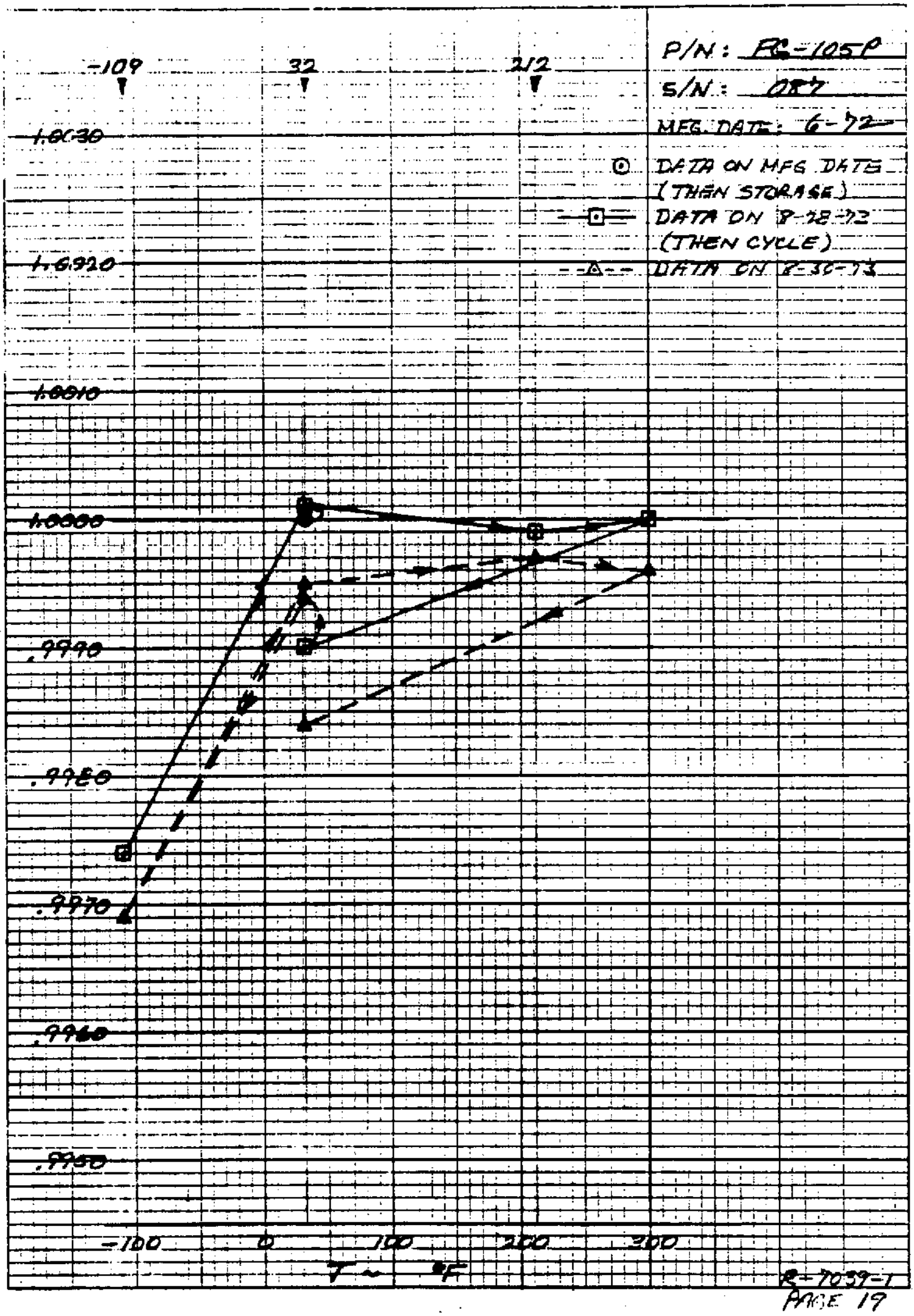
PAGE 18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S/N: 087
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DATA ON 8-28-73 (THEN CYCLE)
DATA ON 8-30-73
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1.0020
1.0010
1.0000
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.9980
.9970
.9960
.9950
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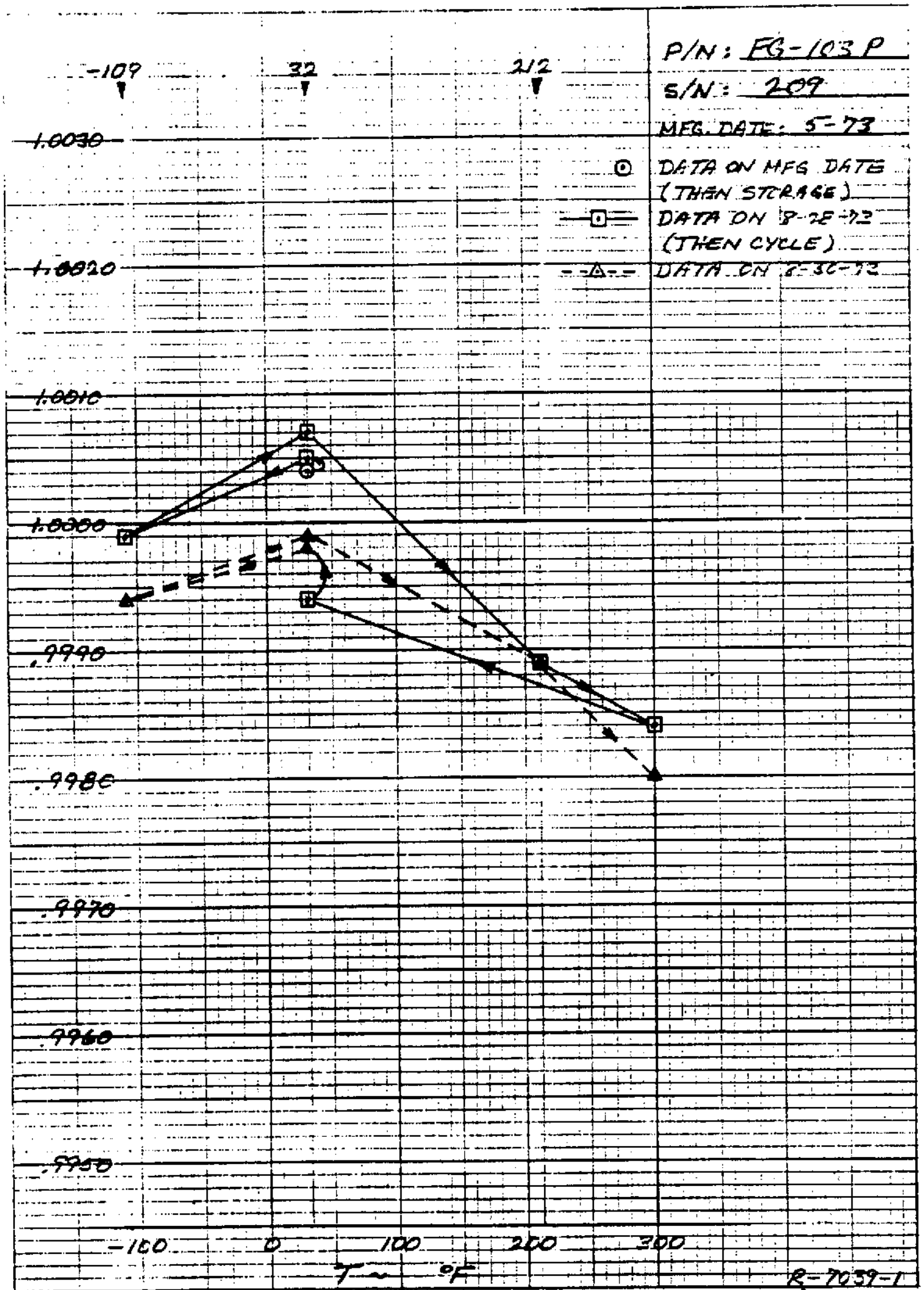
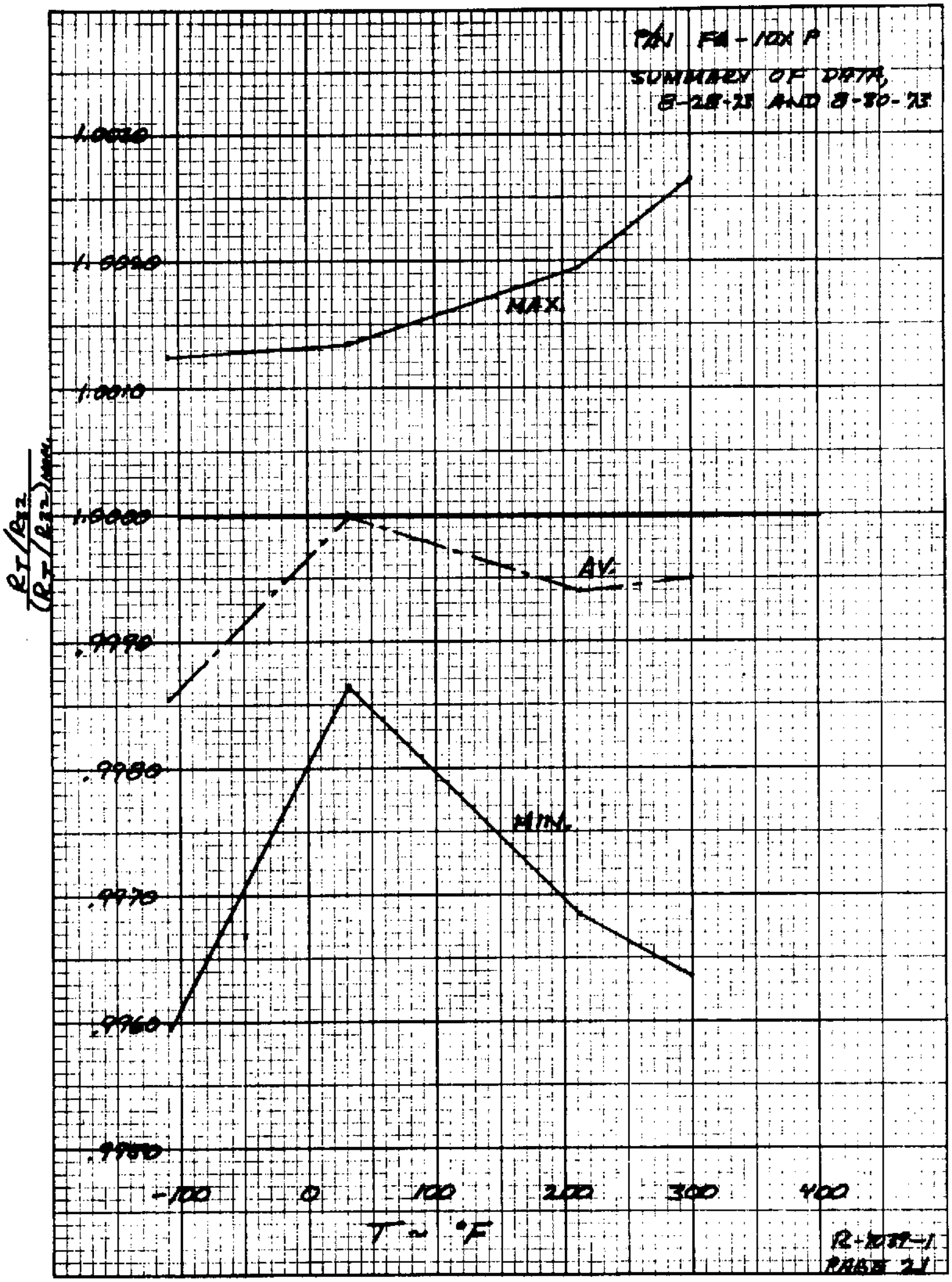
0
100
200
300
T ~ °F
R-7039-1
PAGE 19




R-7039-1
PAGE 20


P/N FA-10X P
SUMMARY OF DATA,
8-28-73 AND 8-30-73
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R-1037-1
PAGE 21

# APPENDIX E

# SUMMARY OF APOLLO CSM WATER TANK GAGING SYSTEM FAILURES

## APPENDIX E

## FAILURE SUMMARY OF APOLLO CSM WATER TANK GAGING SYSTEM

This report presents a review of 25 failures reported on the water tank gaging system that was designed and used in the Apollo CSM environmental control system. The failure reports cover the period of December 1965 through January 1971. These reports were prepared by AiResearch Manufacturing Company, Torrance, California, and the Rockwell International Corporation, Downey, California, including the failure analysis and the implementation of the required corrective action.

The GFE failure reports were furnished to AiResearch for this analysis as part of an ECS transducer development program contracted to AiResearch under NASA JSC Contract NAS 9-13446.

### Apollo CSM Water Tank Gaging System

The Apollo CSM water tank gaging system consists of a cable driven rotary potentiometer as shown in Figure C-1. One end of the cable is attached to the bladder in the water tank and the other end is wrapped around a drum which is part of the rotary potentiometer. The rotary potentiometer incorporates a clock-spring which maintains the cable taut. The inside cavity formed by the expulsion bladder is pressurized with gaseous oxygen thus maintaining the bladder in intimate contact with the water. As water is drawn from the tank, the bladder stretches which causes the cable to reposition the rotary potentiometer. The resistance change in the potentiometer is proportional to water quantity.

### Quantity Gaging System - Operational Characteristics

| | |
|---|---|
| Output signal | dc voltage proportional to water quantity<br>0 vdc = empty tank<br>5 vdc = full tank<br>6.5 vdc = max output for mechanism overtravel |
| Signal accuracy | ±0.5 vdc (±10 percent of full scale) max error |
| Signal ripple component | 10 mv rms max |
| Load resistance | 30,000 ohms |
| Supply voltage | 28 +2, -3 vdc |

The cable-driven rotary potentiometer gaging system provides a straight-forward approach for gaging the contents of expulsion bladder water tanks in zero-g. The problems encountered were largely due to improper assembly (28%) and calibration (20%) of the gaging system. The position of the bladder was dependent on orientation of the tank in one-g and as a result several of the failures

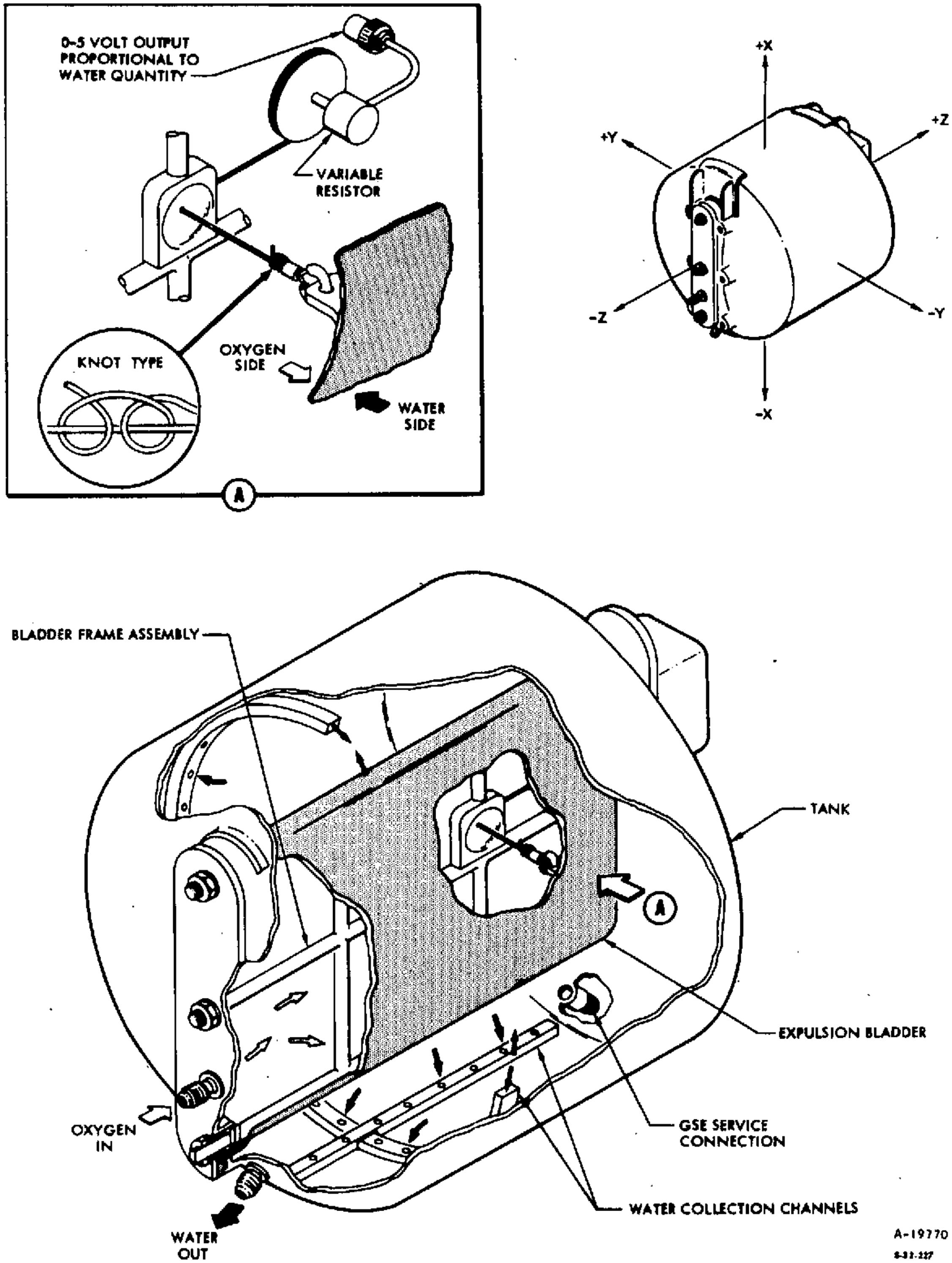


Figure C-1. Apollo CSM Water Tank Gaging System were erroneously reported because the fixture for holding the tank assembly in its proper attitude was not used. Design was responsible for 20 percent of the failures which were not repetitive; however, they were corrected by design changes.

The customer's installation permitted moisture from the urine and waste water dump line to backflow into the gaseous cavity of the expulsion bladder. Twelve percent of the failures indicated that this moisture caused the potentiometer to become corroded resulting in malfunction.

The rotary potentiometer gaging system provides a compact design capable of gaging a long stroke device with little or no increase in size. Attachment of the cable to the center of a bellows or piston-type accumulator would preclude inaccuracies due to rippling as experienced with a bladder.

The failure reports furnished by NASA JSC were reviewed and the pertinent information was reduced to key words that best describe the failure modes and causes. These failures are described in Figures C-2, C-3 and C-4. Figure C-5 contains a summary matrix of the 25 failures including a percentage breakdown for each of the failure categories. The format is relatively self-explanatory, although, for clarification, the definitions of certain terms are presented below:

- Failure type -- This refers to the general type of failure, usually either mechanical, electrical or human.
- Failure mode -- This refers to the failure symptom which the transducer exhibits. Examples would be drift, no output, high output, or set-point shift.
- Failure mechanism -- This refers to what has failed, and in what manner that resulted in the given failure mode. Examples would be bellows leakage, broken leadwire, failed transistor, or cracked sensing bead.
- Failure cause -- This refers to the action that resulted in the occurrence of the failure mechanism. Examples would be overpressure applied to the unit, poor weld quality, inadequate circuit design or test procedure not followed.
- Problem area -- This refers to the general area responsible for the failure cause. This would generally be either design, manufacturing, testing, installation, handling, human or random.
- Corrective action -- This refers to the corrective action taken that is referred to on the trouble report.

# TRANSDUCER FAILURE EVALUATION

TRANSDUCER APPLICATION CONTENTS GAGING - APOLLO CSM WATER TANKS
BASIC PART NUMBER A/R 820978, NAA No. ME192-0007-0021
TRANSDUCER MANUF. AIRESEARCH
TROUBLE REPORT SOURCE AIRESEARCH AND NAA

TRANSDUCER TYPE WIND-UP CABLE DRIVEN POTENTIOMETER
OPERATING PRINCIPLE POTENTIOMETER
MEASUREMENT RANGE
MEASUREMENT MEDIA BLADDER POSITION VS WATER QUANTITY

| PART NUMBER | SERIAL NUMBER | FAILURE DATE | T/R NUMBER | FAILURE TYPE | FAILURE MODE | FAILURE MECHANISM | FAILURE CAUSE | PROBLEM AREA | CORRECTIVE ACTION | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|
| 820978-2-1 | 105-109 | 12-31-65 | AR008209 | HUMAN | OUTPUT HIGH | POTENTIOMETER | PROCEDURE | TESTING ERROR | UNIT CALIBRATED | |
| | 105-112 | 1-15-66 | AR006628 | HUMAN | OUTPUT DOES NOT CHANGE | FRACTURED CABLE | OVERPRESSURIZATION OF TANK BLADDER | TESTING ERROR | RESPONSIBLE PERSONNEL CAUTIONED | |
| | 105-110 | 1-4-66 | AR008213 | HUMAN | CALIBRATION SHIFT | WIRE CABLE | MISROUTED ON POTENTIOMETER | ASSEMBLY | COMPONENT REWORKED | |
| | 105-109 | 1-4-66 | AR008214 | HUMAN | CALIBRATION SHIFT | WIRE CABLE AND POTENTIOMETER | CABLE MISROUTED AND WRONG POTENTIOMETER USED | ASSEMBLY | COMPONENTS REPLACED AND REWORKED | |
| | 105-108 | 1-6-66 | AR008217 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | DESIGN INADEQUACY | DESIGN | INDICATOR ASSY REPLACED IN WATER TANK | |
| | 105-109 | 1-6-66 | AR008218 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | MISROUTED WIRE CABLE | ASSEMBLY | UNIT REWORKED | |
| | 105-110 | 2-3-66 | AR006640 | HUMAN | CALIBRATION SHIFT | AIR IN WATER LINE | LEAKAGE THRU THREADED MOUNTING SCREWS | DESIGN | LOCTITE APPLIED TO THE SCREW THREADS | |
| | 105-114 | 2-22-66 | AR006644 | HUMAN | NO OUTPUT | ELECTRIC LEADS | BROKEN DUE TO MISHANDLING | ASSEMBLY | ASSEMBLY PERSONNEL CAUTIONED | |
| | 105-114 | 3-17-66 | AR007654 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | FREON CLEANING CAUSED POTTING COMPOUND TO SWELL BINDING PULLEY | FREON CLEANING | FREON CLEANING ELIMINATED | |

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA

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OF CALIFORNIA

# TRANSDUCER FAILURE EVALUATION

TRANSDUCER APPLICATION CONTENTS GAGING - APOLLO CSM WATER TANKS

BASIC PART NUMBER A/R 820978, NAA No. ME192-0007-0021

TRANSDUCER MANUF. AIRESEARCH MANUFACTURING COMPANY

TROUBLE REPORT SOURCE AIRESEARCH AND NAA

TRANSDUCER TYPE WIND-UP CABLE DRIVEN POTENTIOMETER

OPERATING PRINCIPLE POTENTIOMETER

MEASUREMENT RANGE

MEASUREMENT MEDIA BLADDER POSITION VS WATER QUANTITY

| PART NUMBER | SERIAL NUMBER | FAILURE DATE | T/R NUMBER | FAILURE TYPE | FAILURE MODE | FAILURE MECHANISM | FAILURE CAUSE | PROBLEM AREA | CORRECTIVE ACTION | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|
| 820978 | 105-112 | 4-28-66 | AR008829 | HUMAN | OUTPUT DOES NOT CHANGE | CABLE DRIVEN POTENTIOMETER | CORROSION FROM INHIBITORS IN WATER GLYCOL | IMPROPER TEST OPERATION | HARDWARE DISASSEMBLED AND CLEANED | |
| | 075102 | 5-25-66 | MA021124 | HUMAN | NO OUTPUT | POTENTIOMETER WIPER WIRE | WIRE FRACTURED WHERE IT PASSES THRU RESISTOR HOUSING | DESIGN | DRAWING CHANGED | |
| | 105-115 | 6-24-66 | MA028737 | HUMAN | NO OUTPUT | PIN IN THE ELECTRICAL CONNECTOR | PIN WAS BENT DURING INSTALLATION | INSTALLATION MISHANDLING | RETURNED TO A/R FOR REPAIR | |
| | 46-103 | 7-21-66 | AR006636 | HUMAN | CALIBRATION SHIFT | TANK BLADDER | OUT OF SYMMETRY | ASSEMBLY PROCEDURE | REVISED PROCEDURE | |
| | 105-116 | 8-30-66 | AR008841 | HUMAN | NO OUTPUT | WIRE CABLE | CABLE WAS OFF OF THE POTENTIOMETER | DESIGN | NONE | |
| | 46-104 | 9-21-66 | AR011303 | HUMAN | OUTPUT LOW | CABLE DRIVEN POTENTIOMETER | UNKNOWN | UNKNOWN | NONE STATED | |
| | 46-114 | 6-16-67 | AR014194 | MECH | LOW INSULATION RESISTANCE | POTENTIOMETER | MOISTURE LEAK IN PACKING | ASSEMBLY | REPAIRED UNIT | |
| | 46-103 | 7-25-67 | AR015437 | HUMAN | CALIBRATION SHIFT | TEST FIXTURE | INCORRECT TANK ORIENTATION | TESTING | NONE | WATER TANK ROTATED 180° RESULTING IN CALIBRATION SHIFT |
| | 0010511 | 8-23-67 | MP012011 | MECH | CALIBRATION SHIFT | VEHICLE INSTALLATION | INCORRECT TANK ORIENTATION | NONE | NONE | INSTL. IN VEHICLE NORMALLY GIVES INCORRECT ORIENTATION |

# TRANSDUCER FAILURE EVALUATION

TRANSDUCER APPLICATION CONTENTS GAGING - APOLLO CSM WATER TANKS
BASIC PART NUMBER A/R 820978, NAA No. ME192-0007-0021
TRANSDUCER MANUF. AIRESEARCH MANUFACTURING COMPANY
TROUBLE REPORT SOURCE AIRESEARCH AND NAA

TRANSDUCER TYPE WIND-UP CABLE DRIVEN POTENTIOMETER
OPERATING PRINCIPLE POTENTIOMETER
MEASUREMENT RANGE
MEASUREMENT MEDIA BLADDER POSITION VS WATER QUANTITY

| PART NUMBER | SERIAL NUMBER | FAILURE DATE | T/R NUMBER | FAILURE TYPE | FAILURE MODE | FAILURE MECHANISM | FAILURE CAUSE | PROBLEM AREA | CORRECTIVE ACTION | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|
| 820978 | 46-117 | 8-24-67 | AR015156 | HUMAN | CALIBRATION SHIFT | ELECTRIC POTTING CRACKED AND LEAD WIRES BROKEN | MISHANDLING DURING ASSEMBLY | ASSEMBLY | STRAIN RELIEF PROTECTION ADDED BY DRAWING CHANGE | |
| | 126-119 | 9-30-67 | AR015190 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | CALIBRATED IN ERROR | ASSEMBLY AND CALIBRATION | UNIT TO BE RECALIBRATED | |
| | 0046111 | 12-27-68 | PF103515 | HUMAN | CALIBRATION SHIFT | CORROSION OF POTENTIOMETER | URINE BACKUP INTO WATER TANK GASEOUS BLEED | DESIGN INSTALLATION | DUMPING PROCEDURE DEFINED | |
| | 39-131 | 4-23-69 | AR019168 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | SPRING RETURN DRUM SLUGGISH, ERRONEOUSLY LOOSENED | ASSEMBLY | CAUTION NOTE INCLUDED ON ASSEMBLY DOCUMENT | |
| | 0078122 | 11-14-69 | PF108521 | HUMAN | CALIBRATION SHIFT | CABLE DRIVEN POTENTIOMETER | CORROSION DUE TO BACK FLOW OF MOISTURE IN DUMP LINES | DESIGN INSTALLATION | NONE | |
| | 0046118 | 4-12-70 | PF109501 | HUMAN | CALIBRATION SHIFT | UNKNOWN | NOT DETERMINED | UNKNOWN | NONE | |
| | 0028120 | 1-21-71 | D63165 | HUMAN | CALIBRATION SHIFT | UNKNOWN | NOT DETERMINED | UNKNOWN | NONE | |
| | | | | | | | | | | |
| | | | | | | | | | | |

| PERCENT | FAILURE MODE: HIGH OUTPUT | OUTPUT DOES NOT CHANGE | CALIBRATION SHIFT | NO OUTPUT | LOW OUTPUT | LOW INSULATION RESISTANCE | FAILURE TYPE: HUMAN | ELECTRICAL | MECHANICAL | FAILURE MECHANISM: FRACTURED CABLE | POTENTIOMETER | CABLE | CABLE AND POTENTIOMETER | CABLE AND POTENTIOMETER | PULLEY | AIR IN WATER LINE | ELEC. LEADS BROKEN | POTENTIOMETER | BROKEN ELEC. WIRE | ELEC. CONNECTOR | TANK BLADDER | POTENTIOMETER | TEST FIXTURE | VEHICLE INSTL. | CABLE DRIVEN POTENTIOMETER | PROBLEM AREA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | | | 3 | 2 | | | 5 | | | | | 1 | | 1 | | 1 | | | 2 | | | | | | | DESIGN | ENGINEERING |
| 4 | | | 1 | | | | 1 | | | | | | | | | | 1 | | | | | | | | | FREON CLEANING | ENGINEERING |
| 28 | | | 5 | 1 | | 1 | 6 | | 1 | | | 2 | 1 | | | | 1 | | | | 1 | 1 | | | 1 | ASSEMBLY | MANUFACTURING |
| 8 | 1 | | 1 | | | | 2 | | | | 2 | | | | | | | | | | | | | | | ASSEMBLY AND CALIBRATION | |
| 8 | | 1 | 1 | | | | 2 | | | 1 | | | | | | | | | | | | | 1 | | | TEST METHOD | |
| 12 | | 1 | 2 | | | | 3 | | | | | | | | | | | 3 | | | | | | | | DESIGN INSTALLATION | CUSTOMER |
| 4 | | | | 1 | | | 1 | | | | | | | | | | | | | 1 | | | | | | INSTALLATION | CUSTOMER |
| 12 | | | 2 | | 1 | | 3 | | | | 3 | | | | | | | | | | | | | | | UNKNOWN | |
| 4 | | | 1 | | | | | | 1 | | | | | | | | | | | | | | | 1 | | NONE | |
| | 1 | 2 | 16 | 4 | 1 | 1 | 23 | 0 | 2 | 1 | 5 | 3 | 1 | 1 | | 1 | 2 | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | TOTALS | |
| 100 | 4 | 8 | 64 | 16 | 4 | 4 | 92 | 0 | 8 | 4 | 20 | 12 | 4 | 4 | | 4 | 8 | 12 | 8 | 4 | 4 | 4 | 4 | 4 | 4 | PERCENT | |
| FAILURE CAUSE | | | | | | | | | | OVERPRESS. OF TANK BLADDER | MISCALIBRATED | MISROUTED | WRONG POT USED | DESIGN INADEQ., BINDING ON POTTING | | LEAKAGE THRU SCREW THREADS | MISHANDLING | CORROSION | WIRE FEEDTHRU | BENT PIN | UNSYMMETRICAL | PACKING LEAKAGE | WRONG ORIENT'N | WRONG ORIENT'N | LOOSE RETURN SPRING | | |

Summary Matrix of Failures Reported on the Apollo CSM Water Tank Gaging System

# APPENDIX F

# BACKGROUND RADIATION

## 1.0 GENERAL INFORMATION

It is expected that many people who will read about and use nucleonic gaging systems will not be familiar with radiation, the use of radioactive sources or the terminology used. While use of nucleonic gaging does not require any specialized knowledge of radiation and is designed to eliminate any hazards to the user, a brief discussion of radiation may be of interest to users of nucleonic gages.

Everyone is exposed to some radiation throughout their life. First, a small part of the cosmic radiation that strikes our atmosphere penetrates the earth's blanket of air to reach the surface. Second, the earth contains naturally occuring radioactive material (Uranium ore, Potasium-40, etc.) and there are minute quantities of radioactivity in practically all the materials we use and even in our bodies. Third, nearly everyone is exposed to medical or dental x-rays from time to time. The following sections discuss the units used in measuring radiation.

## 2.0 UNITS USED IN DISCUSSING RADIATION

### 2.1 The Roentgen

Several units are used when discussing radiation dose or radiation dose rate. Historically, the first unit used was the roentgen, named after the discoverer of x-rays, W.K. Roentgen, which is actually a measure of the amount of ionization caused by radiation. The roentgen is often abbreviated as R and the milliroentgen as mR (1/1000 of one R). The roentgen identifies radiation intensity and not its effect so it is called exposure, or exposure rate when expressed in roentgens per hour (R/hr) or milliroentgens per hour (mR/hr).

### 2.2 The Rad

Because different kinds of radiation have different effect on materials, other units are often used. One of the most used units is the rad, which stands for radiation absorbed dose. One rad is equal to 100 ergs of energy absorbed in each gram of material (100 ergs/gm) and a millirad (m rad) is 0.1 ergs/gm (also rad/hr and mrad/hr for absorbed dose rate).

### 2.3 The Rem

For living tissue, even the same number of rads of different kinds of radiation are not equivalent, so another unit, the rem for "radiation equivalent man" is used. The rem and rem/hr (also milli rem and milli rem/hr) are the standard units for radiation protection. With the rem family of units, we can compare the absorbed dose rate of x-rays, cosmic rays, neutrons, etc.,knowing that the same quantities will have equivalent effects on the person or persons exposed.

## 2.4 The Curie

The curie (named after Madam Curie, the discoverer of Radium) is different from those discussed above; the curie is a measure of the activity of radioactive material in terms of the average number of atoms that undergo disintegration every second. One curie* is $3.7 \times 10^{10}$ disintegrations per second; one millicurie (mCi) $3.7 \times 10^{7}$ (37,000,000) disintegrations each second and one microcurie ($\mu$Ci) is $3.7 \times 10^{4}$ disintegrations per second. A wrist watch with a luminous dial might contain a few micro curies or less of source while a radioisotope powered battery contains thousands or millions of curies. Yet both are quite safe when properly built and properly used.

*Originally defined as one gram of Radium or equivalent. In each gram of pure Radium-226, approximately $3.7 \times 10^{7}$ atoms will decay to radon gas each second.

## RADIATION SAFETY AND HANDLING

### Radiation Dose to Personnel

Radiation safety and the safe handling of the source assembly is prime consideration in the design of each nucleonic system. While the radiation source must have the right gamma energy, and sufficient source strength to accomplish the gaging job, it must not cause any significant radiation dosage to the aircraft crew members, the ground crew or to any personnel who might handle the sources in transit or in storage. The AEC regulations (Title 10, CRF 20) and conforming regulations of the agreement state agencies specify occupational dose limits (maximum allowable radiation dose for people who wear film badges or pocket dosimeters) and much lower dose limits for the general population. Radiation workers may receive up to 5 Rem* per year while personnel who are not on film badge programs should receive less than 0.5 Rem (500 milliRem) per year.

The radiation absorbed dose received each year by any one person is a function of the radiation field they are exposed to and the time of exposure. This is the exposure dose rate and is measured in Roentgens per hour

---

*Rem is the "Roentgen equivalent Man" - the dose of any radiation that has an equivalent biological effect of exposure to one Roentgen of X-rays or gamma rays.

(R/hr) or milliRoentgens per hour (mR/hr). For x-rays and gamma rays, the conversion is direct*, that is exposure to one mR/hr for one hour results in one mRem of absorbed dose. A person will receive 5 mRem if they should spend one hour in a 5 mR/hr field, or 5 hours in a one mR/hr field. More succinctly, absorbed dose is a product of exposure dose rate and exposure time. For the mathematically inclined, it is actually the integral:

$$D \text{ (in Rems)} = \int_0^T \phi(t)\,dt$$

where Ø (t) is the instantaneous exposure dose rate. But it is the concept that is important: every person should keep their absorbed dose to a minimum. This is done by keeping the time spent in any radiation field to a minimum.

Data presented at a 1969 Symposium on Radiation Legislation by Dr. K. Z. Morgan[1,2] shows that 94% of the radiation dose received by the average person in the United States is from medical exposure as shown

*The conversion of Roentgens of exposure to Rems of absorbed dose depends on the Relative Biological Effectiveness (RBE) of the radiation type. The RBE of x-rays and gamma rays is 1 but it is 10 for neutrons and ranges from 1 to 20 per particle.

1. Director, Health Physic Division, Oak Ridge Natl Laboratory
2. Fifty-Fifth Scientific Assembly and Annual Meeting of the Radiological Society of North America at Chicago, Illinois November 30 - December 5, 1969.

in the following table:

ESTIMATED AVERAGE IONIZING-RADIATION EXPOSURE TO PERSONS LIVING IN THE UNITED STATES

| | mRems/year |
|---|---|
| Medical Exposure | |
| Gonad dose from diagnosis (1964) | 55 |
| Gonad dose from therapeutic use (1964) | 7 |
| Bone-marrow dose from diagnosis (1964) | 125 |
| Thyroid dose from diagnosis (mostly dental) (1964) | 1000 |
| Weapons Fallout Dose (1968) | 2 |
| Occupational Exposure | |
| Nuclear energy industry gonad dose (1966) | 0.2 |
| All other occupational exposure gonad dose (1966) | 0.4 |
| Other Man-Made Sources (watches, television, shoe-fitting machines, radioisotope applications, etc.) | |
| Gonad dose (1966) | 0.1 |

The total average absorbed dose is about 1190 mRem/year. Added to this is the radiation absorbed dose from terrestrial radiation (radioactive materials in the earth's crust) and cosmic radiation. Both of these depend on the area a person lives in. The terrestrial component varies between

70 to 200 mRem/year (more living over granite) but is nearly 1000 mRem/year in Kerak, India. The cosmic ray contribution to total absorbed dose varies considerably with altitude from about 50 mRem/year at sea level to about 125 mRem/year in Denver, Colorado.

The total average absorbed dose then is between 1200 and 1400 mRem/year with the largest contribution (and most variation) coming from medical and dental x-rays. Thus, if a person who was not on a film badge program received the maximum allowed, 500 mRem in one year, he would only increase his total dose by about 40% for that year. His total 30 year dose would hardly be increased at all. General Nucleonics feels that it behooves the instrument manufacturers to keep radiation exposure well below the "safe" levels.

In all of the 2000 avionic gaging systems built by GND, the exposure dose rate is kept below 2 mR/hr in any area where maintenance personnel might spend any length of time. When the GND NOQIS (Nucleonic Oil Quantity Indicating System) was first installed on all F104's at Luke AFB, the installing personnel were required to wear film badges. After several months, with the same crew members doing the installation on several hundred aircraft, the requirement for wearing film badges was removed as the film badge did not show any significant readings above natural background (see Attachment 1).

## 3.2 Radioactive Contamination

The potential hazard of radioactive contamination, that is, the possibility that a source will leak or break open and radioactive material will spread around to eventually be ingested or inhaled, has prevented many otherwise useful gages from being used by non-licensed people. Even when use is allowed, most sources must be professionally leak tested at 6 month intervals (or more often) to lessen the chance of contamination. Kr-85 sources need not be leak tested because Kr-85 sources cannot contaminate. The reason Kr-85 is so much safer than almost any other source material is because krypton is an inert gas. Because krypton is inert (like all noble gases, krypton does not combine chemically with other elements), it will not be retained by the body even if some is breathed into the lungs.

ATTACHMENT I

DEPARTMENT OF THE AIR FORCE
2793D UNITED STATES AIR FORCE DISPENSARY (AFLC)
McCLELLAN AIR FORCE BASE, CALIFORNIA 95652

REPLY TO ATTN OF: SMBDOM (Mr. Thoep/33491)

16 JAN 1968

SUBJECT: Installation of the Nucleonic Oil Gage

TO: SMNATA (Mr. Ack)

1. We have monitored the installation of the Nucleonic Oil Gage since April 1966 and the results of the film badge readings are as follows:

| Dates | Readings |
|---|---|
| 4 Apr 66 to 6 Jun 66 | 00.000 |
| 6 Jun 66 to 9 Sep 66 | 00.000 |
| 9 Sep 66 to 7 Dec 66 | 00.000 |
| 7 Dec 66 to 6 Apr 67 | 00.000 |
| 6 Apr 67 to 12 Jul 67 | 00.000 |
| 12 Jul 67 to 11 Oct 67 | 00.000 |

2. To date we have had no exposures that would warrant any concern to the health of the installers listed below:

Marcus G. Buckner
Edward C. Collins
Albert C. Riley
Fred C. Wynn



JOHN J. CERRONE, Capt, USAF, MC
Chief, Mil Public Health & Occ Med Sec

# APPENDIX G

# GENERAL NUCLEONICS DESIGN AND TEST PROGRAM

tyco general nucleonics division

ER-11005

FINAL REPORT

# NUCLEONICS CONTENTS GAGING SYSTEM FOR ZERO-G BLADDER-TYPE WATER TANKS

Prepared for:

GARRETT AIRESEARCH MANUFACTURING COMPANY

TORRANCE, CALIFORNIA

P.O. No. 444-24023-3

Prepared by:
K. V. Pearson
29 April 1974

Nucleonics Division 2611 Metropolitan Pl., Pomona, Ca 91767 Tel. 714 593 4985 TELEX 670409

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## 1.0 ABSTRACT

This report covers the design and test evaluation of a laboratory breadboard nucleonic gaging system for measuring the quantity of water contained in a bladder-type water tank used in a zero gravity spacecraft environment. The gaging system components consist of radioactive source elements containing Krypton-85 gas, Geiger-Muller tube radiation detectors, and processing electronics.

Testing of the gage included quantity measurements in five pound increments from Full tank, at approximately 55 pounds of water, to Empty tank. Quantity measurements at each of the fill levels were obtained with the water tank oriented in six different orthogonal positions with respect to earth gravity.

Included in the report is a brief discussion of the nucleonic gaging technique, system error analysis and an evaluation of the data obtained during the testing of the gage. Gaging system accuracy in a zero-gravity environment was determined to be 1.3% from Empty to 75% Full and approximately 5% at Full tank.

## 2.0 RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

Nucleonic gaging techniques may be applicable to those difficult gaging requirements where conventional gaging methods fail to obtain the desired results. The Apollo CSM Water Tank used a variation of the conventional resistance wire gage as shown on Figure 1. In this application, the water to be gaged is contained between the outside tank walls and an internal pressurized bladder which contains the tank ullage and provides the water expulsion pressure. The quantity of water in the tank is determined by measuring the location of the expulsion bladder with respect to the center of the tank. Although this gaging technique is conceptually sound, a number of technical problems resulted from its use and an alternate gaging method was sought.

Garrett Airesearch granted a sub-contract to General Nucleonics Division of Tyco Laboratories (GND) to investigate the use of a nucleonic gage to measure the Apollo CSM Water Tank quantity. The investigation concentrated upon proving the gaging technique, using off-the-shelf hardware, breadboard electronics, and standard laboratory equipment.

The results of the investigation were quite satisfactory. Gaging accuracies of 5% near Full and 1.3% from 75% Full

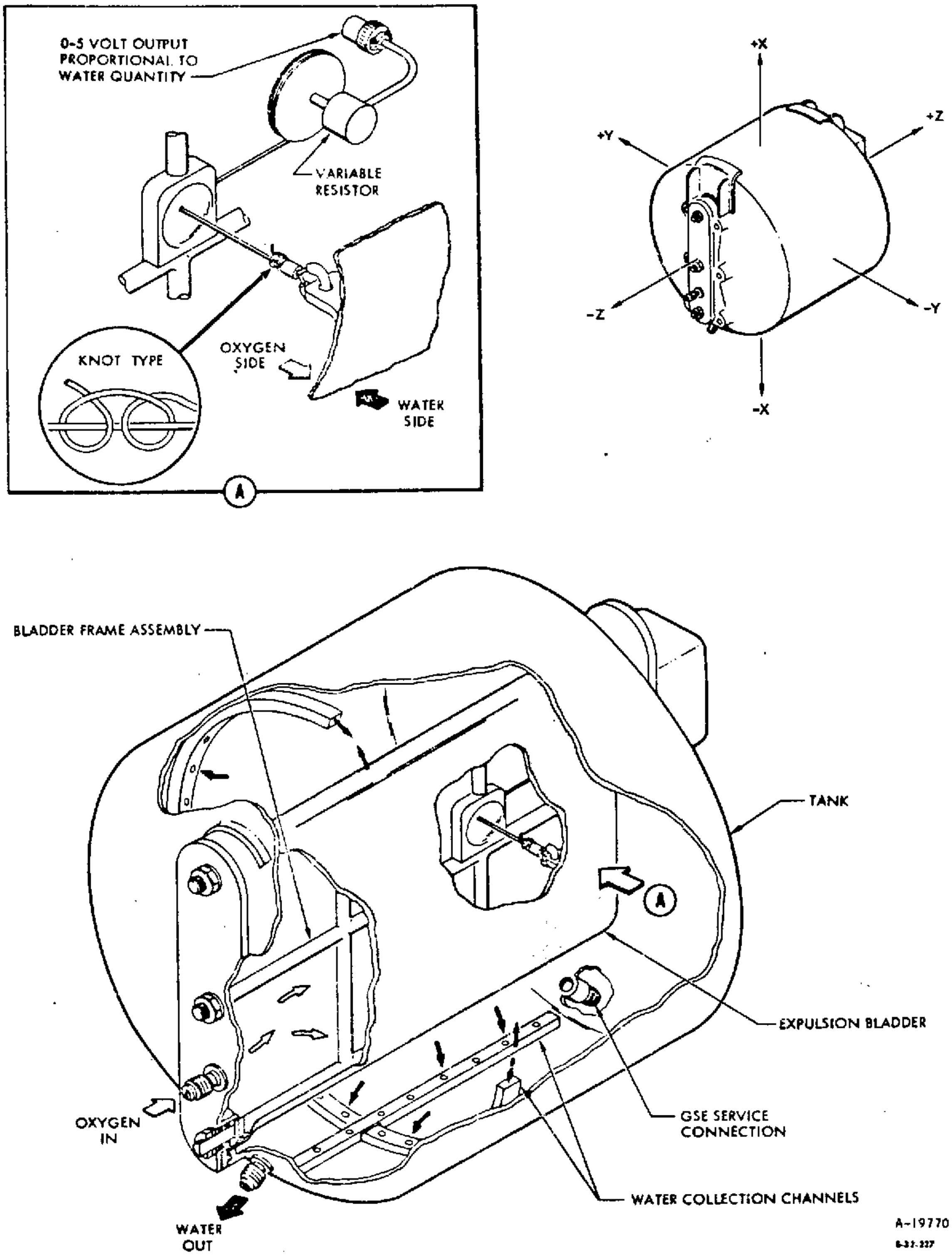



Figure 1. Apollo CSM Water Tank Gaging System

to Empty tank were determined for the gaging system in the zero gravity field. In the earth's gravity field, with the water tank oriented in six different (orthogonal) positions the gaging accuracy was only slightly reduced from that determined for the zero gravity case.

The equipment used in the experiment consisted of assemblies taken from GND's Nucleonic Oil Quantity Gaging System which is used to gage the oil quantity on thousands of military aircraft. GND is also currently supplying nucleonic gages of the same type for measuring the quantity of Hydrazine in bladdered tanks in a space satellite application.

This program established that the Apollo CSM Water Tank can be gaged with adequate accuracy using a nucleonic gaging system. We further believe that a more accurate gage could be developed for this application if required. The reliability of nucleonic gages has been established in both aircraft and space environments as is evidenced by their current use in both.

GND recommends, based upon the results of this program and results from previous and current production programs, that nucleonic gaging be given serious consideration as a viable alternative to the more conventional gaging methods when the conventional methods are difficult or impossible to implement. Nucleonic gaging systems are particularly applicable to Zero-g gaging requirements when the location of the liquid is randomly distributed within the tank. Another salient feature of nucleonic gaging is that it requires no modification of the tankage to install and, in fact, does not even require that the gaging system components be in physical contact with the tank being gaged.

## 3.0 INTRODUCTION

This report discusses the results of a program to investigate the use of a nucleonic gaging system to provide the liquid quantity measurement for the Apollo CSM waste water tank. The stated objective of the program was "to define a highly reliable, lightweight contents gaging system that accurately indicates the amount of water remaining during all flight attitudes and during Zero-g operation for space applications".

To this end, a nucleonic gaging system was designed using off-the-shelf hardware from existing nucleonic gaging systems and interfaced with the Apollo CSM tank. The design effort consisted primarily in optimizing the location of the gaging elements on the tank in order to provide the best gaging system accuracy. The tank was gaged using two basic configurations. Variations of the two basic configurations were tried in order to obtain the best results.

This report contains experimental data obtained from both of the gaging system configurations and discusses the data obtained in view of the system requirements. A brief discussion of the theory of nucleonic gaging preceeds the system description and data analysis.

## 4.0 Technical Discussion

In this section, a brief discussion of the theory and practice of nucleonic gaging and of the specific gaging system used to generate the data presented herein is provided. An analysis of the data and of the system error sources is also discussed.

## 4.1 Brief Theory of Nucleonic Gaging

Nucleonic gages utilize the property of matter that results in the attenuation (through absorbtion and scattering) of radiation flux incident to it. Gages have been designed using radiation particles, neutrons, and gamma rays. The gage classification is normally characterized by the type of radiation employed and by the specific interaction pheomenon used in the measurement. Thus, a beta backscatter gage; which could be used to measure the thickness of one material plated on a substrate; uses a radiation source of beta particles (electrons) and detects those electrons which are scattered back toward the source by the material under investigation. In gaging the total mass or liquid quantity contained within a vessel, as is required in the Apollo CSM Water Tank, a gamma ray attenuation gage is the applicable nucleonic technique.

Gamma ray attenuation gages employ a radioactive source of gamma rays positioned so that the material to be gaged is located between the source and the detection device. The radioactive source emits gamma rays which are radiated isotropically from the source. A certain percentage of these gamma rays are emitted in the direction of the gaging system detector and penitrate the material to be gaged and the walls of the container which holds the material and are detected in the detector.

In penetrating the container walls and the material to be gaged, the gamma rays experience an attenuation which follows the general relationship,

$$I/I_o = e^{-\mu d} \qquad \text{(eq. 1)}$$

where I/o is the fraction of the radiation flux photons remaining after passage thru a thickness of material (d) with an attenuation coefficient ($\mu$). The attenuation coefficient ($\mu$) is a function of the energy of incident gamma ray photons and of the atomic number of the material being measured. For a given radioactive isotope, the the energy of the gamma ray photons is constant; in the case of Krypton 85, (which was used in the Apollo CSM Water Tank Gage) the gamma energy is 514 Kev.

Equation 1 above is the expression applicable for narrow beams of radiation and geometries in which an approximate point source of radiation is used in conjunction with a collimated detector. It results in an exponential curve when detected gamma ray photons (counts per unit time) are plotted versus material quantity, or in this case, the liquid contained in the water tank. If the source is distributed and no detector collimation is employed, then not only the broad beam direct photons but also photons scattered by the tank and liquid contained within the tank are also counted when they are scattered toward the uncollimated detector. In the Apollo CSM water tank, we purposely use a distributed source and an uncollimated detector in order to maximize the detection of both the broad beam direct and the scattered photons. When the source is properly distributed, we can change the exponential plot of equation 1 into an approximately linear relationship of counts per unit time versus liquid quantity. The distribution of the source and the location of the detector on the tank in order to accomplish the linerization of gage output with liquid quantity is called "mapping".

Mapping is primarily an emperical process. We not only attempt to provide a linear gage output with liquid quantity but also to provide the same output irrespective of where the liquid is contained within the tank. This includes tank orientation in a gravity field, where the liquid will respond to the gravity vector, and also in a zero gravity situation where the liquid location within the tank would be determined by smaller forces such as surface tension, etc.

In certain applications, it may not be necessary to provide a linear output so long as the gage output remains constant for a given liquid quantity over the various tank attitudes and the random or zero gravity situation. In these applications, the gage output can be compared to a calibration curve and the quantity information extracted from the curve. This can be accomplished manually, by curve fitting electronics which can be made part of the gaging system, or by a simple computer "table look-up" data processing.

The output function for the Apollo CSM Water Tank is of the latter type, i.e. a non-linear output; however, as will be seen in the data presentation, the output is linear over a large portion of the curve.

## 4.2 Apollo CSM Water Tank Gaging System

The gaging system used to gage the quantity of water contained in the Apollo CSM Water Tank is comprised of three major component assemblies; radioactive source(s) radiation defector(s) and a processing electronics unit. Since the primary objective of the program was to establish the fesibility of nucleonic gaging for this application, the program emphisis was placed upon "mapping" of the radioactive source(s) and in collect-experimental data. As a result, existing detector assemblies and standard instrumentation electronics were used in the gaging system.

The detector assembly used was a Nucleonic Oil Quantity Indicating System (NOQIS) Geiger-Muller tube detector which GND currently manufactures by the thousands for the gaging of aircraft oil tanks. During this program, a single detector gaging system using a GND Part No. 1002-00-300 Detector Assy. (which is specified for the A7D Aircraft Oil Gaging System) was tested as well as a two detector system which used two GND Part No. 1007-00-300 Detector Assys. (which are specified for the F-107 Aircraft Oil Gaging System).

The instrumation electronics used in the testing consisted of a NOQIS Master Indicator (GND Part No. 1002-00-000) packaged into a test box to permit access to various test points, and a standard scaler/timer to measure the counts out of the radiation detector. The NOQIS indicator has a d'Arsonval meter linearly calibrated from Full to Empty; however, this meter was not used in the data taking since the system output of the CSM Water Tank gage has a non-linear output. All data presented is in counts per unit time for a given water quantity as measured on the scaler/timer. The instrumentation electronics only provided the detector high voltage (+700 VDC) and provided access to the detector output pulses for counting.

The radiation sources used all contain gaseous radioactive

Krypton 85 supplied in 0.25 inch O.D. aluminum tubes with a 0.049 inch wall thickness. The aluminum tubes, of various lengths, are filled with the radioactive gas at approximately one half atmosphere pressure.

Krupton 85 is one of the safest radioistopes available since it is an inert gas that does not chemically combine with any other element. Other features such as a 10.7 year half life, sufficient energy to provide penetration of the CSM water tank and its contents while presenting minimum personnel and storage hazards, and the ease in fabricating sources make Krypton 85 the obvious choice for this gaging application.

## 4.3 System Error Analysis

The error sources for the data obtained during this program can be somewhat restricted since we need not consider errors contributed by the environment, (specifically temperature extreemes) or by electronics calibration. These error sources are generally small at any rate, and being independent error sources, that is, they vary randomly with respect to each other, would have little effect on the overall system accuracy.

The total system error is derived from the root sum square (RSS) of the individual error sources:

$$\epsilon^2_{total} = \epsilon_1^2 + \epsilon_2^2 + \cdots \epsilon_N^2 \qquad \text{(eq. 2)}$$

The error sources identified for the system used in obtaining the data for the CSM Water Tank are as follows:

$\epsilon_{stat}$ which is the signal fluctuation error due to the statistical nature of radioactive decay. The one sigma

($\sigma$) fluction is determined entirely by the total number of counts accumulated and is found from the expression

$$\Delta CR = \sqrt{\frac{CR}{ZT}} \qquad \text{(eq. 3)}$$

where ($\Delta$CR) in the one $\sigma$ change in countrate with an experienced countrate of (CR) and ($\tau$) is the electronic system time constant. The system time constant used in the NOQIS is 15 seconds.

To eliminate the error contributed by counting statistics in the data obtained during this investigation, we accumulated count data for 100 seconds with the scaler timer and reintroduced the error based upon a 15 second time constant.

In the single detector system the countrate range was from 215 cps at Full to 668 cps at Empty. In the double detector system the countrate ranged from 488 cps at Full to 1158 cps at Empty. The statistical errors for these systems would be as follows, using equation 3 above:

Single Detector System:

Full $\Delta$CR = 2.68 = 1% System Error

Empty $\Delta$CR = 4.72 = 0.7% System Error

Double Detector System:

Full $\Delta$CR = 4.03 = 0.8% System Error

Empty $\Delta$CR = 6.21 = 0.5% System Error

$\epsilon_{Zero - g}$ This is the error due to the variations in water distribution within the tank for the Zero-gravity and gravity conditions.

In the Apollo CSM Water Tank, the water distribution within the tank is constrained by the pressurized bladder inside the tank. This would be the predominate force acting on the water in the Zero-g condition and as a result, the location of the water for any given fill level would be fairly constant. In the gravity condition, the water location within the tank would be a function of both the force and direction of the gravity field and of the force exerted by the bladder. In our esperimentation, we applied one "g" force in six different directions as described in the next section. Data was taken in each of the positions and then compared. The error that would be experienced in zero gravity would be certainly be no greater than the spread of the six position data and in fact should be much less. The ($\epsilon_{zero-g}$) is a function of water quantity; maximizing near half full and approaching zero at full and empty. The experimental data for the two detectors systems, using the six tank positions, resulted in worst case count rate variations of:

| FILL LEVEL | AVG. COUNTRATE | LOW $\Delta$CR | HIGH $\Delta$CR |
|---|---|---|---|
| Full | 487 | -6 | +4 |
| 73% Full | 540 | -6 | +14 |
| 45% Full | 755 | -24 | +30 |
| 18% Full | 1030 | -29 | +30 |
| Empty | 1158 | -6 | +10 |

Resulting in worst case system errors as follows:

| | |
|---|---|
| Full | -1% to + 0.8% error |
| 73% | -1% to + 2.5% error |
| 45% | -3.2% to + 3.9% error |
| 18% | -2.8% to + 2.9% error |
| Empty | -0.5% to + 0.8% error |

Although it is not a true source of error in the gaging system, the system sensitivity or resolution does impose restrictions on the ability of the gaging system to measure the quantity of water in the tank. The system sensitivity is a function of the water quantity and of the tank "mapping".

In the single detector system, the system has excellent sensitivity from Full (57.5 lbs.) to 20 pounds remaining, fair sensitivity from 20 lbs. to 10 lbs. remaining, and poor sensitivity from 10 lbs. remaining to empty. (See Figure 3 in the next section) In the double detector system, the sensitivity is fair from Full to 40 lbs. remaining and excellent from 40 lbs. remaining to Empty. (See Figure 9 in the next section).

To better understand the significance of the sensitivity problem, consider the following example:
On Figure 3 assume that the system countrate is 300 cps. The measured quantity is 49.7 lbs. of water at 300 cps taken from the figure. If we now experience a countrate change of 10 cps to 310 ps, the measured quantity would be 48.9 lbs.; less than a one lb. change. However, if we have a countrate of 650 cps (12 lbs. quantity) and have a 10 ps change to 660 cps we have quantity measurement of 7 lbs.; a 5 lb. change.

It should be apparent that the steeper the slope of the sensitivity curve, the better the system sensitivity. The double detector system provides much better sensitivity then the single detector system as can be seen by comparing the sensitivity curves (Figures 3 and g).

4.4 Data Analysis

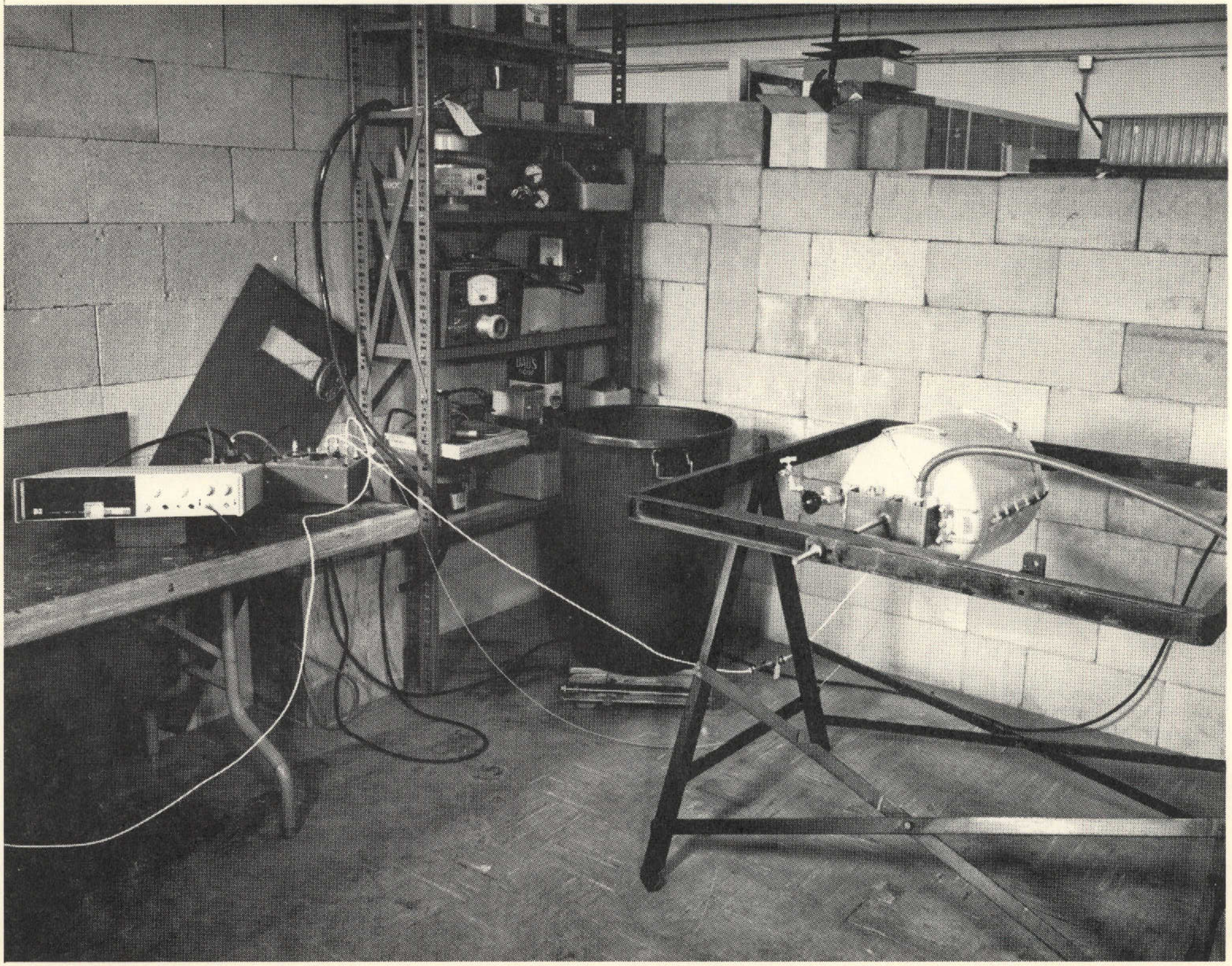
The equipment used during the development and evaluation of the nucleonic gaging system is shown on the Figure 2 photograph. The tank is shown mounted on the tumbling fixture with the bladder pressurant hose entering from the right in the photograph. The valves on the left-hand side of the tank are used in filling and emptying the tank. In operation, the tank is filled using city water pressure and then the bladder is pressurized using a constant 25 psi air supply. The tank is emptied thru the same tank port as is used in filling. A hose connected to the small upper valve shown on the photograph is routed to the waste can shown in the backround. The waste can is setting on a scale to permit determination of the weight of water drained from the tank at the tank fill levels measured.

The electronic instrumentation is shown on the table on the left side of the photograph.

The tumbling fixture permits the tank to be oriented in any position with respect to earths gravity. During the testing, we took countrate data in six positions for each of the tank fill levels.

The six positions employed were, (considering the tank as a cylinder) four positions rotated 90° about the axis of the cylinder with the axis horizontal and two positions rotated 180° about the axis with the axis vertical. The fill levels measured were full (approximately 57.5 lbs. of water) and incremental steps of 5 lbs. down from Full until we reached Empty.

After some initial measurements to determine the approximate location of the water in the tank at various fill levels and in various tank altitudes, we determined a



F-19856

FIGURE 2. TEST SET-UP

trial source and detector location (mapping) in order to gage the tank. The results of this first mapping are shown on the Figure 3 graph. The abscissa is the pounds of the water contained within the tank and the ordinate is the countrate measured for a given tank fill level. As can be seen on the graph, the gage output is linear from Full to 25 lbs. with good sensitivity. From 25 lbs. to Empty tank, the sensitivity drops off rapidly and the gage becomes non-linear. The mapping configuration used in obtaining this data is shown on Figure 4.

As can be seen on Figure 4., the gaging system uses a single detector and a single source shaped like the letter "Z" with the two ends bent to conform to the tank. The source was mapped in this manner since it was discovered that, as the water quantity reached approximately half, the water remaining in the tank was forced near the ends of the tank leaving the middle section with little of no water.

In order to improve the gage sensitivity from 25 lbs. to Empty, a second mapping using a single detector was configured. This mapping is shown on Figure 5.

As can be seen on the figure, we employed six (6) small mapping sources instead of a continuous source as was used in the first mapping. Each of the mapping sources has a source strength of 50 millicuries (mci), so the total strength used in the second mapping was 300 mci. This is slightly less source strength than was used in the first mapping which was 364 mci. The mapping sources are used to simplify the mapping procedure; once a source map has been completed, we generally design a single or in certain cases a double source from a continuous tube that approximates the location of the multiple mapping

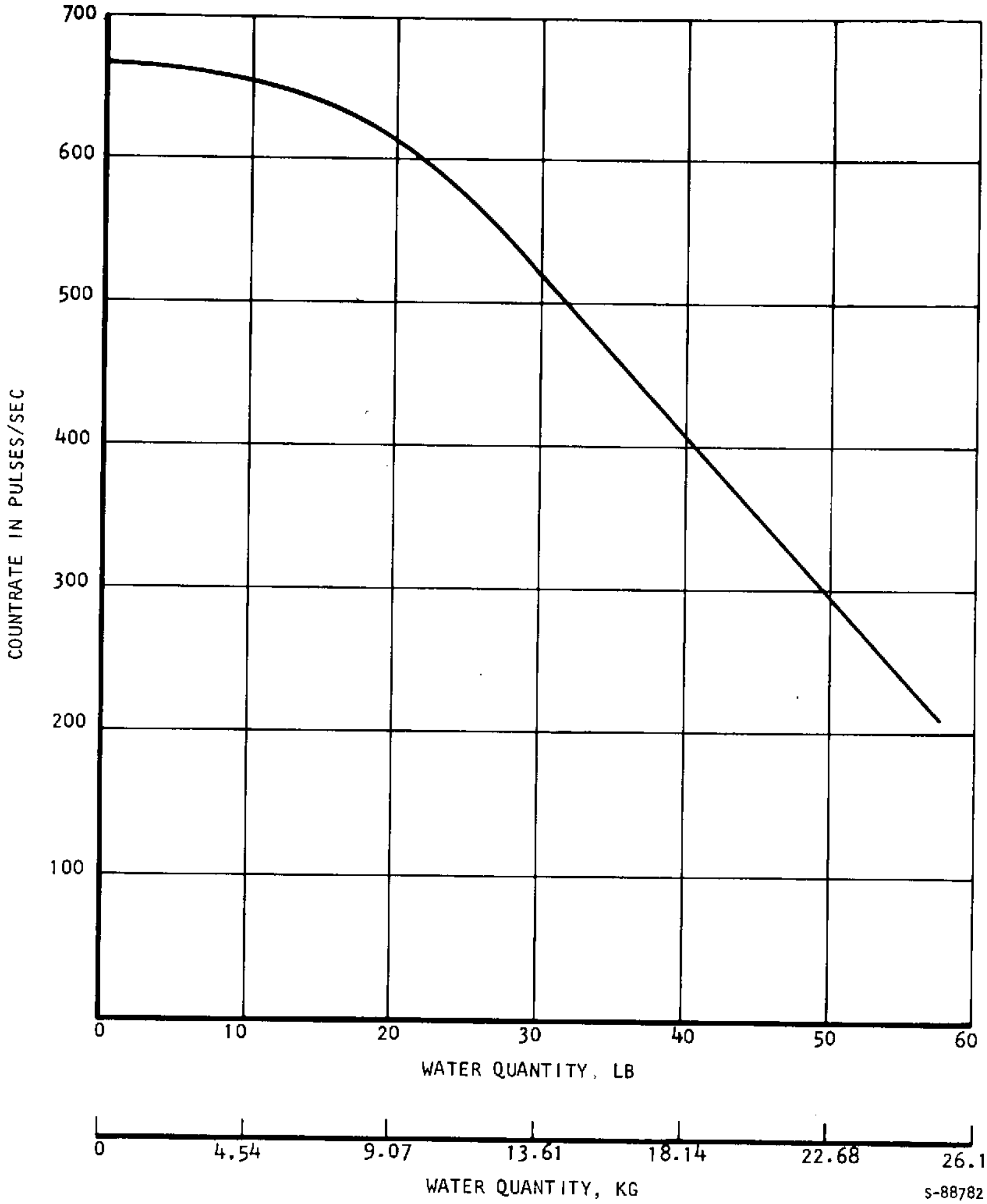
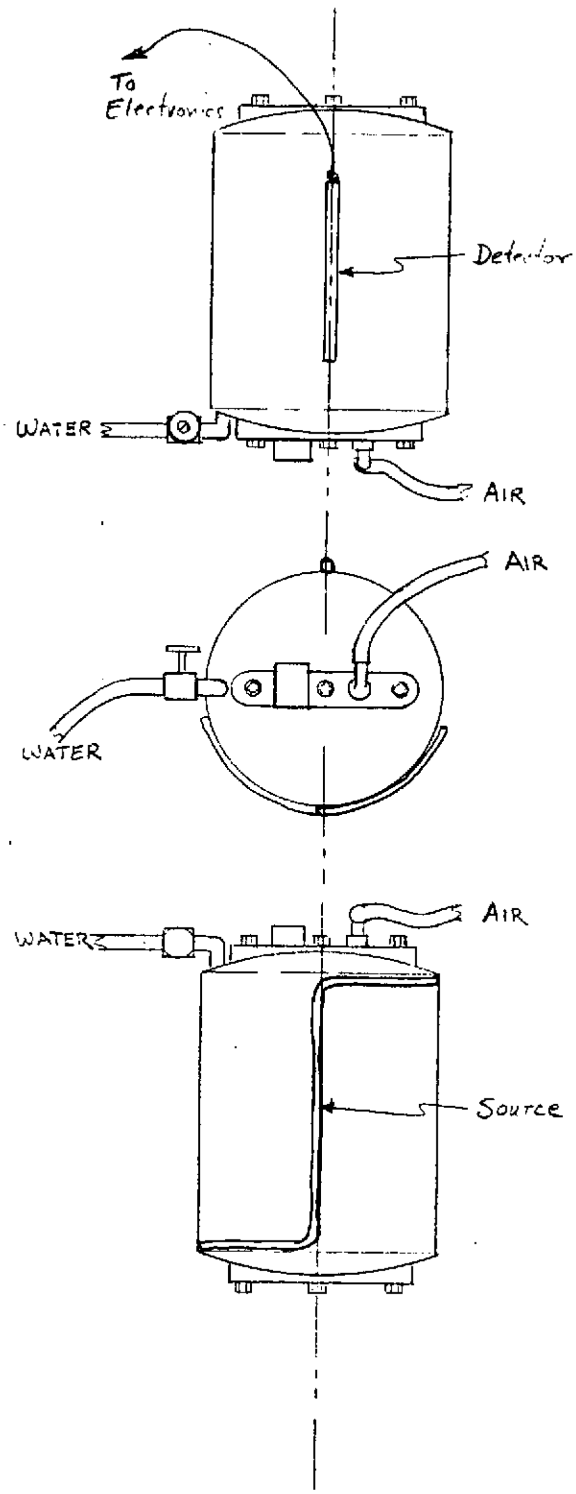



Figure 3. Apollo CSM Water Tank Nucleonic Gaging System Output vs Quantity (Initial Mapping)

FIGURE 4

APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
MAPPING NO. 1
DATE 11-6-73




DETECTOR:

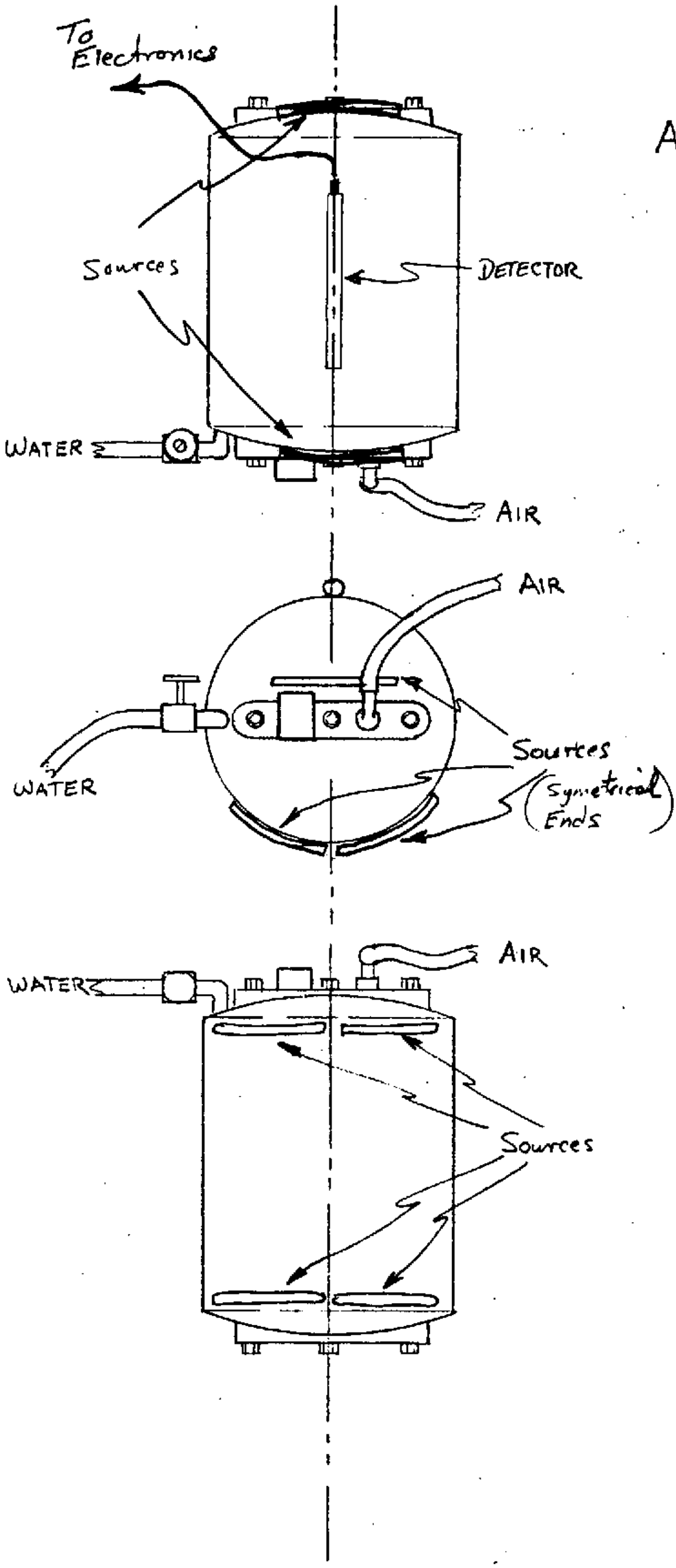
One F-106 Type GM tube. Installed on ℄ with active area symmetrical.

SOURCE:

1/4" Al x .049" wall, 29" long and shaped as shown. Source strength 364 mci.

FIGURE 5

APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
MAPPING NO. 2
DATE 12-17-73




DETECTOR:
One F-106 Type GM tube. Installed on ℄ with active area symetrical

SOURCE:
¼" x .049 wall Al.; 6" long mapping sources, source strength 50 mci each. Used 6 sources for total strength of 300 mci.

sources. Where source is not required in the continous tube, we flatten the tube in that area which reduces the gas volume and thereby the source in that area.

The gaging system output plotted against water quantity for this mapping is shown on the lower curve in Figure 6. The upper curve is the data taken from the first mapping, it is included for reference.

As can be seen from the figure, the slope near empty has been greatly improved over the original mapping. We did, however, lose slope (sensitivity) at the full end in order to improve the sensitivity at the empty end, as was predicicted. We could improve the curve for the second mapping somewhat by "fine tuning" the source locations, particularly to reduce the position errors in a gravity field (data not shown on figure). However, this is about as good a sensitivity curve as we can expect to get by using a single detector configuration.

The reduction in total counts (area under the curves) from the first mapping to the second is due primarily to the reduction in source strength from 364 to 300 mci, in the second map. By increasing the source strength in the mapping sources so that the total would equal the 364 mci we would restore the total counts to approximately the previous value.

The next attempt at mapping the tank involved the use of two detectors instead of the single detector used in the previous maps. In the two detector configuaration, the detectors are mapped on the tank with their outputs feeding a single set of electronics. The detector outputs are fed in parallel to the same rate integrator within the electronics and use a common high voltage power supply.

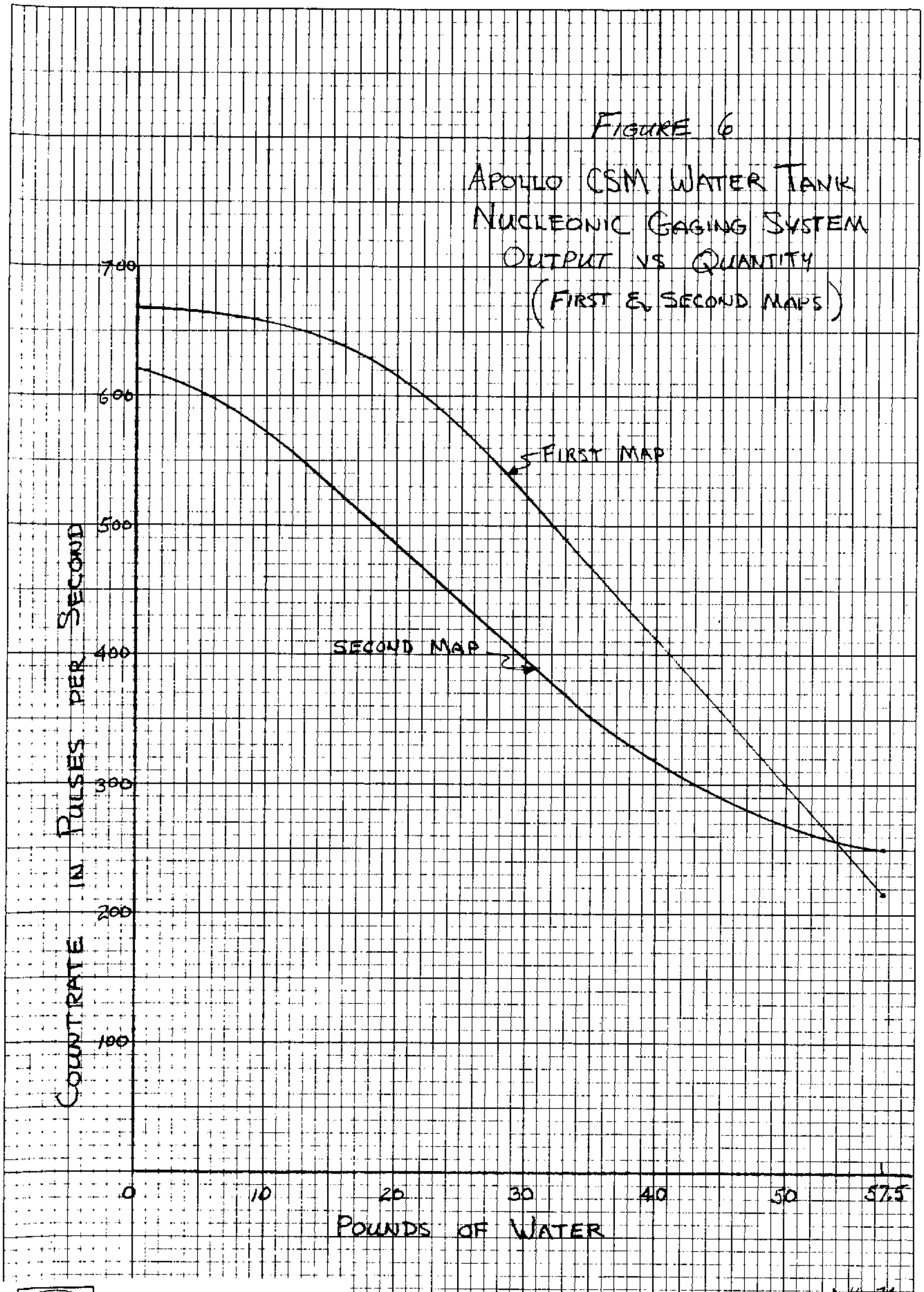


FIGURE 6
APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
OUTPUT VS QUANTITY
(FIRST & SECOND MAPS)
FIRST MAP
SECOND MAP
700
600
500
400
300
200
100
COUNTRATE IN PULSES PER SECOND
0
10
20
30
40
50
57.5
POUNDS OF WATER
1-10-74

Six different double detector maps were tried (Maps 3 thru 8). The difference between these six mappings was subtle to a large extent so only the data from Maps 4 and 8 is presented in this report.

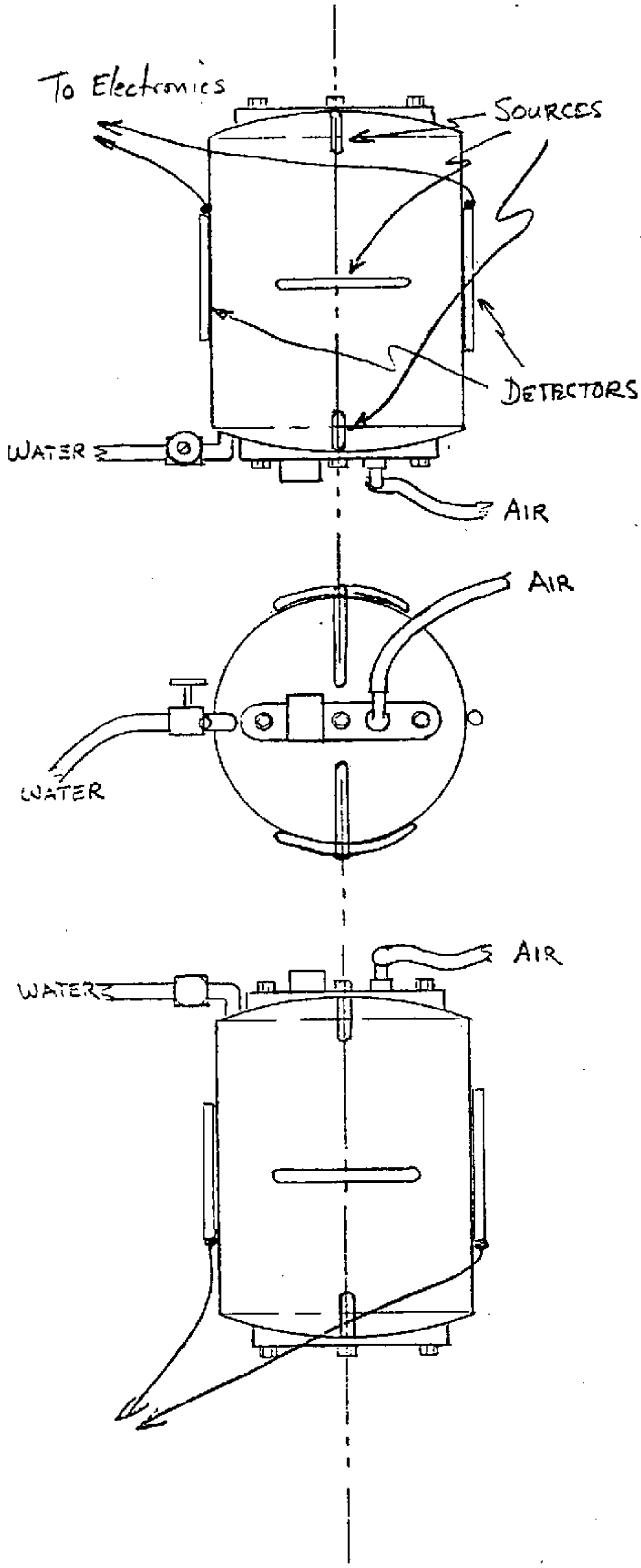
Mapping #4 is shown on Figure 7 and the data is shown on Figure 8.

Figure 8 shows the gage output versus quantity data and also the positional error limits experienced in a one "g" field for the six positions using Mapping #4. The positional error is greatest at 30 lbs. of water or approximately half full, diminishing to little or no error at full and at empty tank. The largest spread in count rate occurs between the tank axis horizontal and tank axis vertical positions. This one- "g" positional error could be reduced by refining the map, however, there seems little reason to do so from a practical viewpoint since the tank fill levels normally experienced in the "G" field would normally not be half tank. Additionally, because of the bladder action in the tank, "g" forces less than one- "g" would proportionally reduce the positional error experienced.

Mapping #4 resulted in good sensitivity from 40 lbs. to Empty but poor sensitivity near Full.

In reviewing the data from earlier mappings, it was discovered that the F-106 type detector with a 6 inch active length provided better gaging resolution near full tank than did the shorter (3 inch active length) A7D type detector which was used on Mapping #4. As a result, we changed to the F-106 type for the next four maps in an attempt to improve this full end resolution. The data

FIGURE 7




APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
MAPPING NO. 4

DATE 2-5-74

DETECTOR :
2 ea. A7D Type GM Tubes, Installed on ℄ with active area symetrical.

SOURCE :
1/4" X .049 wall Al. ; 6" long mapping sources, 50 mci each. 6 sources used, shaped to tank contours. Total source strength 300 mci.

NOTE: Mapping similar to mapping #3. Center source rotated 90° from #3 Map.

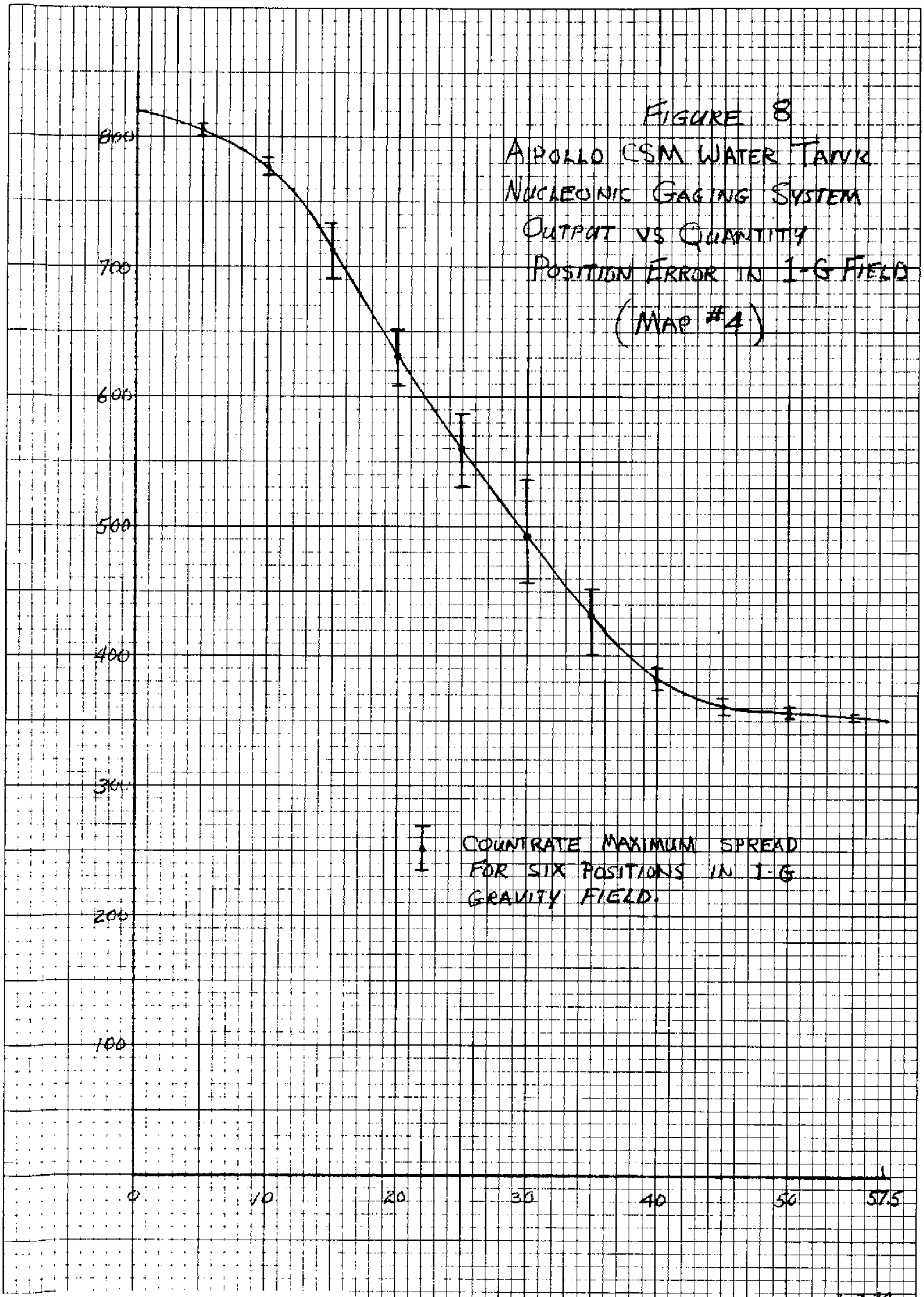


FIGURE 8
APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
OUTPUT VS QUANTITY
POSITION ERROR IN 1-G FIELD
(MAP #4)
COUNTRATE MAXIMUM SPREAD
FOR SIX POSITIONS IN 1-G
GRAVITY FIELD.
800
700
600
500
400
300
200
100
0
10
20
30
40
50
57.5
1-7-74

shown on Figure 9 is the result of the eighth mapping which is shown on Figure 10 and on the photograph Figure 11.

The Figure 9 data shows an improvement in resolution at the full end and an even more dramatic improvement at the empty end. As can be seen on the graph, the countrates are much higher than in the previous maps; we have, however, kept the same scale so that all the data in this report may be compared on a one-to-one basis. The error bars shown are a result of the positional error in a one "g" field and are the maximum excursions seen during the testing for Mapping #8. A tabulation of these errors was presented in Section 4.3 of this report.

The increased countrate in this mapping results from the use of twice as much detector area as was used in the previous two detector mapping which employed the shorter detectors. Note should also be taken of the reduction in source strength from Mapping #4 (300 mci) to Mapping #8 (240 mci). This source strength should really be halved to approximately 120 mci for best test results, however, we did not have any sources on hand with this source strength. The advantage of using a lower system source strength is twofold; first, it reduces the system dead time which can be as much as 10% at 1000 cps and drops to approximately 1% at 100 cps. This dead time results from the duration of a detected gamma ray output pulse from the detector which is approximately 100 microseconds in duration. During this time, the detector does not respond to additional gamma rays and is therefore "dead" to them. The more pulses experienced, the longer the intregrated "dead" time. The overall effect on the gaging system is to introduce an increasing loss in system

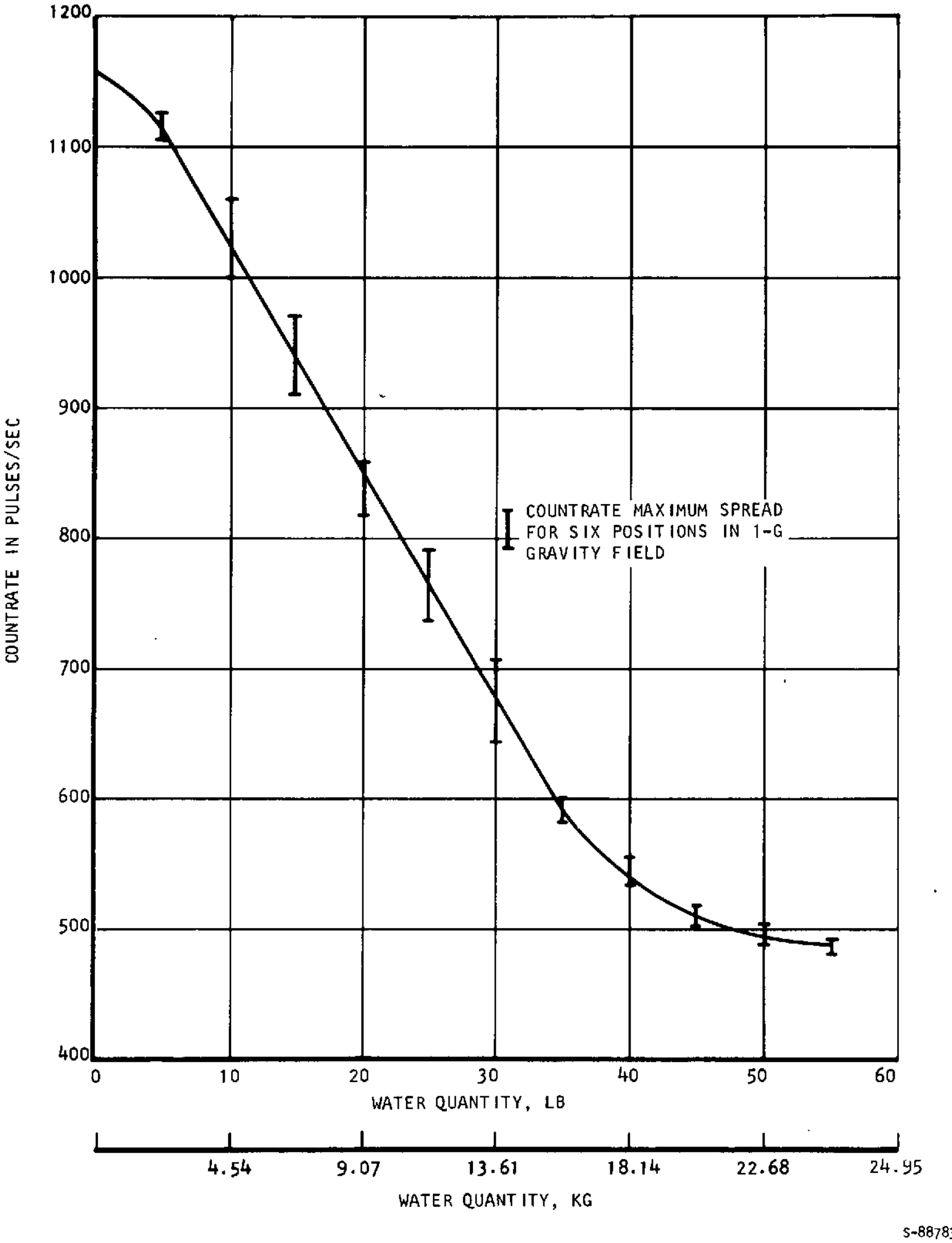
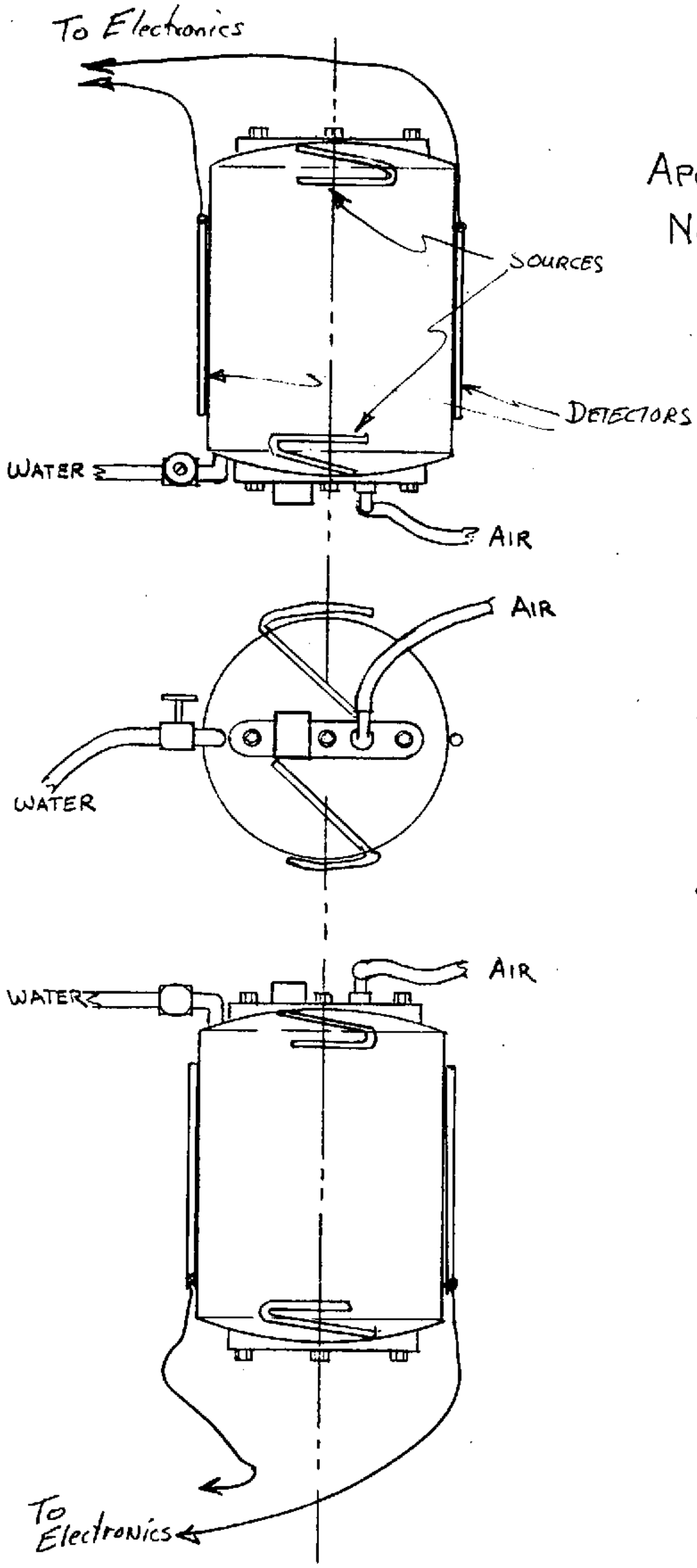



Figure 9. Apollo CSM Water Tank Gage Quantity vs Countrate (Eighth Mapping)

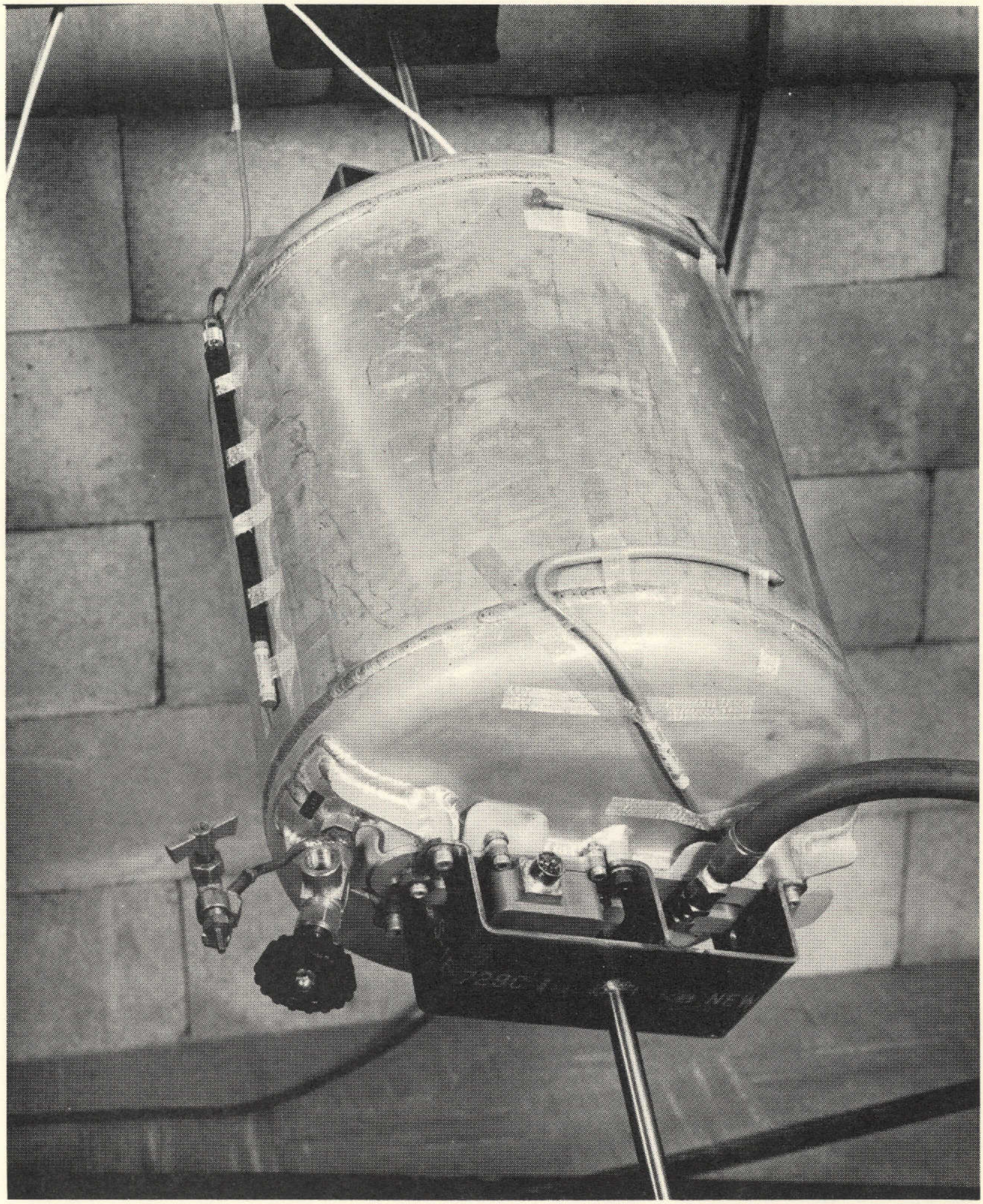
FIGURE 10




APOLLO CSM WATER TANK
NUCLEONIC GAGING SYSTEM
MAPPING NO. 8
DATE 3-4-74

DETECTOR : 2 ea. F-106 Type
SN's 740 & 349

SOURCE : 4 ea., 60 mci
13½" Long shaped as shown.
Total source strength 240 mci.



F-19857

FIGURE 11. APOLLO CSM WATER TANK EIGHTH MAP

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resolution as the countrate increases (which is near the empty end). Part of the tail-off in the countrate near empty, shown on Figure 9, is the result of the increasing dead time at these countrates. If the source strength were halved, we would approximately halve the countrate and reduce the dead time to less than 5% instead of over 10% as in the present situation.

The second advantage in reducing source strength is to reduce the radiation exposure to personnel working near the gage. Although, in the case if thus particular gage, there is very little radiation exposure even at the 300 mci level, it's always good practice to reduce the source strength as much as possible without sacrificing system performance.

Mapping #8 should be adequate for the intended gaging requirement. It still lacks real good resolution near the full end, but it has an almost linear response from Empty to 35 lbs. The sensitivity is excellent from Empty to 35 lbs. and adequate from 35 lbs. to Full tank.

If we take the data from Mapping #8 and add the worst case system errors, the gaging system error profile, for representitive points is as follows:

| Fill Level | Countrate | Estat | $\epsilon_{zero - g}$ | Gaging Accuracy |
|---|---|---|---|---|
| Full | 487 | 0.8% | ±0.9% | ±1.2% |
| 73% | 540 | 0.7% | ±1.8 | ±1.9% |
| 45% | 755 | 0.7% | ±3.6 | ±3.7% |
| 18% | 1030 | 0.6% | +2.9 | ±3.0% |
| Empty | 1158 | 0.5% | ±0.7 | ±0.9% |

These accuracy numbers represent the worst case Zero-g errors as determined by the six positions in an earth gravity field and should be considerably reduced in the zero gravity field as previously discussed. The errors also do not include the effect in the loss of system sensitivity. If we take the statistical error changes at the fill levels indicated to determine the effect on system sensitivity and take realistic zero-g errors (±1%) the error profile would be as follows:

| Fill Level | Countrate | ΔDR (Stat) | Sensitivity | Gaging Accuracy* |
|---|---|---|---|---|
| Full | 487 | 4 | ±5% | ±5% |
| 73% | 540 | 4 | ±1% | ±1.6% |
| 45% | 755 | 5 | ±0.5% | ±1.3% |
| 18% | 1030 | 6 | ±0.5% | ±1.3% |
| Empty | 1158 | 6 | ±1.% | ±1.3% |

The error envelope would seem to be adequate for the gaging requirement under investigation. The error experienced near full may be somewhat excessive and could be improved with additional refinement in the mapping. However, the additional effort involved to refine the mapping did not seem warrented for this program.

* All errors are combined by RSS (See Equation 2 Section 4.3).