NASA CONTRACTOR REPORT

NASA CR - 54085

NASA CR - 54085

FACILITY FORM 602

N65-11004 (ACCESSION NUMBER)
43 (PAGES)
CR 54085 (NASA CR OR TMX OR AD NUMBER)
(THRU)
1 (CODE)
02-14 (CATEGORY)

LIQUID HYDROGEN FILM COOLED PRESSURE TRANSDUCERS

By J. Delmonte

Prepared under Contract No. NAS3-2754 by
ELECTRO-OPTICAL SYSTEMS, INC.
Pasadena, California

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1964

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CONTRACTOR REPORT

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Prepared under Contract NAS3-2754
Electro-Optical Systems, Inc.
300 North Halstead Street
Pasadena, California

December 1964

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Mr. James W. Norris

Lewis Research Center Cleveland, Ohio
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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11004

SUMMARY

The first generation construction and test of three cryogenic-cooled combustion pressure transducers capable of transducing steady state as well as high frequency pressure pulses have been successfully accomplished. These are embodied in Electro-Optical Systems pressure transducers PT15C-2, Serial Nos. 2, 3, and 4, as outlined in Print B 500160-2 Revision 3 of subject contract. Figure 1 is a photograph of the finished transducer.

Optimization of electrical output, leading to improved performance specifications, and reassessment of installation details, reflecting in increased handling strength and field reliability, will result in accurate, rugged, and reliable instrumentation capable of surviving combined environment extremes, with increased output.

The efficiency of film cooling the PT15C-2 transducer with liquid hydrogen is yet to be proven under combustion pressure and temperature conditions. Static tests performed to date indicate that bridge-type solid state pressure transducers are capable of creditable performance to at least LH_2 temperatures with controllable output (sensitivity) and zero shift. Size adaptability, low weight, good output strength, and electrical simplicity are salient features of this type of pressure instrumentation.

1. INTRODUCTION

This document constitutes the final report on NAS3-2754 contract. It covers the specific span of time from March 15, 1964 through the week ending April 25, 1964, as well as documents and summarizes the results of the entire contract work. It includes recommendations and conclusions based upon the experience and results obtained.

To Messrs. S. Kaye of the Semiconductor Department and Wm. McLellan of the Mechanical Engineering Department is due much appreciation for the expediency in developing the highly-doped four-active arm silicon strain gage configuration and tests thereon, within their respective laboratories at Electro-Optical Systems, Inc. Mr. J. Frassrand of the Electro-Optical Systems, Inc. transducer laboratory exhibited unusual skill in fabrication and assembly techniques.

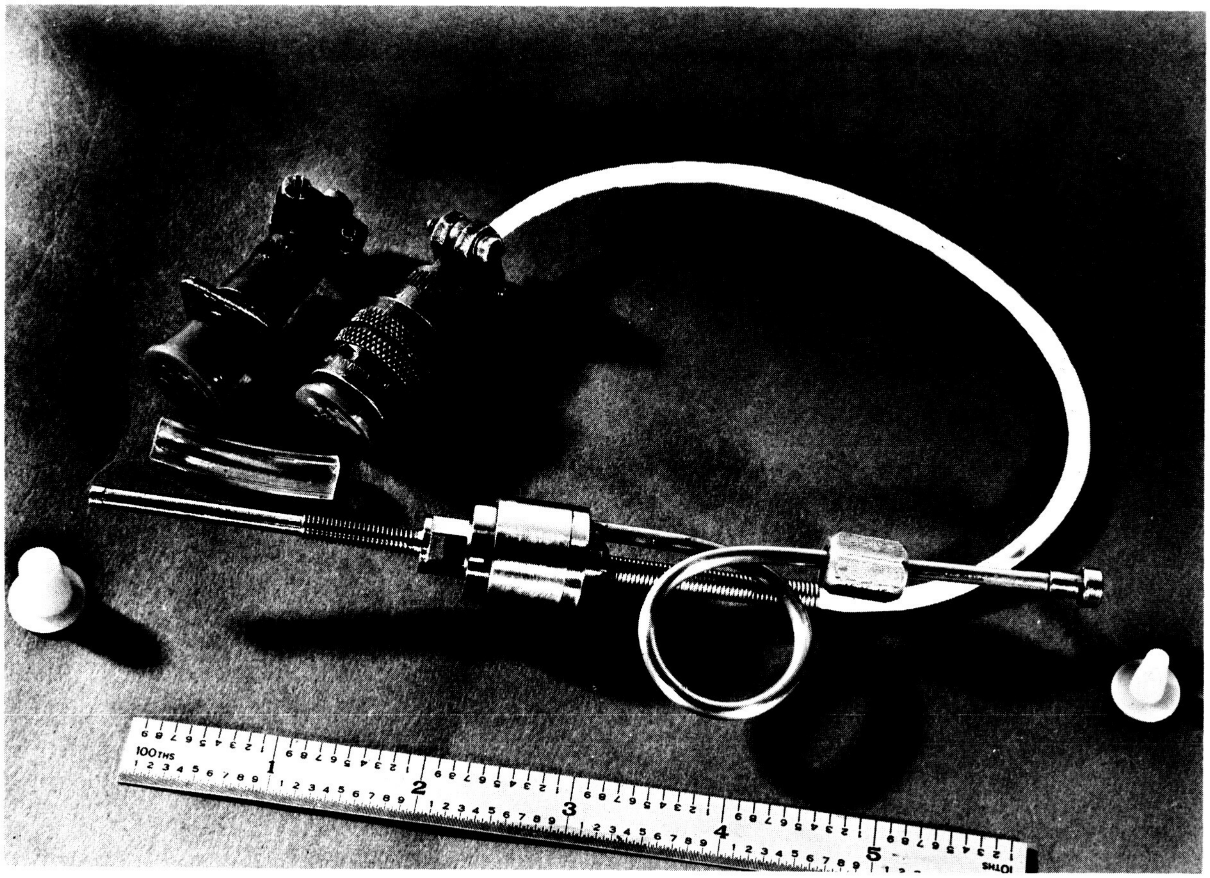

FIG. 1 PT15C-2 PRESSURE TRANSDUCER

2. TECHNICAL DISCUSSION

2.1 Prototype program for 300^{o}K to 20^{o}K operational pressure transducer capable of being cooled by liquid hydrogen.

Phase I: From basic technologies previously pursued at Electro-Optical Systems and its subsidiary, Micro Systems, Inc., the diffused four-active element solid state piezoresistive gage beam had been successfully proven and transducer* tested.

However, to span the temperatures required of this project an exhaustive literature search had to be instituted by the Semiconductor Department under Mr. S. Kaye, and many intensive trail and error tests accomplished within a relatively short time to produce acceptable silicon strain gage elements with the proper mechanical configuration, electrical resistance, temperature coefficient of resistance, and gage factor. Handling characteristics for contacting an ultimate bonding had to be reduced to the level of the skill of average assembly technicians.

A best compromise condition, resulted in relatively high P dopant level diffusion into the bulk silicon, a lowered gage factor of about 50, at room temperature, and a relatively low temperature coefficient of resistance for the four individual resistances. Mr. Kaye has prepared a section on fabrication of single chip beams in silicon, having four active strain gage arms. See Appendix II in which four significant references are cited.

Final chip configuration is illustrated in Fig. 2; an actual photograph of the four-active element gage is to be seen in Fig. 3.

Phase II: Testing the silicon element from the transducer viewpoint of end use:

This involved the mechanical, thermal, and electrical integration of the silicon chip with a suitable pressure summing device. The latter, an integrally machined clamped diaphragm, was already defined, size-wise, not to exceed 0.115 inch diameter, because of previous constraints imposed by the available entry geometry to the rocket combustion chamber.

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*Electro-Optical Systems Patent application pending.

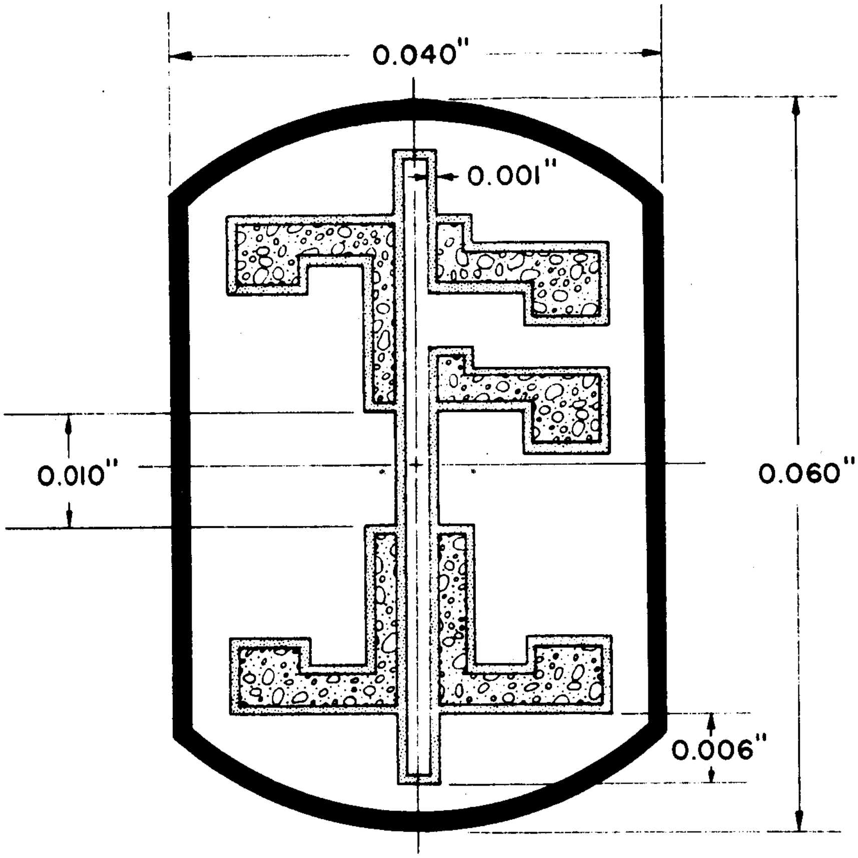

FIG. 2 LAYOUT OF DIFFUSED FOUR-ACTIVE ARM SILICON STRAIN GAGE BEAM CHIP

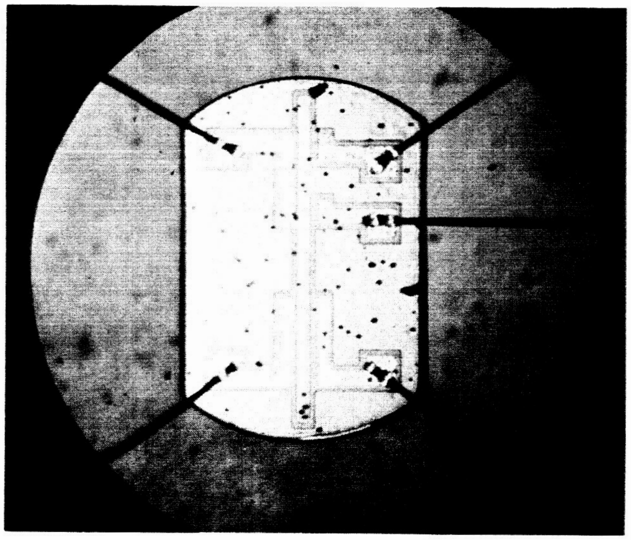

FIG. 3 SILICON CHIP WITH FULL BRIDGE
DIFFUSED INTO SURFACE.
SIZE 0.040 IN. X 0.060 IN.

Integrity of the silicon chip was assured by shock testing to LH_2 and intermediate temperatures, repeatedly, and recording the changes in its four resistances, in the unbonded and bonded condition. This was accomplished both at EOS's transducer laboratory and at the Norco facility of Wyle Laboratories. Typical data accumulated from these tests is shown in Table 1 of Appendix III.

Figure 4 shows the 304 SS test setup.

Figure 5 depicts the chip mounted on Invar constant stress beam.

Knowing that the silicon element responds either more or less linearly with its original "clamping" stress (a function of the adhesive used, the cure temperature, and the difference in thermal contraction between silicon and the diaphragm metal), we decided to bracket thermal expansion coefficient of the silicon chip by mounting it on a 300 series stainless steel diaphragm and comparing the results with that of an Invar steel diaphragm.

The following set of conditions was investigated:

Silicon chip bonded to 304 SS: flat bar; diaphragm
Silicon chip bonded to Invar: constant stress beam; diaphragm
Silicon chip bonded to NiSpan C: diaphragm

Tests were conducted at LO_2 - LN_2, CO_2 and LH_2 temperatures, repeatedly. Typical data is tabulated in Tables 2 and 3, Appendix III.

That the silicon chip geometry did not require altering and its electrical characteristics and performance with a variety of metals behaved according to prediction attests to the fundamental integrity of the semiconductor element, the contacting and bonding methods employed. (TCB-aluminum contacting leads were used to join to the silicon element in all the above tests.)

Phase III was the actual buildup of a small group of complete pressure transducers, testing and electrically compensating for operation between LH_2 and room temperature.

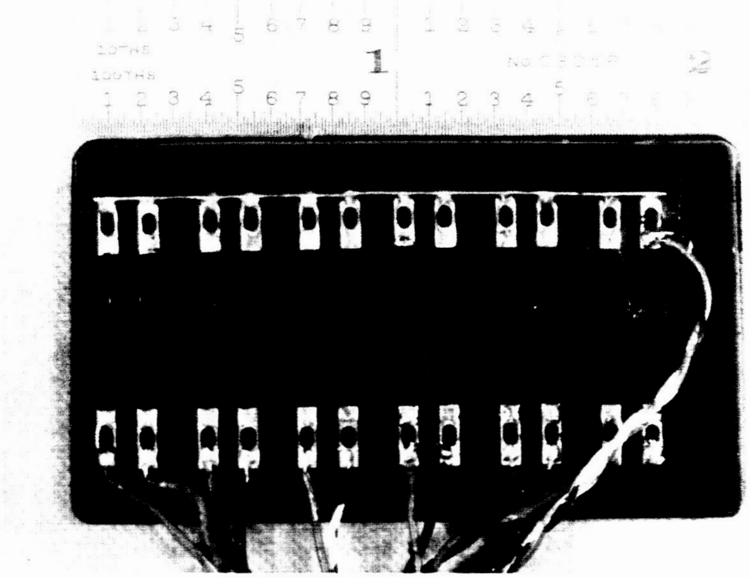

FIG. 4 FOUR-ACTIVE ARM SILICON CHIPS ON 304 SS, SOME SILICON CHIPS BONDED, SOME SUSPENDED OFF THE METAL BAR

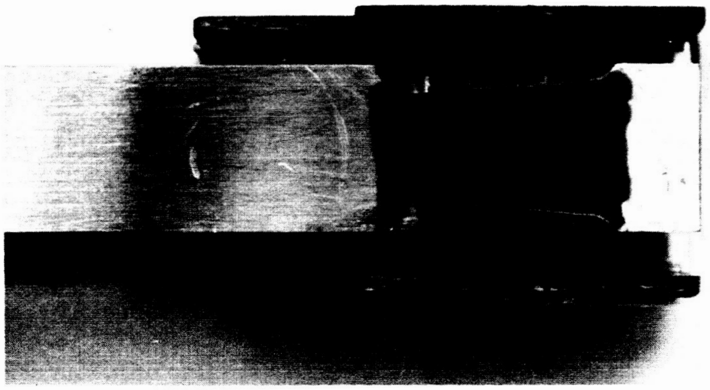

FIG. 5 MULTIPLE ELEMENT SILICON CHIP MOUNTED ON INVAR CONSTANT STRESS BEAM

Figure 6, Drawing D-427021, shows the top assembly construction of the EOS PT15C-2 combustion pressure transducer.* Installation and calibration information is included in Figs. 7, 8, and 9. Actual calibration test details for Serial Nos. 2, 3, and 4 are included in Appendix III, Table 4. Appendix IV tabulates a complete parts list.

2.2 Work accomplished between March 15 and April 25:

The buildup and final calibration runs of four transducers were partially accomplished during this period. Three of the four survived intact calibration through liquid nitrogen temperatures at EOS. They were PT15C-2 Serial Nos. 2, 3, and 4.

For field calibration runs to LH_2, we elected to partially pot the compensation network with a coating of RTV silastic resin to protect the final cable interconnect wires, balance, zero shift, and sensitivity compensating resistors, from humidity changes and vibration fatigue effects. However, upon testing the units at LH_2 for the first time at the Norco facility of Wyle Laboratory, all these units developed minor difficulties which were not correctable in the field.

Unit No. 2: bridge intact; compensation network open

Unit No. 3: bridge intact; compensation network intact; gold seal leak

Unit No. 4: bridge intact; compensation network open

Upon returning to EOS, all three were made operational and checked again at LN_2. All closely repeated their original drift, sensitivity, and linearity characteristics from RT to LN_2, and return to room temperature. This time no potting was used to protect the compensation network other than brush coating with a heat-cured furane thermoset adhesive. Placement of the fixed bridge compensation resistors so that they would be protected against gross shock mishandling was emphasized.

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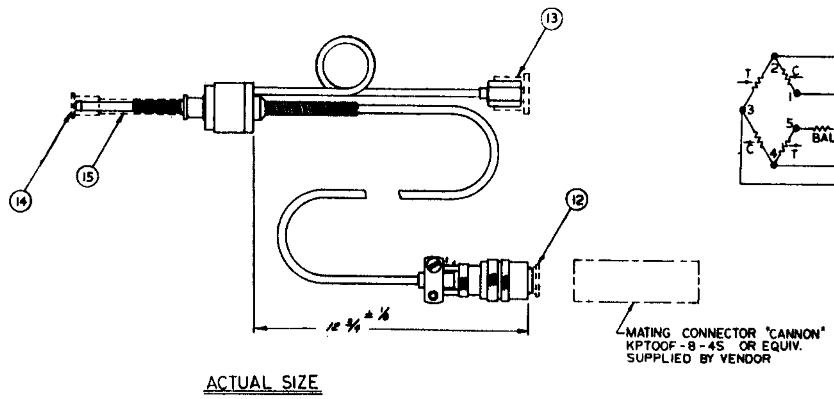
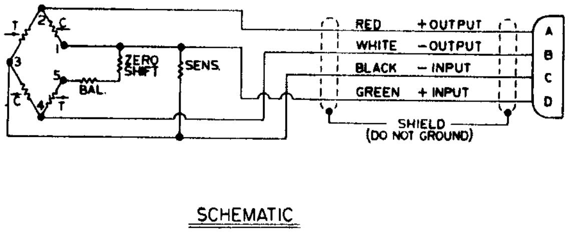
* Note that the original 0.170-inch front diameter was further reduced to 0.150 inch. This change would aid in the installation entry machining problems by presenting a transducer dimension less than the minor diameter of the threaded 10-32 boss (0.156 inch) and still reduce the area of direct heat impingement in the combustion zone.

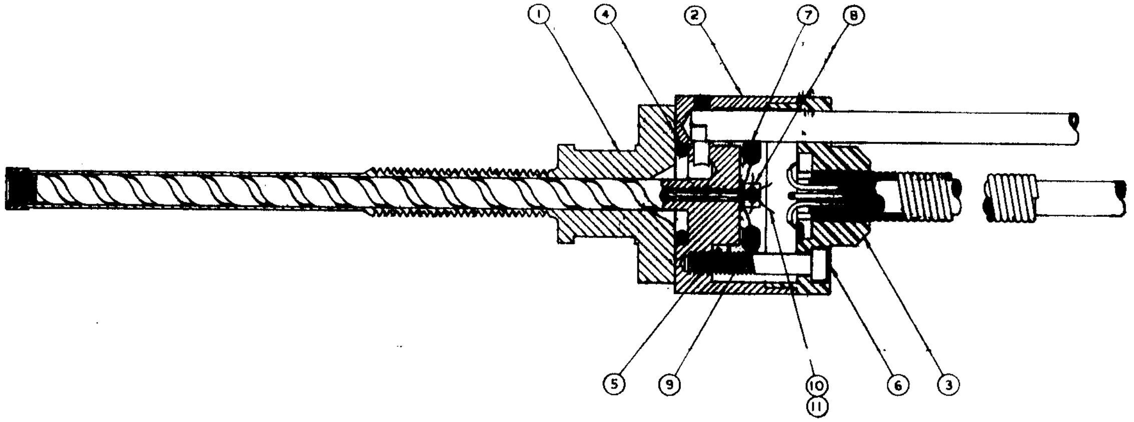


ACTUAL SIZE

MATING CONNECTOR "CANNON" KPTOOF-8-4S OR EQUIV. SUPPLIED BY VENDOR



SCHEMATIC



AR	15		SLEEVING			
1	14		DUST CAP			
1	13		DUST CAP			
1	12		DUST CAP			
AR	11		SOLDER		Sn 95% Ag 5%	

427021

AR	10		WIRE	.010 DIA	COPPER	
1	9		RESISTOR			
1	8		RESISTOR			
1	7		RESISTOR			
3	6		SCR-MACH-HEX HD.	2-56 X 1/2	SST	
4	5		SCR-MACH-HEX HD.	2-56 X 1/4	SST	
1	4		O-RING		METAL	
1	3		CABLE ASSY.			
1	2		INST. HOUSING ASSY.			
1	1		BLAST TUBE ASSY.			
REQ'D	ITEM	PART NO.	DESCRIPTION	SIZE	MATERIAL	SPECIFICATION

LIST OF MATERIALS

NONE		WA 4270	
NEXT ASSY	QTY	UNIT	QTY
ORIGINAL APPLICATION			

UNLESS OTHERWISE NOTED:
1. LINEAR DIMENSIONS IN INCHES.
2. TOLERANCES:
DECIMAL ± [illegible] FRACTIONS ± 1/16 ANGULAR ± 1/2°

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APPROVED
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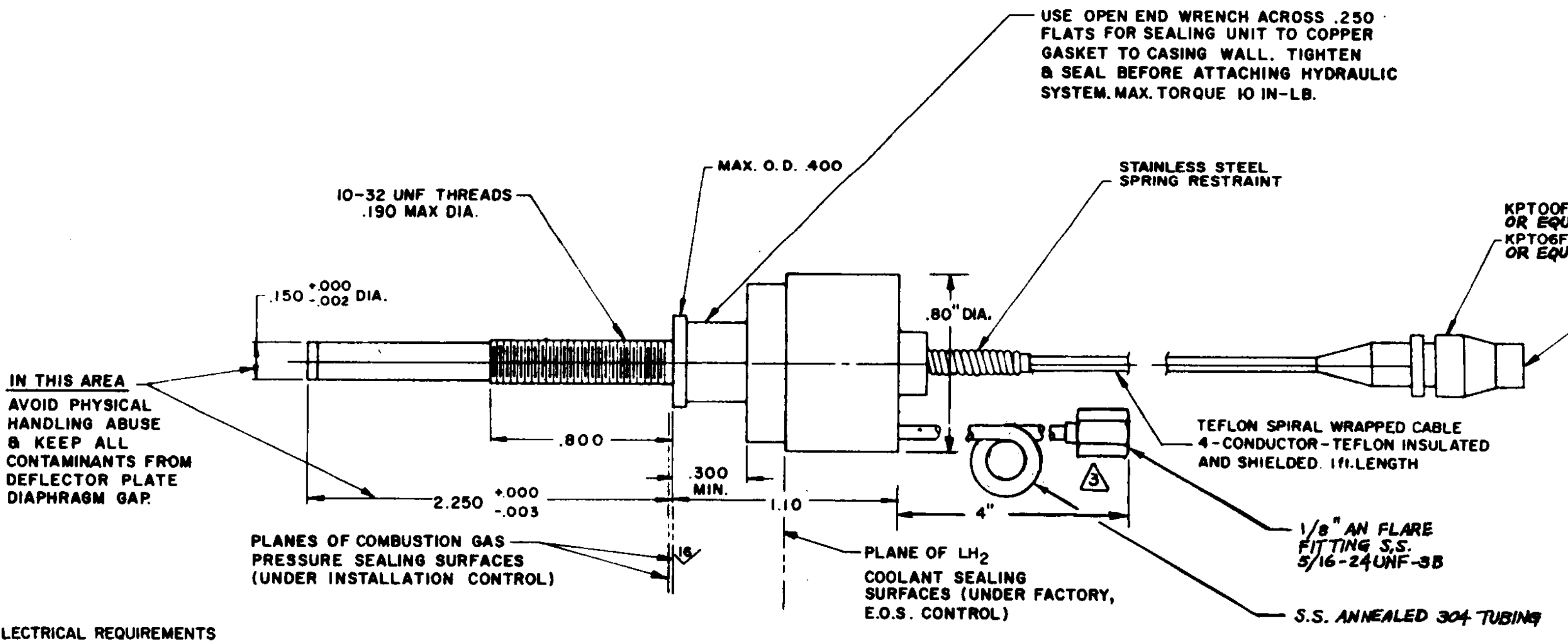
ACT. WT.
CALC. WT.

ELECTRO-OPTICAL SYSTEMS, INC.,
Pasadena, California • MUrray 1-4671, SYcamore 5-9981

TITLE:
PRESSURE TRANSDUCER
MODEL PT15C-2

SECURITY CLASSIFICATION
SIZE D
NUMBER 427021
REV.
CODE IDENT NO. 12705
SCALE 4 X 1
SHEET 1 OF 1

FIG. 6 TOP ASSEMBLY - PRESSURE TRANSDUCER MODEL PT15C-2



A ELECTRICAL REQUIREMENTS

PIN A (+) OUTPUT
B (−) OUTPUT
C (−) INPUT
D (+) INPUT

C SPECIFICATIONS

AT 10 MA-I=K TO THE BRIDGE
BRIDGE RESISTANCE INPUT 420 Ω
OUTPUT 540 Ω
" " TO CASE >100 MEGOHMS AT 30 VDC MAX.
AT 1500 PSIG FULL SCALE
F.S. SENSITIVITY = 825 MVDC
ZERO BALANCE = +24 MVDC
L-H & R
BEST FIT STRAIGHT LINE = < 1 % F.S.
ZERO DRIFT TO LH_2(-420°F) = -7.0 MVDC; -1.585 %FS/100°F = ΔZ
F.S. SENSITIVITY AT LH_2 = 76.6 MVDC; -2.17 " " = ΔS
ZERO DRIFT TO LN_2(-320°F) = -14 MVDC; -4.28 " " = ΔZ
F.S. SENSITIVITY AT LN_2 = 82.2 MVDC; -.092 " " = ΔS
UNIT TESTED TO 2000 PSIG - NO BRIDGE BALANCE SHIFT
UNIT CLEAN, DRY, POTTED, TUBE OPENINGS SEALED AND MATING CONNECTOR ENCLOSED

B CRYOGENIC COOLANT REQUIREMENTS

1. LOCATE A 400 MESH STRAINER ON 1/8" DIA. S.S. COOLANT TUBING
2. PROPERLY SUPPORT [1.] ABOVE AGAINST VIBRATION & SHOCK FORCES
3. PROVIDE AT THE STRAINER TO THE TRANSDUCER:
   1 GPM (NOM.) AT 1000 PSIG
   OR
   1/2 GPM (NOM.) AT 400 PSIG
4. COOLANT SYSTEM PRESSURE SHOULD ALWAYS BE HIGHER THAN COMBUSTION PRESSURE BY A MINIMUM OF 200 PSI
5. COOLANT FLOW MUST BE MAINTAINED AFTER RUN UNTIL AMBIENT CASING TEMPERATURE REDUCES TO 150°F (NOM) FOR OPTIMUM REPEATIBILITY. A CASING TEMPERATURE REACHING 380°F AFTER A RUN COULD RESULT IN PERMANENT DAMAGE TO THE TRANSDUCER UNDER CONDITIONS OF ZERO COOLANT FLOW.
6. COOLANT SUPPLY TEMPERATURE SHOULD BE CONSTANT DURING ANY ONE RUN.

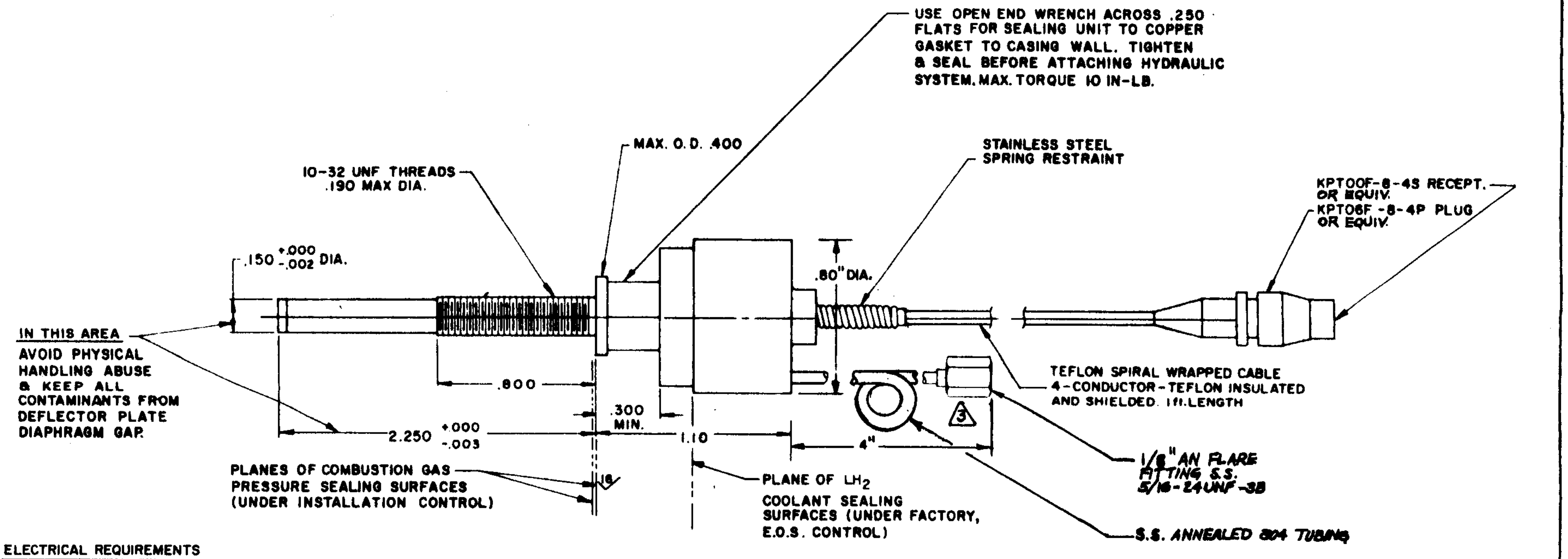
ELECTRO-OPTICAL SYSTEMS, INC.

TITLE
CALIBRATION AND
DIMENSIONAL OUTLINE MODEL PT 15C-2 COMBUSTION PRESSURE TRANSDUCER FOR CRYOGENIC SERVICE
SERIAL #2

SECURITY CLASSIFICATION	SIZE	NUMBER	REV
24 APR. 1964		500160-2	3

CODE IDENT NO	DWN BY:	SCALE	SHEET
4270	J.D.	2:1	SHEET 1 OF 1

FIG. 7 INSTALLATION AND CALIBRATION - SER. NO. 2, PT15C-2



A ELECTRICAL REQUIREMENTS

PIN A (+) OUTPUT
B (–) OUTPUT
C (–) INPUT
D (+) INPUT

C SPECIFICATIONS

AT 10 MA-I•K TO THE BRIDGE
BRIDGE RESISTANCE INPUT 435 Ω
OUTPUT 560 Ω
" " TO CASE >100 MEGOHMS AT 30 VDC MAX.
AT 1500 PSIG FULL SCALE
F.S. SENSITIVITY =694 MVDC
ZERO BALANCE =+25 MVDC
L-H & R
BEST FIT STRAIGHT LINE = < 1 % F.S.
ZERO DRIFT TO LH_2(-420°F)=-17.6 MVDC; -4.77 %FS/100°F = ΔZ
F.S. SENSITIVITY AT LH_2 = 64.3 MVDC; -2.62 " " = ΔS
ZERO DRIFT TO LN_2(-320°F)=-11.9 MVDC; -4.34 " " = ΔZ
F.S. SENSITIVITY AT LN_2 = 73.2 MVDC; +1.385 " " = ΔS
UNIT TESTED TO 2000 PSIG - NO BRIDGE BALANCE SHIFT
UNIT CLEAN, DRY, POTTED, TUBE OPENINGS SEALED AND MATING CONNECTOR ENCLOSED

B CRYOGENIC COOLANT REQUIREMENTS

1. LOCATE A 400 MESH STRAINER ON 1/8" DIA. S.S. COOLANT TUBING
2. PROPERLY SUPPORT [1] ABOVE AGAINST VIBRATION & SHOCK FORCES
3. PROVIDE AT THE STRAINER TO THE TRANSDUCER:
   1 GPM (NOM.) AT 1000 PSIG
   OR
   1/2 GPM (NOM.) AT 400 PSIG
4. COOLANT SYSTEM PRESSURE SHOULD ALWAYS BE HIGHER THAN COMBUSTION PRESSURE BY A MINIMUM OF 200 PSI
5. COOLANT FLOW MUST BE MAINTAINED AFTER RUN UNTIL AMBIENT CASING TEMPERATURE REDUCES TO 150°F (NOM) FOR OPTIMUM REPEATIBILITY. A CASING TEMPERATURE REACHING 380°F AFTER A RUN COULD RESULT IN PERMANENT DAMAGE TO THE TRANSDUCER UNDER CONDITIONS OF ZERO COOLANT FLOW.
6. COOLANT SUPPLY TEMPERATURE SHOULD BE CONSTANT DURING ANY ONE RUN.

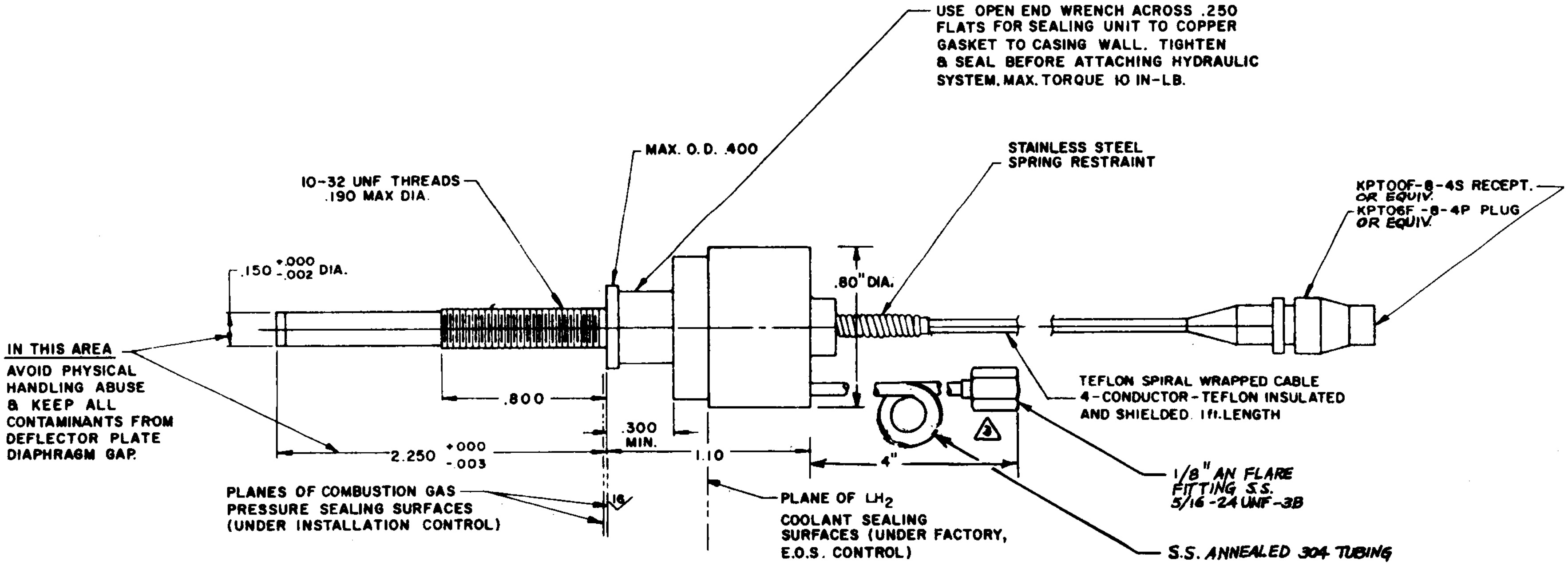
ELECTRO-OPTICAL SYSTEMS, INC.

TITLE
CALIBRATION AND
DIMENSIONAL OUTLINE MODEL PT 15C-2 COMBUSTION
PRESSURE TRANSDUCER FOR CRYOGENIC SERVICE
SERIAL #3

SECURITY CLASSIFICATION	SIZE	NUMBER	REV
24 APR. 1964		500160-2	3

CODE IDENT NO	DWN BY:	SCALE	SHEET 1 OF 1
4270	J.D.	2:1	

FIG. 8 INSTALLATION AND CALIBRATION - SER. NO. 3, PT15C-2



A ELECTRICAL REQUIREMENTS

PIN A (+) OUTPUT
B (–) OUTPUT
C (–) INPUT
D (+) INPUT

C SPECIFICATIONS

AT 12 MA-I=K TO THE BRIDGE
BRIDGE RESISTANCE INPUT 365 Ω
OUTPUT 570 Ω
" " TO CASE >100 MEGOHMS AT 30 VDC MAX.
AT 1500 PSIG FULL SCALE
F.S. SENSITIVITY = 70.4 MVDC
ZERO BALANCE = +1/6 MVDC
L-H & R
BEST FIT STRAIGHT LINE = < 1 % F.S.
ZERO DRIFT TO LH_2(-420°F)= +6.3 MVDC; +4.63 %FS/100°F = ΔZ
F.S. SENSITIVITY AT LH_2 = 64.1 MVDC; -1.82 " " = ΔS
ZERO DRIFT TO LN_2(-320°F)= +11.5 MVDC; -4.13 " " = ΔZ
F.S. SENSITIVITY AT LN_2 = 65.5 MVDC; -1.76 " " = ΔS
UINT TESTED TO 2000 PSIG - NO BRIDGE BALANCE SHIFT
UNIT CLEAN, DRY, POTTED, TUBE OPENINGS SEALED AND MATING CONNECTOR ENCLOSED

B CRYOGENIC COOLANT REQUIREMENTS

1. LOCATE A 400 MESH STRAINER ON 1/8" DIA. S.S. COOLANT TUBING
2. PROPERLY SUPPORT [1.] ABOVE AGAINST VIBRATION & SHOCK FORCES
3. PROVIDE AT THE STRAINER TO THE TRANSDUCER:
   1 GPM (NOM.) AT 1000 PSIG
   OR
   1/2 GPM (NOM.) AT 400 PSIG
4. COOLANT SYSTEM PRESSURE SHOULD ALWAYS BE HIGHER THAN COMBUSTION PRESSURE BY A MINIMUM OF 200 PSI
5. COOLANT FLOW MUST BE MAINTAINED AFTER RUN UNTIL AMBIENT CASING TEMPERATURE REDUCES TO 150°F (NOM) FOR OPTIMUM REPEATIBILITY. A CASING TEMPERATURE REACHING 380°F AFTER A RUN COULD RESULT IN PERMANENT DAMAGE TO THE TRANSDUCER UNDER CONDITIONS OF ZERO COOLANT FLOW.
6. COOLANT SUPPLY TEMPERATURE SHOULD BE CONSTANT DURING ANY ONE RUN.

ELECTRO-OPTICAL SYSTEMS, INC.

TITLE
CALIBRATION AND
DIMENSIONAL OUTLINE MODEL PT 15C-2 COMBUSTION
PRESSURE TRANSDUCER FOR CRYOGENIC SERVICE
SERIAL #4

SECURITY CLASSIFICATION	SIZE	NUMBER	REV
24 APR. 1964		500160-2	3

CODE IDENT NO	DWN BY:	SCALE	SHEET 1 OF 1
4270	J.D.	2:1	

FIG. 9 INSTALLATION AND CALIBRATION - SER. NO. 4, PT15C-2

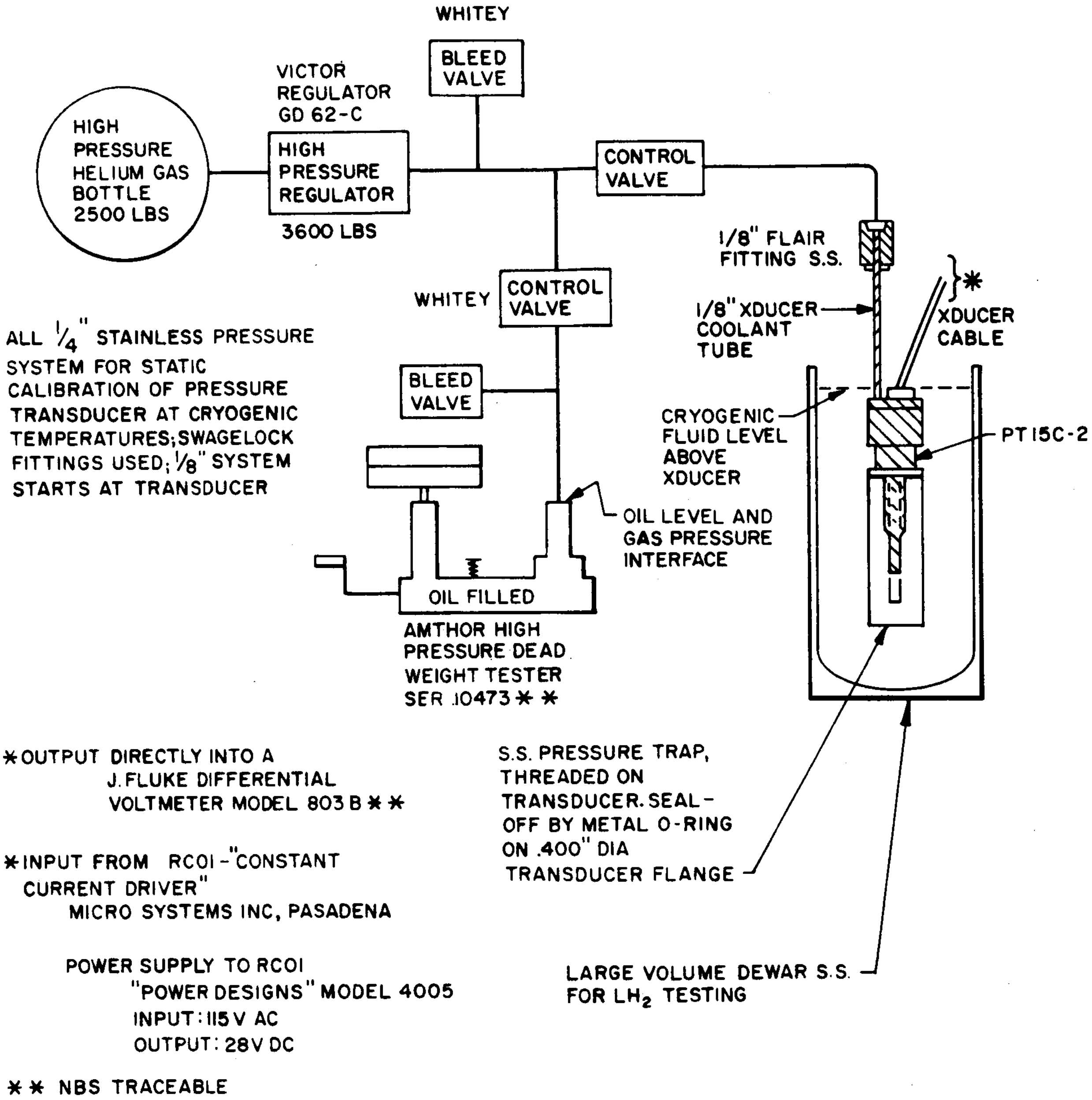
On the second series of tests at Norco on April 22, all three units were successfully calibrated at LH_2 temperatures without mishap. High pressure helium gas was the pressurizing medium and was simultaneously introduced into the dead weight testing lines and into the LH_2 submerged transducer coolant tube, then through the transducer into a fixed stainless steel trapped volume which was threaded on the 10-32 threads, and pressure sealed against the 0.400-inch diameter flange area (see Fig. 10).

Final checkout at EOS disclosed no internal moisture condensation problem and complete return to normal room temperature calibration condition. All three transducers were thoroughly cleaned, vacuum dried, open tube endings capped and made ready for shipment to the contractor.

2.3 Review of Statement of Work:

In the design, fabrication and test of three cryogenic film cooled pressure transducers, the following statements are made in a numerical sequence to coincide with the specific Work Statement, item for item:

1. The only construction materials in contact with liquid hydrogen are stainless steels (300 series), nickel steel (NiSpanC), copper, and copper brazing alloys.
2. Sensing element is the piezoresistive type strain gage constructed upon high purity elemental silicon.
3. All the transducers will withstand pressure to 2,000 psig without recalibration and without causing permanent change in transducer characteristics.
4. Active working diameter of the flush-mounted transducers is 65 mils exposed to the rocket chamber environment.
5. Mounting: as described in B-500160 drawing (Fig. 6)
6. Pressure range: 0 to 1500 psig.
7. Frequency response: flat from dc to 10 kc; undamped natural frequency by calculation is > 100 kc.



APPARATUS AND PRESSURE SYSTEM USED AT E.O.S. TRANSDUCER LABORATORY AND AT WYLE LAB. (NORCO) FACILITY

FIG. 10 LABORATORY AND FIELD TEST APPARATUS AND PRESSURE SYSTEM

8. Combined accuracy: L-H and R = < 1 percent F.S. (at steady state temperature condition).

9. Full scale output: > 60 mvdc, unamplified.

10. Excitation voltage: < 10 vdc
Constant current: < 15 Ma
Bridge impedance: < 1000 ohms
See individual calibration sheet, Figs. 7, 8, and 9 and Table 4, Appendix III.

11. Liquid H_2 has heat of vaporization = 194.22 Btu/lb, at one atmosphere pressure; and

12. By forcing liquid H_2 through the unit at greater than combustion pressures and at a rate of 1 to 2 gallons a minute, the four-active arm silicon sensor should survive and not heat up under large heat fluxes. Liquid coolant must be passed through the transducer at least 30 to 60 seconds before combustion is initiated to stabilize the active bridge and fixed compensating network. Coolant must continue to flow after combustion cutoff until motor casing cools below 300°F.

13. Bridge zero-drift and bridge sensitivity drift have been examined at LN_2 and LH_2. Whereas it is possible to achieve ± 1 percent full scale per 100°F at one cryogenic temperature (LH_2); it seems more practical to open this specification slightly until testing at LH_2 becomes more commonplace. See individual calibration sheets, Figs. 7, 8, and 9, and further remarks under Section D, Recommendations.

In summation, three pressure transducers have been designed, built, and tested for operation at LH_2 conditions to a specific entry-mounting geometry and have successfully fulfilled all the basic requirements of the contract Work Statement.

3. RECOMMENDATIONS

3.1 Mechanical Features of EOS' PT15C-2 Design

3.1.1 Although it can be demonstrated that a geometry employing 10-32 threads in the mounting area is not unreasonable to achieve, it is more realistic to admit that it is also too easy to damage these threads by inadvertent overtorquing. The LH_2 cooled combustion pressure seal must be metal, and the natural tendency is to overtighten. We recommend that where possible a motor chamber internal threaded boss of 7/16-20 size be used and threaded to a controlled depth, thence to a small through bore into the combustion chamber. This would have the result of distinct improvement in field handling and reliability of the transducer installation.

3.1.2 The internal cryogenic coolant seal and the external combustion gas seal areas should be upgraded to handle high pressure and thermal shock loading beyond the present scope of the contract. Present design is capable of withstanding cryogenic thermal shock and full scale static test pressures. Combustion thermal conditions, as they would affect the mounting boss area, have not yet been considered. Multiple chevron (metal, teflon, metal) or K-seals are recommended for testing. Special sizes are required.

3.1.3 Diaphragm burnout conditions should be considered, and escape of combustion gases should be restricted. Multiple internal pressure baffling and possible threaded cable cap construction should be reviewed.

3.2 Four-active-element Silicon Chip Beam

3.2.1 Change in electrical resistance of the individual elements of the silicon chip beam with from zero to full scale distributed pressure on the diaphragm indicates that the compression gages (position 2 and 4) (see Table 2, Appendix III) are contributing only a small amount in the way of output. It should be possible, without overdriving the diaphragm, to redesign the silicon chip to increase the full scale output to at least 100 mv. Increased output would: (1) decrease the L-H and R error band and (2) decrease thermal effects (sensitivity change and zero drift). Also further geometrical changes in the gage layout should be investigated to enhance the output and reduce the normal bridge electrical imbalance.

3.3 Thermal Environment: Transient and Steady State

3.3.1 By submerging the transducer completely in cryogenic fluid to a depth beyond the cable cap (see Fig. 6), thermal equilibrium is quickly achieved, both in the diaphragm area as well as in the electrical bridge compensation area. If both areas are not at identical temperatures nor achieve it simultaneously, transient thermal output could be large and the electrical compensation for thermal effects either slow to stabilize or never quite achieved. To achieve fast stability, submersion technique was employed. In terms of field (or flight) tests, this latter procedure is probably unrealistic. Relocation of the passive compensation elements to the liquid cooled region of the transducer is desirable.

3.3.2 To achieve a realistic thermal environment error band of ΔS and ΔZ for the PT15C-2, testing over the entire cryogenic temperature range is believed necessary. Tests were conducted at LN_2 and LH_2; however, ambiguities in the results (see calibration sheets) indicate a need for further investigation in this area. The problem here is probably related to the passive compensating components used in the three subject transducers. Further component testing should correct this situation.

4. CONCLUSION

Modification to Electro-Optical Systems' novel combustion pressure transducer*, commerically available in two sizes, the PT15C-3 for a minimal access geometry problem, and PT15B-2 (Figs. 11, 12, and 13) for insertion in an AND 10050-4 boss geometry, such that it could be cooled by LH_2, has resulted in a useful first generation device.

The results prove the feasibility of the use of a solid state silicon four-active-arm piezoresistive element, arranged as a Wheatstone bridge, over a large temperature span, $20^{\circ}K$ to $> 300^{\circ}K$, with good output for direct recording and within a transducer geometry utilizing the sensor's inherent small size, fast thermal response, and linear characteristics. These transducers, identified as model PT15C-2, can provide the electromechanical means for measuring static (0 to 1500 psig) and dynamic (flat dc to 10 kc) pressures under combustion environment, flush within a liquid rocket cryogenic-cooled motor.

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*Patent pending

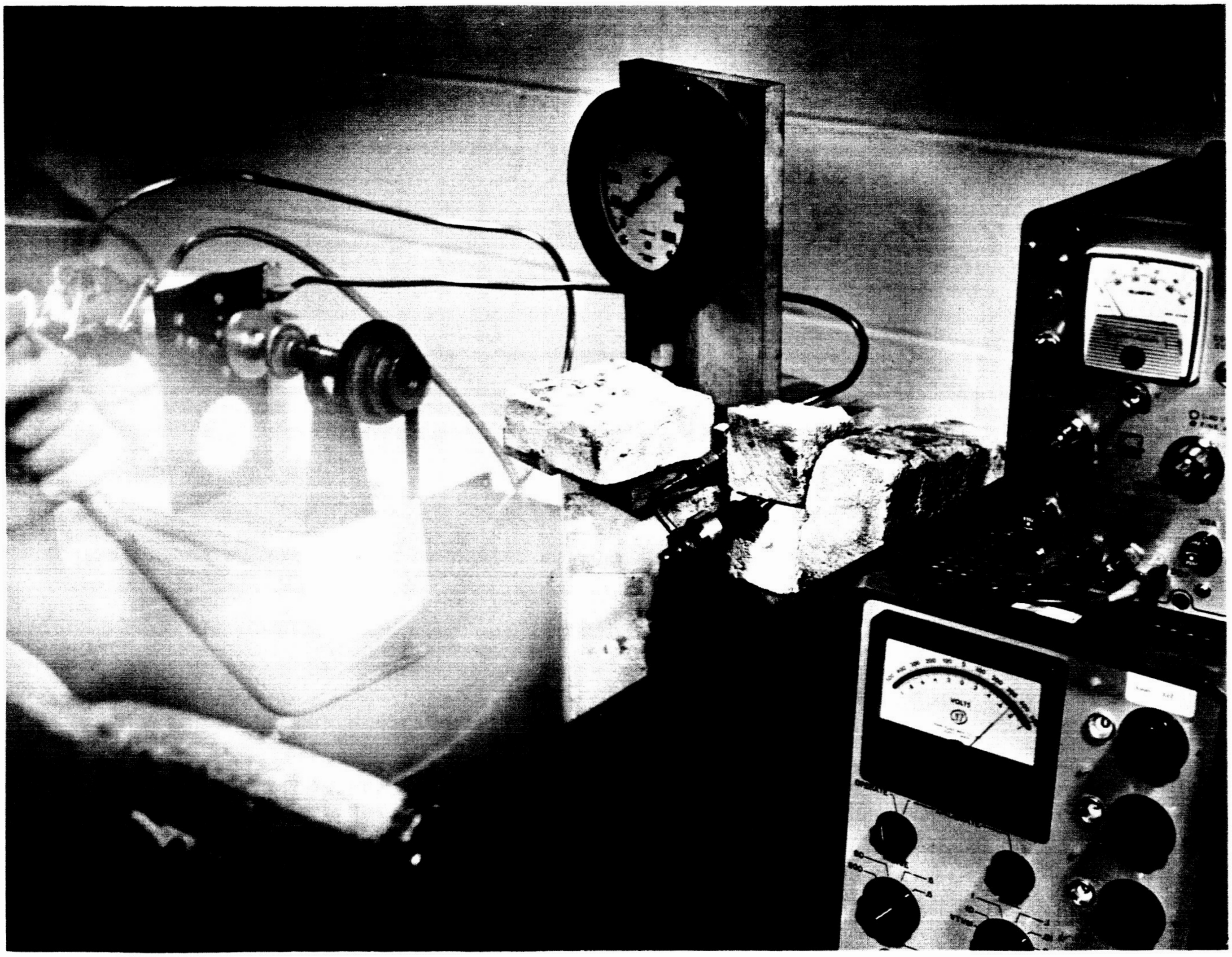


FIG. 11 EOS DEVELOPED PT15B COMBUSTION PRESSURE TRANSDUCER WITH COOLANT FLOW IN OPERATION JUST PRIOR TO FLAME IMPINGEMENT

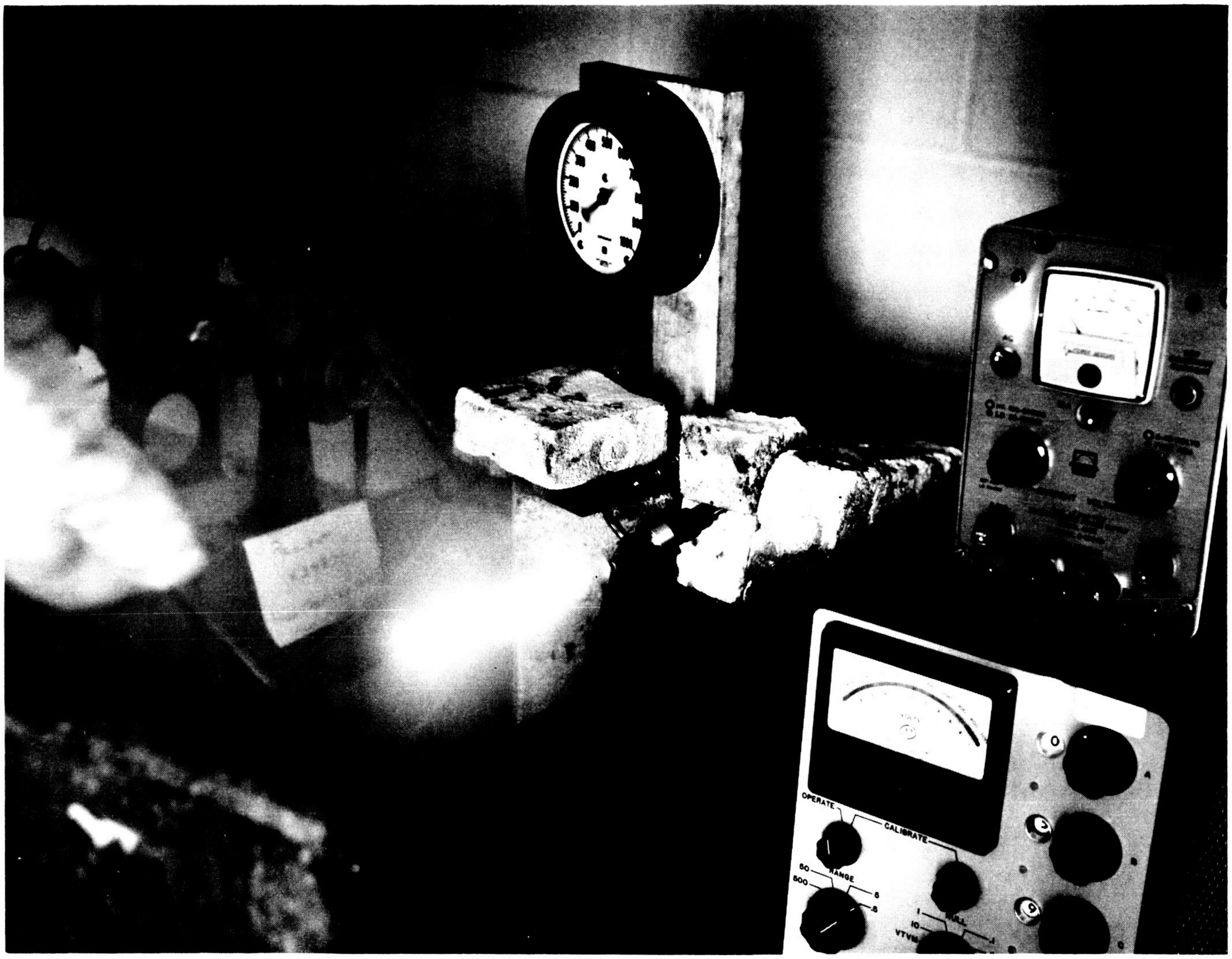
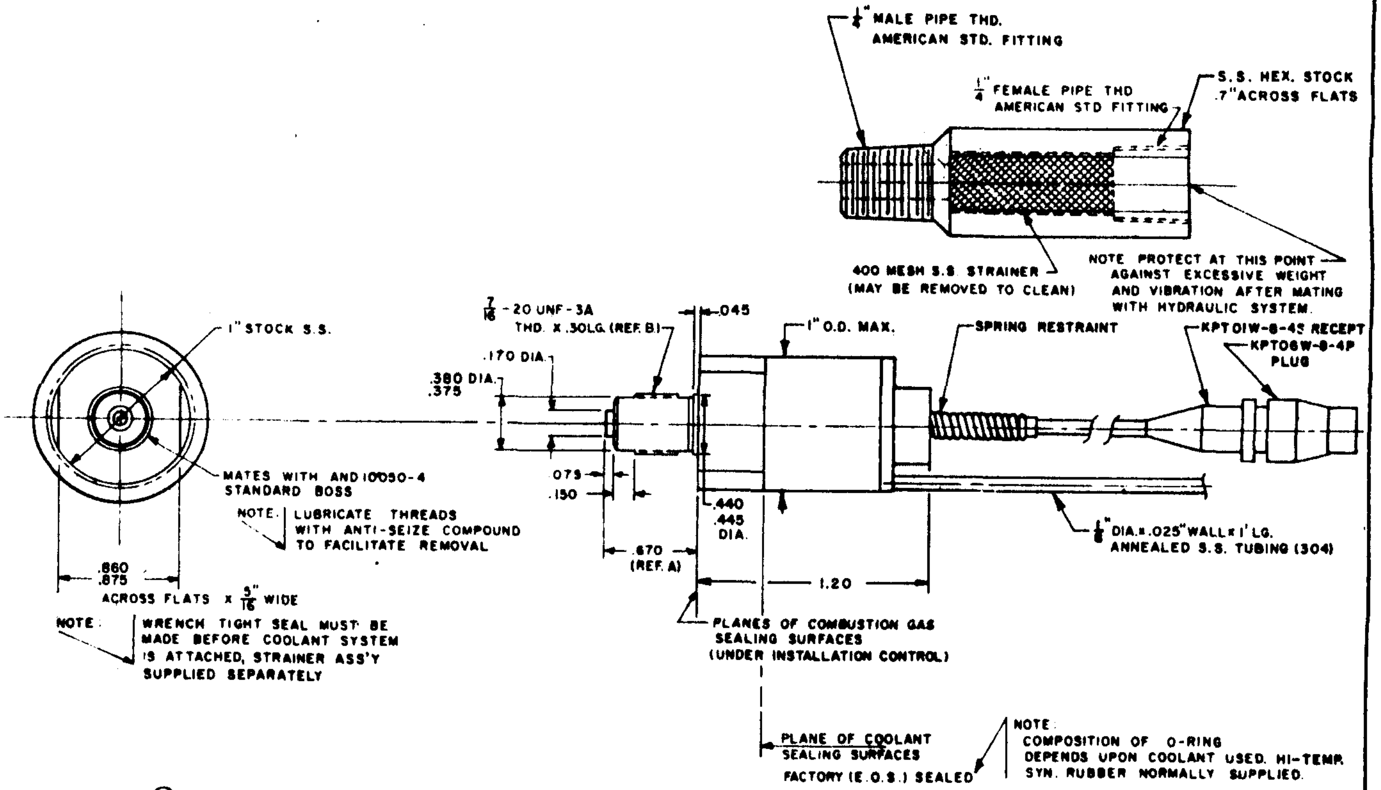


FIG. 12 OXY-HYDROGEN FLAME IMPINGEMENT DIRECTLY ON DIAPHRAGM OF PT15B COMBUSTION PRESSURE TRANSDUCER

NOTES:
1. REFERENCE DIMENSIONS A & B CAN VARY DEPENDING UPON SPECIFIC INSTALLATION REQUIREMENTS.



Ⓐ TYPICAL ELECTRICAL REQUIREMENTS

PIN A +5VDC INPUT
B (−) EXCITATION
C + SIGNAL OUTPUT
D (−) SIGNAL OUTPUT

1. BRIDGE NOMINALLY UNBALANCED TO +32 MV AT "0" FLOW (COOLANT) CONDITION AT 5 VDC ± .5MV DRIVE.
2. FULL SCALE OUTPUT AT ZERO COOLANT FLOW & 1200 PSIG. HYDRAULIC PRESSURE = 150 MV.
3. BRIDGE OUTPUT SHOULD NOT EXCEED ± 7.5 MV WITH CHANGE IN COOLANT PRESSURES FROM 200 PSI TO 1000 PSI, WITH STEADY COOLANT. TEMPERATURE (5 VDC EXCITATION)
4. BRIDGE RESISTANCE = 1000 OHMS MAX. AT 75°F
5. BRIDGE RESISTANCE TO CASE AT ROOM TEMP = >100 MEGOHMS.

Ⓑ HYDRAULIC SYSTEM REQUIREMENTS BASED UPON H_2O COOLANT

1. LOCATE 400 S.S MESH STRAINER WITHIN 12" OF TRANSDUCER ON $\frac{1}{8}$" TUBING SUPPLIED.
2. PROVIDE AT THE STRAINER TO THE TRANSDUCER
   $\frac{1}{2}$ GPM (NOM) AT 1000 PSIG (NOM)
   OR
   $\frac{1}{3}$ GPM (NOM) AT 400 PSIG (NOM)
3. COOLANT SYSTEM SHOULD ALWAYS DELIVER FLOW AT A PRESSURE HIGHER THAN COMBUSTION PRESSURE BY A MINIMUM OF 200 PSI.
4. COOLANT FLOW MUST BE MAINTAINED AFTER RUN UNTIL AMBIENT CASING TEMPERATURE REDUCES TO 150°F (NOM) FOR OPTIMUM REPEATABILITY. A ROCKET CASING TEMPERATURE REACHING 450°F AFTER A RUN COULD RESULT IN PERMANENT DAMAGE TO THE TRANSDUCER UNDER CONDITIONS OF ZERO COOLANT FLOW.
5. COOLANT SUPPLY TEMP SHOULD BE CONSTANT DURING ANY ONE RUN.

E S
ELECTRO-OPTICAL SYSTEMS, INC.,
Pasadena California · MUrray 1 4671 SYcamore 5 9961

TITLE
PRELIMINARY INFORMATION ON
INSTALLATION OF FILM COOLED (H_2O)
COMBUSTION PRESSURE TRANSDUCER PT-15B-2

SECURITY CLASSIFICATION
SIZE B
NUMBER 500157
REV
CODE IDENT NO PT-15 B-2
12-63 J.D.
SCALE
SHEET OF

FIG. 13 PRELIMINARY INFORMATION ON INSTALLATION OF FILM COOLED (H_2O) COMBUSTION PRESSURE TRANSDUCER PT15B-2

APPENDIX I

LIST OF ABBREVIATIONS

APPENDIX I

List of Abbreviations

T'N = tension gage
C'N = compression gage
TCB = thermo-compression bonded
F.S. = full scale
S = sensitivity (output over the full scale pressure range)
RT = room temperature
S_{RT} = sensitivity at room temperature
ΔS = change in full scale output over temperature range
Z = zero balance of the transducer electrical bridge
ΔZ = change of zero balance over temperature range
R = resistance
ΔR = change of resistance
V = voltage (dc)
T = temperature
G.F. = gage factor = $\frac{\Delta R / R}{\epsilon}$
ϵ = strain, inches per inch
μ = micro, one millionth
Ω = ohms
UP = increasing pressure steps (as during a calibration run)
DN = decreasing pressure steps (as during a calibration run)
E_o = voltage output
E_{IN} = voltage input
I = K = constant current
V = K = constant voltage
L-H & R = combined accuracy; linearity, hysteresis, and repeatability
SS = stainless steel

APPENDIX II

FABRICATION OF SINGLE CHIP BEAMS IN SILICON, HAVING FOUR-ACTIVE STRAIN GAGE ARMS

Author: Stephen Kaye

FABRICATION OF SINGLE CHIP BEAMS IN SILICON, HAVING FOUR-ACTIVE STRAIN GAGE ARMS

S. Kaye

1. Design

The design of the silicon diaphragm for use in pressure measurements, where the silicon is intended to be bonded to a clamped metal diaphragm of 60 mils diameter, was undertaken.

It was decided to use a diffused construction where the gages were p-type diffused into an n-type 20 ohm cm silicon substrate. The substrate material selected had a [110] orientation and gages, each of which has an active area of 10 x 1 mils, were oriented with their long dimensions parallel to the [110] direction lying in the plane of the slice. In this way the strain transverse to the gage was in a [100] direction where the piezoresistive coefficient is negligible (Ref. 1).

O. N. Tufte and E. L. Stelzer (Ref. 2) have shown that the piezoresistive properties of a diffused layer are characterized by the surface concentration, once a particular distribution of impurities is assumed. Their data, which assures complementary error function distribution of impurities, was used in estimating the gage factor.

Since the gages are designed to work down to 20^{o}K, it was necessary to select a surface concentration sufficiently large that the gage resistance would not vary significantly over the temperature range of interest.

From Morin and Maita's data (Ref. 3), it appears that p-type material, having boron concentrations in excess of 1.5×10^{19} atoms/C.C. has a resistivity almost independent of temperature in the range of 15^{o}-300^{o}K. It was decided, therefore, to aim for a surface concentration of 10^{20} atoms/C.C.

Ref. 1 - O. N. Tufte, et al., "Silicon Diffused Element Piezoresistive Diaphragms"; J.A.P. Vol. 33, p. 3322, November 1962

Ref. 2 - O. N. Tufte and E. L. Stelzer, "Piezoresistive Properties of Diffused Silicon Layers," J.A.P. Vol. 34, p. 313, February 1963

Ref. 3 - F. J. Morin and J. P. Maita, Phys. Rev., Vol. 96, p. 28, October 1, 1962

Under the diffusion conditions used, it was expected that a gaussian distribution of impurities would result. It was decided to use a 1μ junction depth. Using Irvin's data (Ref. 4), it was found that this would give a sheet resistance of 40 ohms/square, and hence a gage resistance of 400 ohms per element.

Using the curves in Ref. 1, a gage factor of 65 was predicted. Values were also calculated for a surface concentration of 5×10^{19}. This gave a gage resistance of 800 ohms/square, and a gage factor of 75.

The stress distribution expected in a clamped diaphragm is such that it is desirable to place two gages close to the center of the diaphragm where they will be in tension, and two close to the edge where they will be in compression. It was decided to make each element 10 mils x 1 mil, and the configuration shown in Fig. 2 of the main text of this report was used. In order to avoid unwanted stiffening of the diaphragm by soldered contacts, it was decided to use 1 micron of aluminum evaporated and alloyed to form ohmic contacts to the active elements, and then attach external leads by bonding or welding to contact pads placed on approximately the neutral axis of the diaphragm.

2. Fabrication Techniques

Table I lists the major process steps in the fabrication of the silicon chips.

Steps 1-27 are carried out on complete slices each having approximately 60 units. Steps 28 and 29 are on individual units.

Ref. 4 - J. C. Irvin, "Resistivity of Bulk Silicon and of Diffused Layers in Silicon," B.S.J.T., Vol. XLI, p. 387, March 1962

TABLE I

1. Procure silicon - 20 ohm cm n-type [110] orientation with (100) face marked by a flat ground on one edge. Slices 1" ±1/8 diameter, .010" thick.
2. Polish etch - remove approximately 2 mils.
3. Oxidize - 1200°C 2 hours, wet oxygen.
4. Coat with photoresist and align mesa pattern with (100) edge.
5. Expose, develop, and bake resist.
6. Etch mesas - approximately 1 mil deep.
7. Remove photoresist, clean, slice, and remove oxide.
8. Reoxidize - 1200°C 1 hour, wet oxygen.
9. Coat with photoresist and register gage pattern.
10. Expose, develop, and bake resist.
11. Etch oxide.
12. Remove resist and clean slice.
13. Predeposit boron - 1050°C 20 minutes B_2O_3 source
14. Drive in - 1050°C 30 minutes.
15. Coat with photoresist and register contact pattern.
16. Expose, develop, and bake resist.
17. Etch oxide.
18. Remove resist and clean slice.
19. Check gage resistance.
20. Evaporate aluminum - 1μ thick.
21. Coat with photoresist and register inverted contact pattern.

22. Expose, develop, and bake resist.

23. Etch aluminum.

24. Alloy aluminum.

25. Check gage resistance.

26. Mount for etching face down.

27. Etch back of slice to separate and reduce gage thickness to .0005".

28. Demount, clean, and visual inspect.

29. Bond leads.

APPENDIX III

TABLES

Table 1

		Unbonded S-G 4B Gage			Bonded to 304 SS S-G 4B Gage	
	T °K	Compression Gage	Tension Gage		Compression Gage	Tension Gage
	296	498.8Ω	460.1Ω	(EOS)	488.3Ω	390.0Ω
LN_2	77	390.3	356.5		343.7	256.5
LO_2	90				348.7	259.8
CO_2	195	443.4	407.7		411.4	312.0
	296	499.2	460.6		489.3	391.0
	77	390.3	356.6		343.7	256.5
	90				348.7	299.8
CO_2	195	443.0	407.4		411.3	311.9
	296	499.2	461.2	(EOS)	488.3	389.9
	300	500.7	462.4	(Wyle Lab)	491.0	392.3
LH_2	20	372.7	340.2		329.7	247.4
	300	499.1	462.8		492.4	393.7
	20	372.7	341.1		329.9	247.4
	300	500.6	465.2		492.9	394.2
	20	372.9	342.3		330.0	247.5
	300	502.4	466.8		495.1	396.3
	20	372.8	342.5		330.1	247.6
	300	501.9	466.8		494.7	396.6
	20	373.0	342.7		330.1	247.5
	300	503.6	468.8	(Wyle Lab)	495.7	396.8
	297	500.0	465.3	(EOS)	491.4	392.6
Boil H_2O	370			(EOS)	552.1	454.0
	297			(EOS)	491.4	392.7

Typical resistance readings of individual elements of a silicon beam chip vs. temperature as read by the wheatstone bridge method; 1-1/2 VDC power.

Table 2

Typical bonded silicon chip, individual element resistance changes with temperature:

I 304 S.S. Diaphragm

T, °K	R, Ω	R, Ω	R, Ω	R, Ω
297	415.7	533.0	430.0	486.7
77	270.6	374.0	279.2	337.5
297	414.7	531.9	429.1	485.7
77	270.7	374.1	279.2	337.3
297	416.0	533.0	430.1	486.4
297	414.2	531.8	428.8	485.4

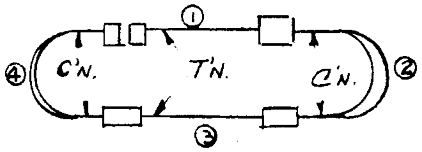
II Invar Steel Diaphragms

Typical bonded resistance change with temperature:

T, °K	R, Ω	R, Ω	R, Ω	R, Ω	R, Ω	R, Ω
297	471.1	597.4	474.1	503.8	468.4	559.8
77	359.3	464.3	362.2	387.0	359.5	440.2
297	469.5	595.6				
195	416.5	531.7				

All the above resistance elements were pressure cycled while at the indicated temperature.

III Typical resistance changes with temperature before and after bonding to Invar constant stress beam and when strained to 1000 microinches.



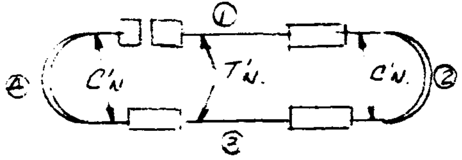
Data S=K=Beam

Gage #25 S.G. 6C - Aluminum thermal compression bonded leads

T, °K	Step 250 μ in. strain	Strain Gage Element Position ①	②	③	④	
297		419.9	537.5	429.8	476.9	Unbonded
77		327.3	419.0	333.1	371.8	〃
297	0	405.8	516.0	415.7	465.8	Bonded to Invar constrant stress beam
	1	410.8	519.0	420.8	469.1	
	2	415.8	522.0	425.7	472.3	
	3	420.9	525.1	430.9	475.8	
	4	426.1	528.1	436.1	479.1	
77	0	282.3	377.5	287.4	337.3	0 microstrain "/"
	1	286.7	381.0	291.9	340.9	250 "
	2	291.2	384.5	296.5	344.7	500 "
	3	296.3	388.3	301.7	348.8	750 "
	4	302.0	392.4	307.4	353.3	1000 "

Table 3

Unbonded and bonded resistance of actual 4-element silicon beam chips on NiSpan C diaphragms used in PT15C-2 transducers:



4-element silicon chip
.040" x .060"

Gage No.:	①	②	③	④	Method
Unit #2					
Unbonded @ RT	463.5Ω	515.9Ω	467.4Ω	564.9Ω:	Wheatstone bridge, 1.5v excitation
Bonded* 0 PSIG	457.0Ω	495.0Ω	458.0Ω	541.0Ω:	Oil dead weight tester and Wheatstone bridge network 5 VDC excit.
at R.T. 1500 PSIG	476.0	492.0	477.0	537.0	
Δ R	+ 19.0	- 3.0	+ 19.0	- 2.3	
Element #12					
Unit #3					
Unbonded at RT	485.0Ω	604.1Ω	484.1Ω	553.9Ω	Wheatstone bridge, 1.5V excitation
Bonded* 0 PSIG	480.0Ω	583.0Ω	495.0Ω	523.0Ω	Oil dead weight tester and Wheatstone bridge network 5 VDC excit.
at R.T. 1500 PSIG	497.0	583.0	514.0	520.0	
Δ R	+ 17.0	0	19.0	- 3.0	
Element #5					
Unit #4					
Unbonded* @ R.T.	438.3Ω	524.3Ω	449.9Ω	564.5Ω	Wheatstone bridge, 1.5v excitation
Bonded* 0 PSIG	426.0Ω	519.0Ω	437.0Ω	533.0Ω	Oil dead weight tester and Wheatstone bridge network 5 VDC excitation
at R.T. 1500 PSIG	443.0	517.0	453.0	529.0	
Δ R	+ 17.0	- 2.0	+ 16.0	- 4.0	
Element #9					

---

*To NiSpan C material diaphragm.

Table 4

CALIBRATION TEST DATA

T	Pressure PSIG	PT15C-2 Serial #3 E_o Up	 E_o Dn.	PT15C-2 Serial #2 E_o Up	 E_o Dn.	PT15C-2 Serial #4 E_o Up	 E_o Dn.
RT	0	+25.2 mv	25.0 mv	24.6 mv	23.2 mv	+16.1 mv	14.6 mv
75°F	250	36.5	34.0	38.0	36.0	27.4	26.0
	500	47.9	45.4	51.4	49.5	38.8	37.4
(EOS)	750	59.4	56.8	65.1	63.9	50.4	49.2
	1000	71.0	68.9	78.5	77.3	62.3	61.5
	1250	82.6	81.2	92.8	91.8	74.4	73.6
	1500	94.6		107.1		86.5	
		S_{RT}=69.4mv at I=K=10 MA		S_{RT}=82.5 at I=K=10 MA		S_{RT}=70.4 at I=K=12 MA	
LN_2	0	+13.3	14.3	+10.6	10.2	+ 4.6	+ 4.6
	250	24.7	25.3	23.0	23.0	14.7	14.4
	500	35.7	36.8	36.2	36.1	23.7	23.7
(EOS)	750	47.9	48.3	49.5	49.4	34.9	34.8
	1000	60.0	60.5	63.5	63.4	46.2	46.0
	1250	73.0	73.0	77.5	77.5	58.0	57.7
	1500	86.5		92.8		70.1	
		S_{LN_2}=73.2mv at I=K=10 MA		S_{LN_2}= 82.2 at 10 MA		S_{LN_2}= 65.5 at 12 MA	
RT	0 psig	23.6 mvDC		RT 0	+30.5	RT 0	+12.7
	1500 psig	97.6 mvDC		1500	116.4	1500	83.2
(Norco)	0 psig	23.6 mvDC		0	30.5	0	11.7
	0	+ 6.0	6.0	(23.4)	23.7	29.0	29.0
	250	15.6	15.6	35.4	35.6	39.1	39.3
	500	27.7	25.7	47.5	47.3	49.5	47.2
LH_2	750	36.1	36.1	60.0	60.1	59.8	57.8
(Norco)	1000	47.0	47.0	73.3	72.6	70.5	70.6
	1250	58.5	58.5	86.8	86.3	81.8	80.6
	1500	70.3		100.3		93.1	
		S_{LH_2}=64.3 mv at I=K=10 MA		*S_{LH_2}=76.6 mv at 10 MA		S_{LH_2}=64.1 mv at 12 MA	
(EOS)	0 psig	22.6 mvDC		0 psig	30.8 mvDC	0 psig	11.4 mvDC
RT	1500 psig	96.6 mvDC		1500 psig	112.3 mvDC	1500 psig	82.0 mvDC
	0 psig	22.2 mvDC		0 psig	30.8 mvDC	0 psig	10.5 mvDC

	RT to LN_2	RT to LH_2	RT to LN_2	RT to LH_2	RT to LN_2	RT to LH_2
Δ Zero Shift % FS/100°F	- 4.34	- 4.77	- 4.28	- 1.585	- 4.13	+ 4.63
Δ Sensitivity Change: % FS/100°F	+1.385	- 2.62	- .0922	- 2.17	- 1.76	- 1.82
Effect of Mass Coolant Flow on Zero Balance, H_2O at 650 psi=	.2mv I=K=10 MA		.2mv I=K=10 MA		.3mv I=K=12 MA	
Weight =	85 gms.		85 gms.		85 gms.	
Final Bridge Resistances: Output A-B	560Ω		540Ω		570Ω	
Input D-C	435		420		365	
D-A	360		350		380	
D-B	420		400		440	

*Several runs made.

APPENDIX IV

PT15C-2 PARTS LIST

ENGINEERING PARTS LIST

ITEM NO.	DWG SIZE	PART NO.	REV.	REQ'D. PER ASSEMBLY										DESCRIPTION
1	D	427021		1			/							Pressure Transducer Model PT15C-2
2					1									Hex Blast Tube Assembly
3	C	612732-2				1								Blast Tube, Hex
4	C	4270010				1								Plate, Deflector
5						AR								Silver Solder
6														
7														
8					1									Instrument Housing Assembly
9	D	612733-2				1								Housing, Instrument
10		427019				1								Tube, Coolant
11						AR								Silver Solder
12														
13														
14		427018				1								Diaphragm Assembly
15							1							Anchor Assembly
16	C	4771001						1						Diaphragm
17	C	4771002						1						Anchor, Diaphragm
18								AR						Silver Solder

APPROVED		
NEXT ASSEMBLY TITLE None	DWG NO. 427021	COMPILED BY R. Pyce	PAGE 1 OF 4
EOS ELECTRO OPTICAL SYSTEMS INC.	ASSY. TITLE Pressure Transducer Model PT15C-2	P/L 427021

EOS FORM No. 310

ENGINEERING PARTS LIST

ITEM NO.	DWG SIZE	PART NO.	REV.	REQ'D. PER ASSEMBLY	DESCRIPTION
19				1	Harness and Strain Gage Assembly
20		427016		1	Silicon Strain Gage Assembly
21		427013		1	Silicon Strain Gage Chip
22				AR	Wire, Aluminum (.001 Dia.)
23		427015		1	Strain Gage Wire Harness
24				5	Insulated Magnet Wire (.003 dia. x 3")
25				AR	Solder (SN 95% AG 5%)
26					
27				AR	Cement (Furane x 5B)
28		427017		1	Harness Support Block
29				AR	Cement, Epoxy No. 502
30		427014		1	Seal (Gold)
31					
32				8	Solder Tab
33				AR	Solder (SN 95% AG 5%)
34					
35					
36					

APPROVED			
NEXT ASSEMBLY TITLE None	DWG NO. 427021	COMPILED BY R. Pycz	PAGE 2 OF 4
EOS ELECTRO OPTICAL SYSTEMS INC.	ASSY. TITLE Pressure Transducer Model PT15C-2		P/L 427021

EOS FORM No. 310

ENGINEERING PARTS LIST

ITEM NO.	DWG SIZE	PART NO.	REV.	REQ'D. PER ASSEMBLY	DESCRIPTION
37	C	4771011		1	Cable Assembly
38	C	4771007		1	Cap, Cable
39	C	4771008		1	Insulator, Cable
40	B	4771014		1	Spring
41				1	Set screw, Hex Hd. No. 0-80 x 1/8 Cup Point
42				1	Connector (Cannon KPT06F8-4P or equiv.)
43				AR	Solder (SN-60)
44				AR	Epoxy - Clear
45				AR	Catalyst
46	B	4771009		1	Cable
47					
48					
49		427020		1	O-Ring, Metal
50				4	Screw, Machine-Hex Hd. No. 2-56 x 1/4
51				3	Screw, Machine-Hex Hd. No. 2-56 x 1/2
52				1	Resistor (Sensitivity)
53				1	Resistor (Balance)
54				1	Resistor (Zero Shift)

APPROVED			
NEXT ASSEMBLY TITLE None	DWG NO. 427021	COMPILED BY R. Pycz	PAGE 3 OF 4
EOS ELECTRO OPTICAL SYSTEMS INC.	ASSY. TITLE Pressure Transducer PT 15C-2		P/L 427021

EOS FORM No 310

ENGINEERING PARTS LIST

ITEM NO.	DWG SIZE	PART NO.	REV.	REQ'D. PER ASSEMBLY	DESCRIPTION
55				AR	Wire Copper (.004 dia.)
56					
57				AR	Solder SN 95% AG 5%
58				1	Dust Cap
59				1	Dust Cap
60				1	Dust Cap
61				AR	Sleeving
62				AR	Cement (Furane x 5B)
63					
64					
65				1	Connector (Cannon KPT00P-8-4S or Equiv.)
66					
67					
68					
69					
70					
71					
72					

APPROVED

NEXT ASSEMBLY TITLE None	DWG NO. 427021	COMPILED BY R. Pycz	PAGE 4 OF 4
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ABSTRACT

A film cooled pressure transducer, designed for flush mounting within a rocket combustion chamber has an all silicon piezoresistive bridge network. It senses steady state pressures and has a high flat frequency response. It is capable of being cooled with liquid hydrogen, and will operate at LH_2 temperature with small change in sensitivity and bridge balance. Exposed frontal area is only 0.018 square inch.