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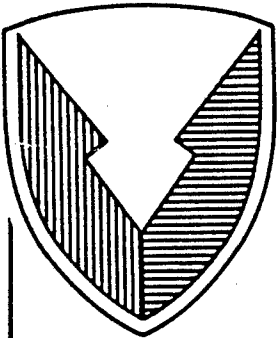
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R D & E

C E N T E R

Technical Report



No. 13500

DIFFERENTIAL TRANSDUCER FOR VEHICLE DIAGNOSTICS

CONTRACT NUMBER DAAE07-86-C-R088

FEBRUARY 1990

H.M. Spivack
West Coast Research Corporation
P. O. Box 25061

By Los Angeles, CA 90025-0061

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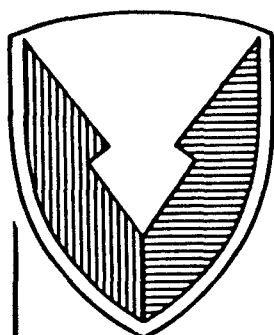
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U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH, DEVELOPMENT & ENGINEERING CENTER
Warren, Michigan 48397-5000

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The STE/ICE program of TACOM required that continuous analog monitoring of pressure loss across automotive fluid components be performed. The Diagnostic Connector Assembly (DCA) maintenance application assures that problems can be anticipated and corrected, avoiding failures, rework and replacement efforts. A research and development effort was therefore undertaken to produce a Continuous Analog Differential Pressure Transducer (CADPT) to support the DCA program. The transducer would be suitable for measurement of losses in air filters, hydraulic filters, fluid lines and similar flow components. Fluid component status can be monitored on an on-going basis and conformance within operating limits verified, <u>prior</u> to breakdown and mandatory corrective maintenance.					
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19. ABSTRACT (Cont'd)

The Continuous Analog Differential Pressure Transducer development was evolved as a basic one-piece structural unit which was to be instrumented with strain gage sensing elements. The requirements for the sensing elements are to produce a precision instrument response, in a cost-effective design, which is directly compatible with the Diagnostic Connector Assembly test equipment.

A variety of base materials have been investigated including composite polymers, aluminum alloy castings, bar stock aluminum alloy, high tensile stainless steel, ceramic, and powder metallurgy.

High output sensing elements were applied, including silicon and platinum strain gages to produce a 100mv span sensitivity. Research into in-situ deposition of sensing elements was carried out by sputtering and evaporation techniques in a vacuum facility.

EXECUTIVE SUMMARY

An economical continuous analog differential transducer has been developed for compatibility with the Simplified Test Equipment/Internal Combustion Engine (STE-ICE) Vehicle program matching the input to the Diagnostic Connector Assembly (DCA).

The requirement for a transducer which is capable of continuously measuring the differential pressure drop across pneumatic or hydraulic system components has been fulfilled under this contract sponsored by TACOM. A broad program was carried out to investigate materials, processes, and sensing elements which would be applicable to design of a Continuous Analog Differential Pressure Transducer (CADPT).

Materials investigated for the transducer body included:

- Composite polymers,
- Cast aluminum and other metal castings,
- Powder metals, and
- Bar stock aluminum.

The properties studied encompassed tensile strength, elastic modulus, formability, structural stability and cost. The fabrication processes considered were injection molding, die casting, rubber mold casting, automatic machining, powder metallurgy, hot isostatic pressing, and other high-pressure forming procedures.

The sensing elements considered were primarily of the strain sensor types and included bonded strain gages, vacuum-deposited thin films and thick film.

Prototypes were constructed and tested. Data was obtained on the materials, processes and sensors. The results demonstrated that glass-filled polymers, aluminum casting, and bar stock transducer fabrication could all be produced on an economical basis in reasonable quantity production. The cost basis probably favors the bar stock fabrication method, because secondary machining operations are eliminated. Where only low precision is needed, the injection molded bodies would be favored from a cost standpoint.

The sensing element requirements are met by installation of bonded silicon or platinum foil strain gages. The high full-scale output required (100mv) to match the DCA signal input eliminates the use of other strain gage materials. While the vacuum-deposited thin-film sensing elements under development

could meet requirements of the STE-ICE Vehicle Diagnostic equipment, extended study of the masking techniques and refinement of the deposition process is required (Phase III).

A computer-aided testing and processing method for strain gage bridge installation was developed. Automatic printout of calibrations are incorporated in the computer-integrated testing algorithms.

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1.0. INTRODUCTION

A broad program of investigation was undertaken to research the ways in which an efficient, accurate, and economical transducer could be produced to measure differential pressure on a continuous basis. A comprehensive plan was laid out as a road map to guide the Research and Development (R&D) effort. The plan is outlined in Appendix A.

The investigation considered application of both new materials and new processes. In the category of materials, metals for sensing elements and for the transducer base or body were covered. Study of the body for the transducer included: metals in original forged or rolled form, as well as in castings; and composite polymers with glass or other reinforcement. Properties of other specialized materials such as ceramics and powder metallurgy were also considered.

The processes for fabrication of the metal transducer bodies included consideration of sand castings, investment castings, centrifugal casting, hot isostatic pressing of sintered and powder metals, deep drawing, forging, coining. For the composite reinforced polymers, attention was primarily directed to injection molding as the basis for a suitable economical production method.

The sensing element selection paid attention to use of bonded strain gage devices as well as deposited film sensors. The standard strain gage techniques are well established, but application of thin films by high vacuum sputtering required research and development to refine the technique and provide a production-acceptable process.

In order to design for simplified construction, the research and development of the CADPT was targeted to the one-piece configuration (plus a simple cover plate). Figure 1-1 shows opposite sides of the one-piece construction: one side being the gaging section of the force collector; the other side shows the concentric input ports. Figure 1-2 is a photograph of an assembled unit. Establishing this as the basic approach, it was possible to consider a variety of production processes for efficient execution of a design. As these processes were investigated, conclusions were drawn, based on anticipated production quantities, and resulted in concentrating on (a) casting, (b) injection molding, (c) Computer-Numerical-Controlled (CNC) machining. Each process, of course, has advantages and drawbacks, which are discussed.

Construction of the prototypes was carried out with a number of materials by the several processes. Each prototype was

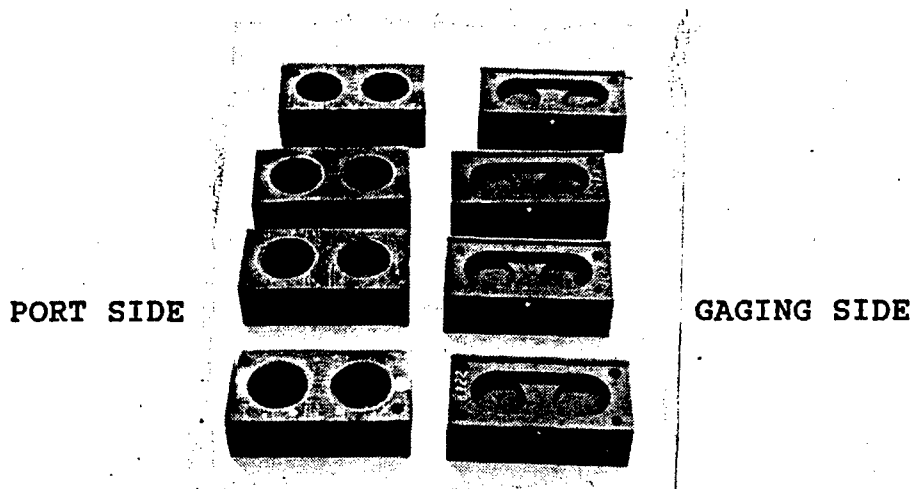
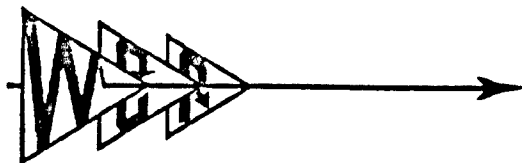


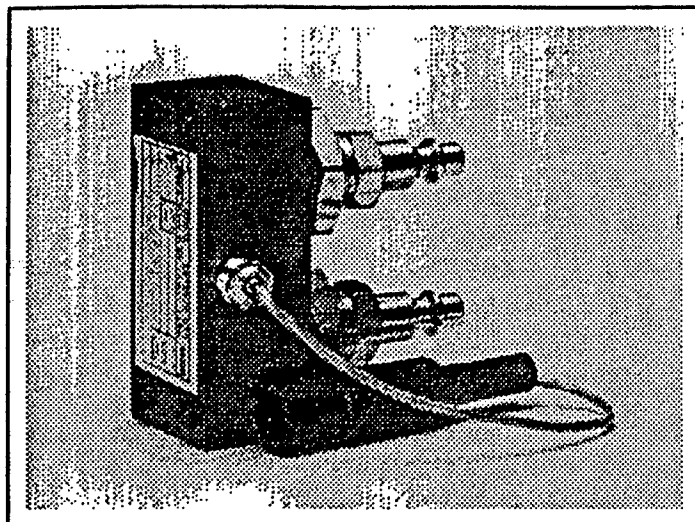
Figure 1-1. Two Views of CADPT Configuration



Model 237 Continuous Analog Differential Pressure Transducer

XX November 1989

- Low Cost
- Small Size
- Simple Installation
- Rugged
- Wide Temperature Range



Description

The West Coast Research Model 237 is a Continuous Analog Differential Pressure Transducer (CADPT). It is useful for diagnosis of existing or potential failures in automotive fluid systems.

The Model 237 Differential Pressure Transducer has a continuously varying analog electrical output that is directly proportional to the difference in pressure between the input ports. It is intended for providing data on pressure build-up or losses in air or fluid systems. It may be connected to fluid lines, air filters, oil filters, cooling systems, or hydraulic system components. It can also be used to determine valve pressure drop, manifold losses, and other engine losses. It is ideal for the early detection of clogged oil or air filters in vehicular applications.

The Model 237 is furnished in a compact configuration. It is easily mounted and installed in a flow line or across any flow component. The transducer can provide early detection of flow restrictions or other abnormal conditions to provide protection of engine or hydraulic components from premature failure.

The analog output of the Model 237 is compatible with the input requirements of diagnostic computers, and can be interfaced with external monitors or internal vehicle computer systems. The output can also be connected to a West Coast Research Series 5500 microprocessor based electronic monitor, which can scan up to 64 pressure transducers connected to a system.

The West Coast Research Model 237 CADPT can also be used to monitor fluid or air systems in gasoline, turbine, or diesel industrial engines, and in all types of hydraulic or fluidic systems.

Specifications

Range	±5, 10, 15, 30, 100, 200, 300, 500, 1,000 psid full scale
Excitation	12 Vdc
Output	100 mV full scale
Repeatability	±0.25% of full scale
Hysteresis	±0.25% of full scale
Non-Linearity	±0.50% of full scale
Thermal:	
Compensated Range	0 °F to 150 °F
Compensation	0.02% of FS per °F
Operating	-20 °F to +200 °F
Storage	-40 °F to +250 °F
Overrange	100% of full scale with negligible calibration shift 200% of full scale with no structural damage
Vibration	
Shock	50 g rms, 11 ms 200 g rms, 0.5 ms
Frequency Response	25 - 2,000 Hz, depending on range
Materials	Aluminum alloy or composite body
Dimensions	1.00" x 1.50" x 2.88"
Pressure connection	3/4" NPT
Electrical connection	Cannon 120-1800 connector
Weight	Less than 165 grams

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Specialists In Transducer Technology

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Figure 1-2. Assembled CADPT

instrumented with strain gages and wired into a wheatstone bridge circuit for evaluating performance under pressure.

In this report, the results of many tests of sample prototypes are summarized and conclusions drawn for design and fabrication of the final prototypes.

2.0. OBJECTIVES

The TACOM diagnostic program for internal combustion engines and vehicle maintenance⁽¹⁾ mandated that continuous analog differential pressure measurements be provided. Differential transducers to determine pressure losses caused by incipient malfunction, clogging and build-up of foreign particles in automotive filters, hydraulic components, air, water or other fluid flow components was required. Previous equipment used in the STE/ICE program Diagnostic Connector Assembly (DCA) employed discontinuous switching alarm signals to indicate a condition requiring immediate servicing attention but generally could not be relied on to anticipate problems.

West Coast Research set about a research and development effort which was directed to provide optimum selection and integration of materials, manufacturing processes, sensing elements, and test procedures in an economical configuration.

3.0. CONCLUSIONS

The research carried out has led to the development of three differential transducer models which would fulfill the goals of the program. Continuous analog differential transducers have been shown to be producible in composite polymer, aluminum casting or computer-controlled machining of bar stock. Each of these materials and the corresponding manufacturing process have resulted in effective procedures, which are modest in cost and comparably priced. The accuracy of results are similar to, or better than, more conventional transducer performance.

(1) Technical Manual TM9-4910-571-12&P "Operator's and Organizational Maintenance Manual Including Repair Parts and Special Tool List, Simplified Test Equipment for Internal Combustion Engines (NSN 4910-00-124-2554)", Headquarters, Department of the Army, 15 October 1984.

New methods, material applications, sensing elements, and testing procedures have been developed in the course of the contractual effort.

4.0. RECOMMENDATIONS

The CADPT development provides the means for continuous analog differential measurements in an automotive vehicle environment. The configuration can be applied to anticipate and prevent operating problems or premature failures in vehicle operation.

Application to air, water, hydraulic fluid filters, actuators, pumps, and related fluid flow components is indicated.

Further work under a Phase III effort is needed and is continuing to advance the state of the art and perfect the deposited film-sensing techniques as applied to the CADPT and to refine computer-aided transducer testing and adjustment procedures.

5.0. DISCUSSION

5.1. Design Approach

A differential pressure transducer design requires consideration of the form as well as function. In Figure 5-1, the general layout of several conventional differential transducer arrangements is shown for comparison to the CADPT configuration. It may be seen that various conventional design complexities are avoided for the CADPT. Where the pressure sensor requires only a single input port, the form usually is resolved in a cylindrical (or parallel-piped) configuration with the pressure to be sensed entering on one end. If the application requires that a reference pressure, such as atmospheric be sensed as well as gage pressure, then a limited type of differential can be created by simply supplying a reference port on the opposite end (or to one side) of the gage port, as shown in Figure 5-1(a). However, the reference fluid must be inert, clean and nonconductive. Otherwise problems would be created in contamination, electrically shorting, or otherwise modifying the sensing element output.

A bidirectional transducer, referred to as "wet-wet," measures fluid pressures from two ports. In the wet-wet application, where an active, conductive or contaminant fluid is to be measured differentially, the fluid cannot be allowed to come in contact with the sensing element. Consequently, dual sealed ports must be employed. These ports may be located on the ends of a cylindrical form transducer as in Figure 5-1(b).

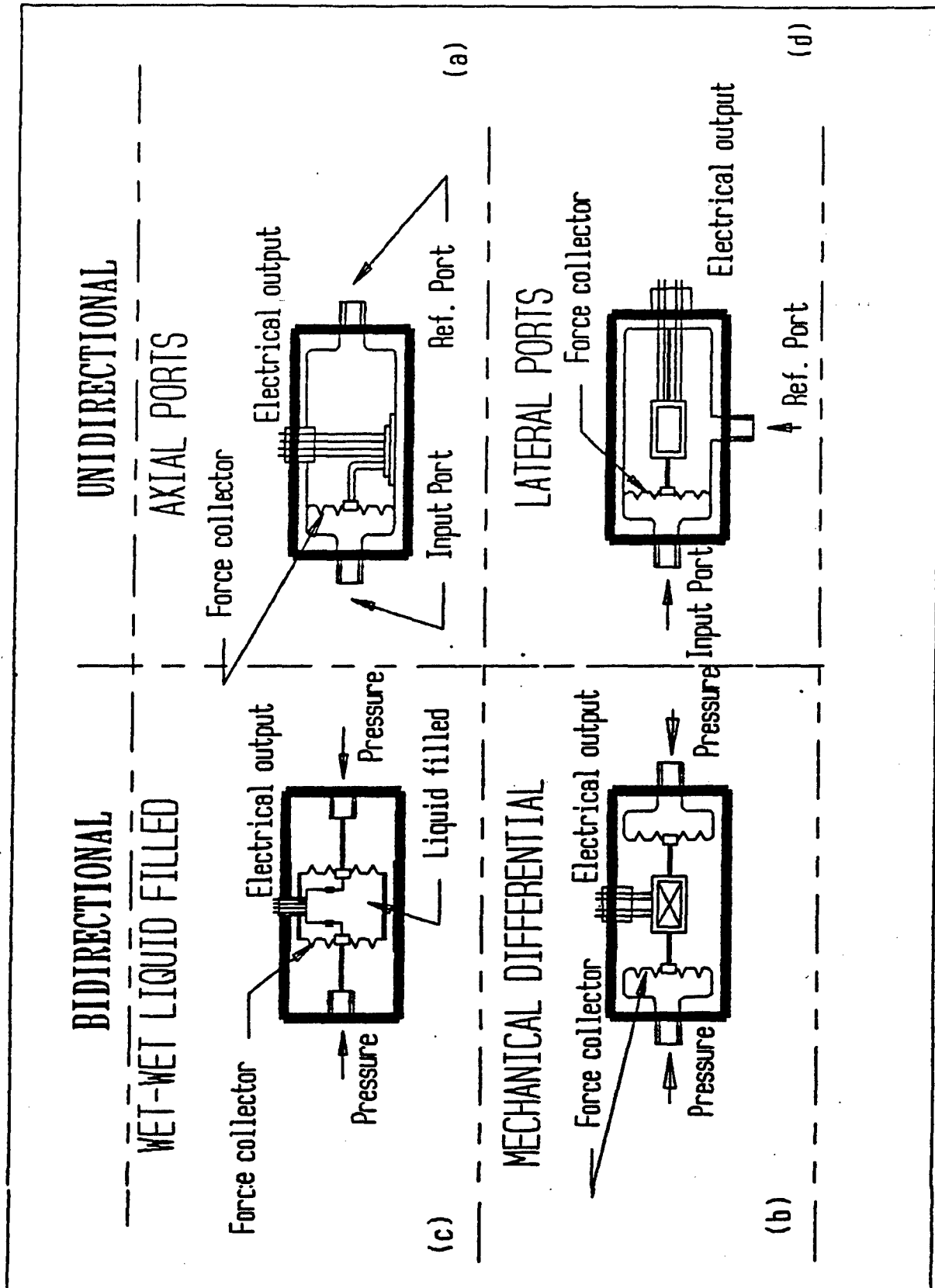


Figure 5-1. Differential Pressure Transducer, Conventional Designs

In this case, the sensing element must be installed internally in the cylindrical housing, creating problems in access and processing. Many such designs employ a sealed-in fluid filling to distribute the differential pressure between the two sensing ports as in Figure 5-1(c). Of course the entire unit must be sealed off to retain the internal working fluid. The pertinent designs illustrated in Figure 5-1, include one utilizing a lateral reference pressure port as in Figure 5-1(d).

Various other forms can be applied, including connection of differential pressure tubes directly to the sensing elements, which has advantages in restricted locations but creates a pressure lag in the tube assemblies.

5.2. Configuration Management

The configuration of the CADPT is dependent on compatibility of several major aspects of the design. These require integration with form and function factors.

- (1) Functional Performance
 - Method of Measurement
 - (2) Materials Selected
 - (3) Fabrication Processes
 - (4) Compatible Match to DCA Input
 - (5) Cost
- (1) The functional performance is governed by specification requirements for a continuous, bidirectional, analog signal which is obtainable in the ICE environment with a variety of media.
 - (2) The materials considered were intended to advance the state of the art of pressure transducers. Improved handling, newer manufacturing process, economy and ruggedness of the final product, as well as engineering performance entered into selection of suitable composites and metals.
 - (3) Manufacturing procedures had to take into account the mechanical and physical properties of the material considered. The fabrication machinery available, the tooling, and the access to specialized processing plants were important considerations.
 - (4) A signal to match the input requirements of the DCA equipment had to be arranged.

- (5) The cost of processing, as well as cost of material and the instrumentation expense, enter into the economy of the design. However, functional performance is always the key to decision on selection of any operational factor.

The materials and processes chosen must contribute to endurance under the range of environmental conditions with accuracy of measurement required.

For the CADPT design, we have chosen a relatively open configuration in which both differential ports are located on one side of a rectangular form. A sectional layout is shown in Figure 5-2. This allows convenient access for the differential pressure ports on the same transducer face, but more importantly, it allows a relatively free access for installation of sensing elements on the opposite rectangular face. Adjustments to the sensing bridge are facilitated and assembly of the entire unit simplified. In addition, the parallel-piped form is amenable to low-cost production techniques not readily realized in other more complex differential transducer designs. This configuration allows a "one-piece" construction, enhancing the economy of production.

The mechanical configuration of the CADPT was selected for simplicity and cost-effectiveness consistent with good performance. The most straightforward design places the sensing element directly on the force collector. This eliminates mechanical gage-mounting problems when compared to designs with intermediate sensing structures. Any relative deflection in the connections could give rise to hysteresis and non-repeatability effects. An application for a patent on the "one-piece" construction is being prepared. The layout is shown in Figure 5-2.

The compact design allows for a pair of installation bolts to mount the CADPT on a suitable flat surface of a vehicle frame, hydraulic component, or engine structure. It may not be necessary to utilize more than one hole for mounting. See Figure 5-3 for suggested installations. Depending on the rigidity of the pressure line supporting the transducer, even a single installation bolt may not be necessary because of the light weight (<160 gm) of the CADPT.

A cover to enclose and seal the sensing circuit is also mounted with screws, as seen in Figure 1-2. A sealant is employed to keep out dust, grime, oil, or hydraulic vapor from the strain gage wiring area. However this is a secondary precaution since the strain gage circuit is normally coated with a waterproofing/sealing encapsulant and would not be affected

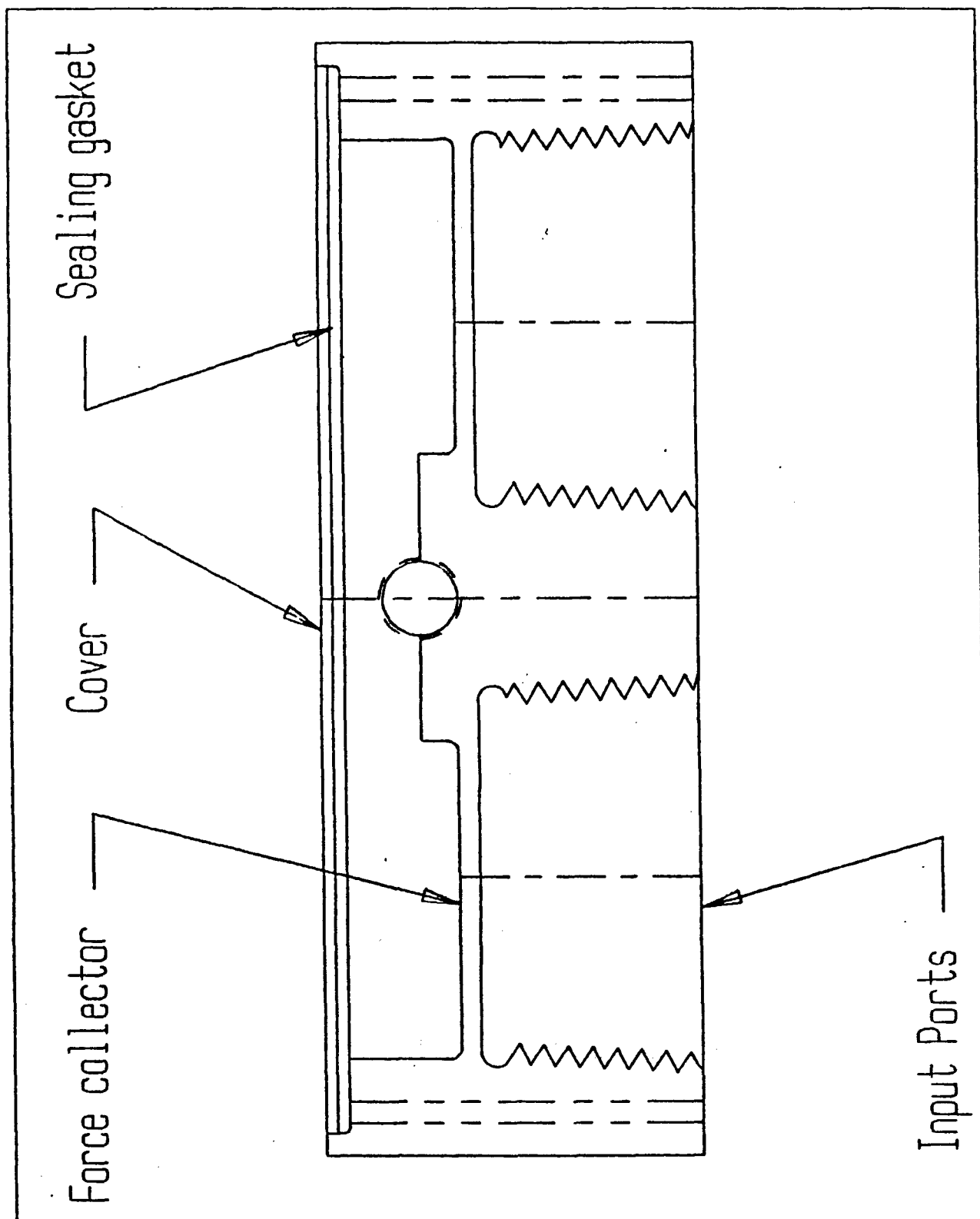


Figure 5-2. One-Piece Construction

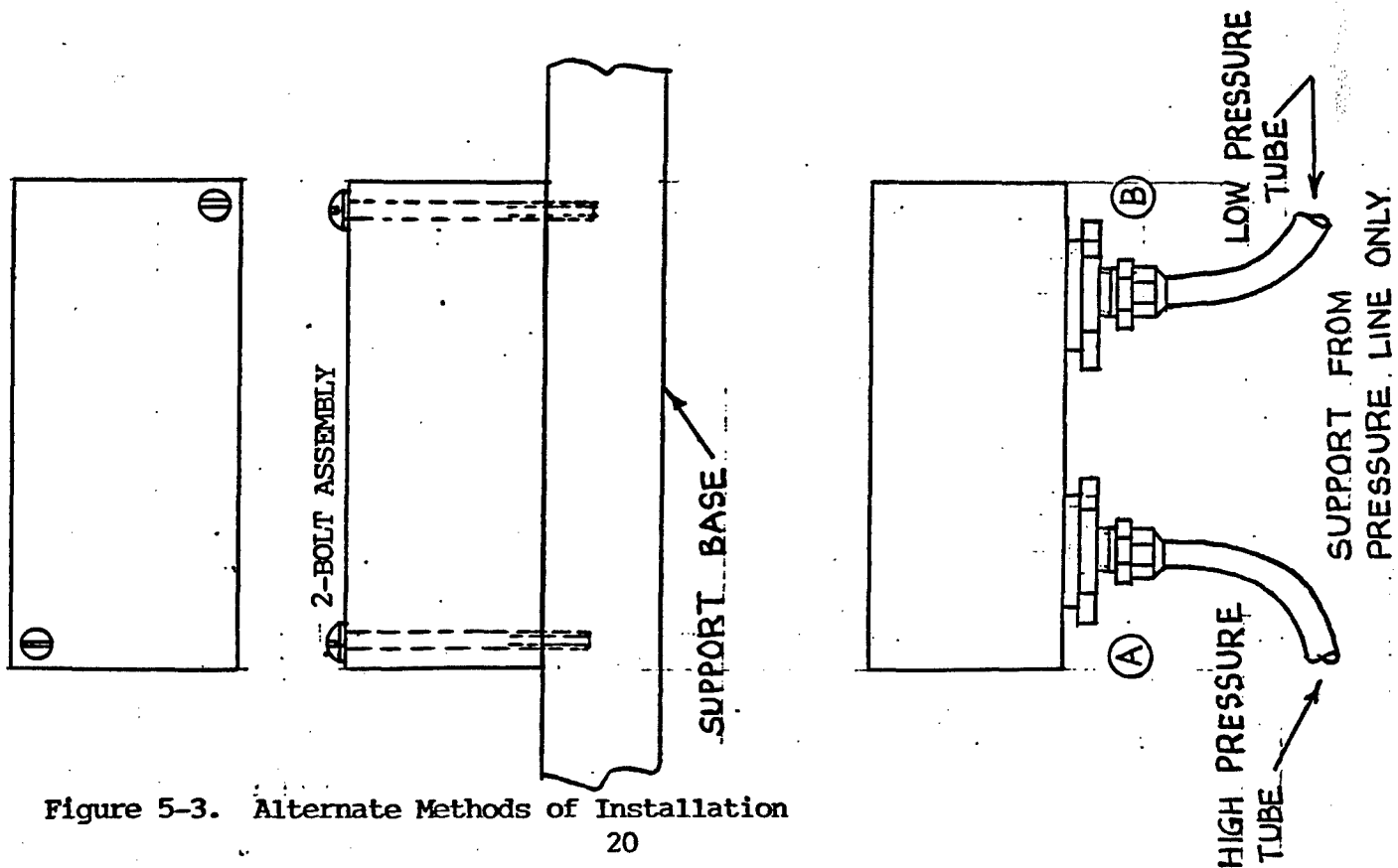
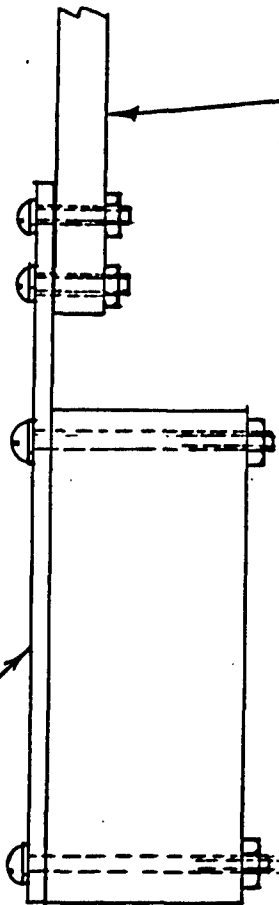
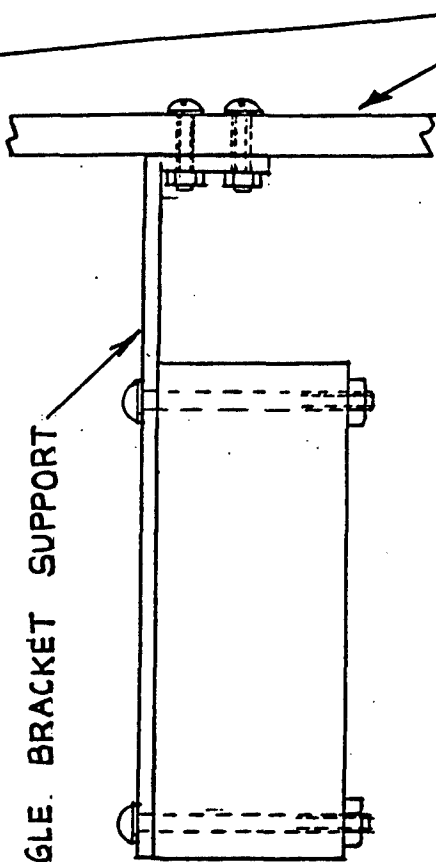


Figure 5-3. Alternate Methods of Installation

FLAT BRACKET SUPPORT



ANGLE BRACKET SUPPORT



SUPPORT FRAME

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by any but direct corrosive contaminants or contact with conductive fluids.

5.3. Materials

The substances that can be considered for use in the CADPT design are evaluated in two diverse categories. One covering the more conventional structural properties; the other is the relatively "high tech" approach to the sensing element function.

Instrumentation of the transducer sensing function is discussed under Section 5.11.

There exists a broad array of materials which could conceivably be applied to the construction of the CADPT body. Among these are a few basic categories which have properties of interest for production of rugged, accurate, economical, pressure transducers. Included are a range of metals, polymers, composite polymers, powder metals, and ceramics. The criteria used to make selections are those which principally affect the required performance:

- Tensile Strength
- Elastic Modulus
- Thermal Properties
- Material Cost
- Fabrication Cost
- Bonding Compatibility With Strain Gages
- Weight

From the standpoint of fabrication cost, we search out materials that could be converted into the CADPT form by repetitive production process. The processes would cover such operations as casting, injection molding, press forming and automatic machining.

The material cost is a function of the weight and the scrap generated. This criterion would perhaps favor the polymers, although aluminum formed by casting is a low-cost candidate. However, the basic polymers do not possess the requisite tensile strength without reinforcement. Therefore, use of glass-filled polymers provide the physical properties that would be useful. Some carbon-reinforced polymers provide improved properties, but the price is approximately eight times that

of the glass-reinforced types. Since we are dealing with weight of the finished CADPT, which is of the order of 160 grams, the amount of material used in injection molding, even for high-cost raw material, could be within our budget estimate. The cast aluminum bodies are also close to this weight and have a favorable rating in this regard.

Solid aluminum alloy bar stock has a similar weight, but when producing these by machining methods, there is a penalty in the scrap generated. This is also true of any other machined material. In this regard, superior elastic property performance is a definite capability of high tensile (aluminum or stainless) alloys. The stainless material has a high cost, plus the weight (= 3X aluminum bar) and increased machining time tends to rule out such stainless alloys, except for other higher performance applications.

The investigation carried out for material properties beyond those conventionally employed in strain gage pressure transducer technology was guided by the criteria of Table 5-1.

All of the materials covered appear to have compatibility with strain gage bonding techniques. Two special cases are of consideration, however. In the vacuum deposited gaging process, the characteristics of the substrate must be given special attention. Porosity of cast materials; and glass-fiber ends produce protrusions in the polymer molded types requiring additional attention to preparation of the gaging surface for sputtering, or evaporation. This is necessary to assure that adhesion of thin-film depositions have a stable and durable base. Also, characteristics of the carbon-filled polymers may require an alternate surface treatment to enhance gage adhesion. This has not been evaluated for carbon reinforcement, although the glass-filled polymers appear to fulfill the adhesion requirement.

Table 5-2 provides a list of the materials whose properties have been investigated. It compares a number of compounds and alloys from which prototypes were selected for fabrication and evaluation.

5.4. Process Research

Selection of an efficient fabrication process for appropriate materials is the key to production of an economical and accurate differential pressure transducer.

In order to select the optimum methods of producing the CADPT bodies, an extensive investigation was undertaken into the variety of industrial techniques available.

Table 5-1. Material Properties Criteria

-
-
- (1) A high tensile strength to withstand pressure loading of the force collector section with
 - (2) A high fatigue cycle limit for long term repeated loading and
 - (3) An elastic modulus high enough to insure stable response to the input loading frequency band.
 - (4) Minimal hysteresis to provide repeatability of the output signal, and
 - (5) Relatively linear response for precision data,
 - (6) Structural stability over an extended period.
 - (7) Economical processing.
 - (8) In addition, the material employed in the CADPT structure must present a satisfactorily uniform surface for application of the sensing gage elements and be compatible with the gage bonding process.
-
-

Table 5-2. Properties of Candidate Materials

Source	Description	Composition	Strength	Elasticity	Modulus	(Ultimate Tensile)	Melt ^o F	Coef. x 10 ⁵	Gravity
Dupont	Rynite 555	85%G/Pet	35,000		3.0 x 10 ⁶	1.3%	445	1.3	1.80
	Zytel 70G33	Nyl/33G	27,000		1.3 x 10 ⁶	3.0%	491	1.3	1.38
	VespeI	Polyimide	12,500		.450 x 10 ⁶	7.5%	680	2.8	
LNP	Verton RF-700-10EM	Nyl 6/6/50G	33,000		2.3 x 10 ⁶	4.0%			
	" UF1006	PRS/30G	20,000		1.6 x 10 ⁶		430	1.8	
	" PF1006	Nyl 6/30G	23,000		1.2 x 10 ⁶		460	1.7	1.56
	" RF1006	Nyl 6/6/30G	26,000		1.3 x 10 ⁶		490	1.2	1.37
	" RF7006	Nyl 6/6/30G	27,000		1.5 x 10 ⁶	3.5%	495	1.6	1.65
Phillips	Ryton R-4	PRS	20,000		1.6 x 10 ⁶			1.3	1.56
	Ryton 20-40		23,000	1.7 x 10 ⁶					1.66
	BR-90A		27,000		1.9 x 10 ⁶	1.5%	500		1.65
	AC50-30	PRS/30C	24,000	4.0 x 10 ⁶	3.2 x 10 ⁶	0.8%			1.45
Celanese	Vectra 150		26,000	3.2 x 10 ⁶	2.9 x 10 ⁶		484	5.0	1.75
GE	Uitem 2400	40%G/PEI	27,000	1.7 x 10 ⁶		2.5%		.8	1.38
	Uitem D7201		25,000	1.6 x 10 ⁶		2.0%	414	2.2	
	Uitem D7801	25%C/FEI	25,000	2.0 x 10 ⁶			725		1.37
	Uitem D7700	15%C/FEI	21,000	1.3 x 10 ⁶			725		1.33
Various*	Castable Aluminum Alloy								
	356		47,000			3.5%			
Various*	Aluminum Bar Stock								
	2024		47,000	10.3 x 10 ⁶		3.5%		2.0	2.71
SKS Gries Zinc/Aluminum Alloy	7075		70,000						
	Zn7								
Various*	Zn27	7% Al.	60,000			1.3		14.4	5.0
	17-4PH	27% Al.							
Various*	Stainless Steel Bar	17% Ni.	140,000	30 x 10 ⁶		2.0%		.6	

*See Table 5-5. "Metal Processing Survey"

Applicable processes were reviewed, and a continual survey of the industry for sources and services was conducted over the life of the Phase II Contract. In this manner, later developments and advances could be considered for the manufacture of the transducers.

5.5. Fabrication Processes

In order to achieve a cost-effective design, fabrication processes amenable to high production were investigated. Among the production technologies that would appear to lend to the design objective were methods of casting and injection molding. When it appeared that the process involved might require secondary operations, it was decided to investigate fabrication by means of direct high-speed machining.

Moderate cost in a precision transducer should avoid the necessity for redundant secondary machining and finishing operations. To obtain reasonable repeatability in transducer performance, the finished tolerance required for the dimensions of the force collector is approximately .001". While correction of mechanical tolerance offsets is available by means of electrical adjustments, trimming of the sensing element circuit in a secondary operation tends to defeat the goal of efficiency of the design. Likewise, adjustment of dimensions in a final finish machining operation impedes production.

The processes covered is outlined in Table 5-3.

5.5.1. Castings. In general, the best casting tolerance available from any foundry is of the order of $\pm .005"$. This level of fabrication error can actually be accommodated in adjustments of the transducer sensing element, but this would be at a penalty to the low-cost advantage of casting of the transducer body. Thus, this low-cost process would not appear to have great enough advantage in recommending it over injection molding of composite polymers or automatic machining from solid bar stock.

Porosity in castings is a problem that has to be dealt with in avoiding leakage and finish roughness not compatible with installation of the strain gage sensors. This is true whether bonded sensing elements or thin-film deposited sensors are installed. In general, the thin-film sensing elements require a closer control of the surface finish at the force collector than the bonded gage installation whether the metal foil types or the semiconductor types are used.

Casting provides an economical method of producing devices of some complexity. There are several casting procedures which

Table 5-3. Options for Fabrication of Transducer Bodies

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-
1. Casting Methods
 - Die Cast
 - Rubber Mold
 - Investment
 - Centrifugal
 - Vacuum Cast
 2. Specialized Forming
 - (High Pressure/Temperature Pressing)
 - Powder Metallurgy
 - Hot Isostatic Pressing
 - Metal Injection Molding
 3. Plastic Injection Molding
 4. Automatic Machining
 5. Ceramic Forming
 6. Other (Forging Related)
 - Metal Impact
 - Stamping - Coining
 - Deep Drawing
 - Explosive or Hydraulic Forming
-
-

can be considered from the standpoint of economics and precision.

For castings, one low tooling cost method was the principal target of the current investigation. In this method, urethane forms are employed primarily to shape the casting, and the final material (356 aluminum alloy) is poured in epoxy molds. Secondary operations appeared necessary to hold tolerance on the force collector element and bring the thickness to required dimensions. Other problems with this type casting were with porosity in thin force collector sections required for low-level pressure ranges, i.e., below 100 psi. Mechanical failure or leakage could occur in the sections thinner than the test data demonstrated in Table 5-4.

- (a) The urethane (rubber) pattern is used to form an epoxy mold, similar to sand casting, but provides improved finish and tolerance. This process was employed for casting the initial aluminum alloy CADPT units. The mold is shown in Figure 5-4. It was found that the tolerance on critical sections could be held to approximately $\pm .005$. This indicated secondary finishing operations to obtain the required response from the force collector sections. In Figure 5-5, the dependence of bridge output sensitivity is plotted as a function of thickness.

Other types of aluminum casting were also examined. This included centrifugal casting and investment casting, which were evaluated as a basis for ordering dies to improve the tolerance. See Table 5-5.

- (b) In investment casting, tolerance can be improved a little, but the process involves higher precision molds. The investment molds are more costly and production costs can be higher than the epoxy mold casting.
- (c) Die casting produces higher repeatability between successive parts than the rubber mold or investment castings. However, the dies apparently work better with small intricate zinc or magnesium forms than with higher-strength aluminum alloys. Zinc/aluminum alloys were studied. Zinc/aluminum alloys are frequently cast to closer tolerance than aluminum. These are significantly heavier than conventional aluminum alloys. Data taken with sample prototypes is shown in Figure 5-6. Acceptable results are indicated, but the higher cost of parts is involved. A comparison of preliminary results with injection molded polymers and metal castings is given in Figure 5-6.
- (d) Centrifugal castings produce precision parts but primarily in thin, artistic elements that are configured in

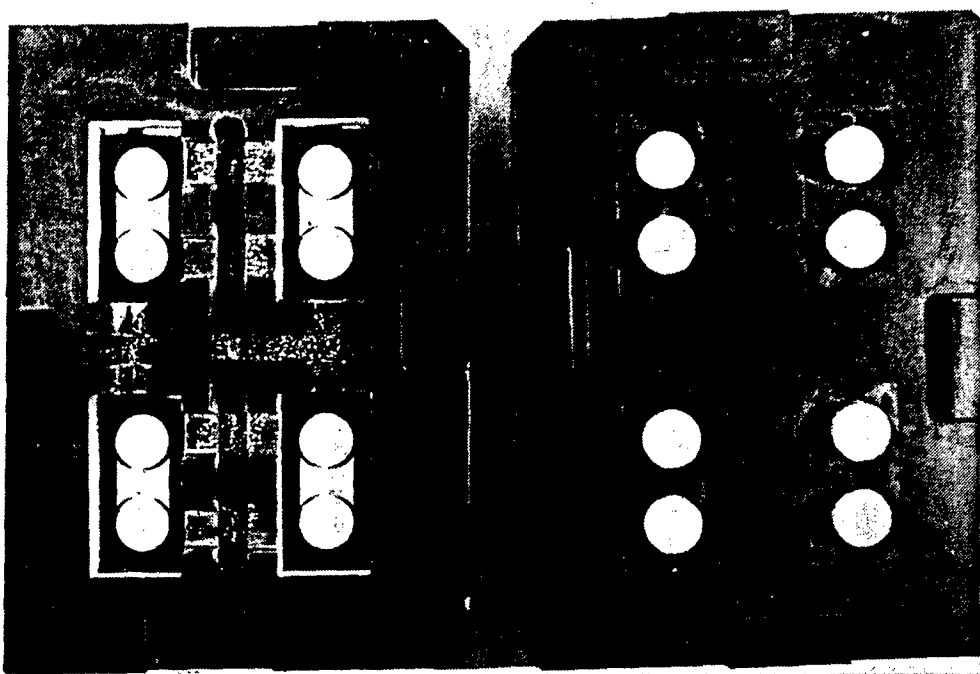


Figure 5-4. Epoxy Casting Mold

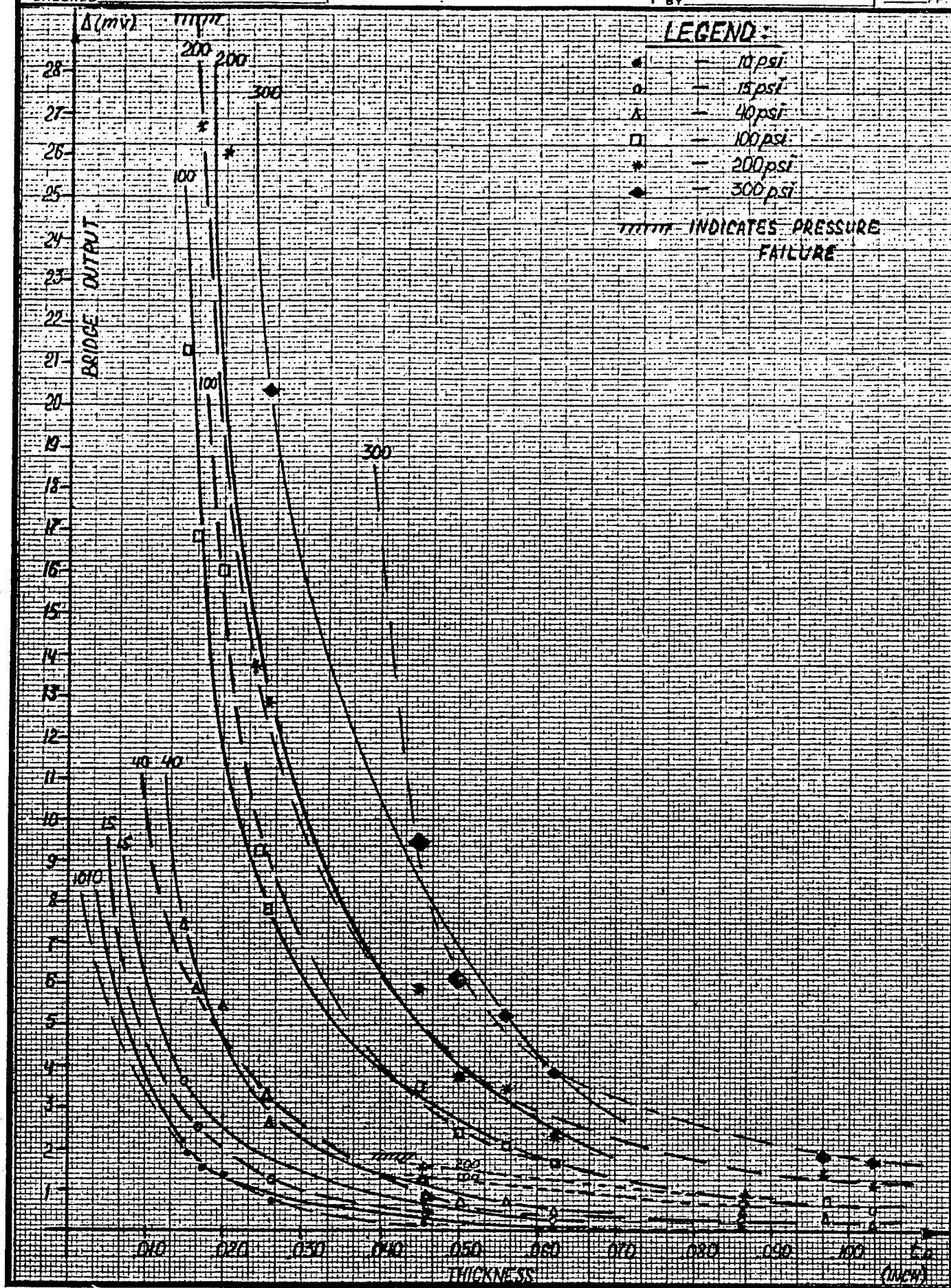


Figure 5-5. Performance Test of CADPT (Al-356 Casting)

Table 5-4. Collector Thickness Tests

Material	Pressure Range (Psi)								
	30	50	75	100	150	200	250	300	400
Al 2024(machined)					.029		.055	.061	
Al 356 (cast)		.015		.020	.032	.043	.055	.076	.095
ZA27(machined)					.040	.047			
ZA8 (machined)	.023			.025	.025	.040			.055
(4)INP RC1008(1)	.053			.061					
(4)INP RC1006(1)	.061								
<u>Polymer Design</u>									
PD-100 (machined)			.040		.089	.099			
<u>Dupont</u>									
Vespe1(1)									
Rynite 555(3)		.050			.060				
Zytel 70G33(3)		.036			.047				
<u>General Electric</u>									
Ultem 2400(3)			.047	.053	.060	.061	.072		
<u>Phillips</u>									
Ryton AG20-40(3)(5)					.053		.062	.088	
(machined)									
R-4(3)	.028		.044		.057			.088	
(molded)									
BR-90A(3)									
AC50-30(4)	.053					.085			
Vectra 150(2)(molded)									
Notes:									
(1)Failed in Machining									
(2)Failed in Molding									
(3)Glass-filled, Machined									
(4)Carbon-filled									
(5)Not Injectable									

Table 5-5. Metal Processing Survey

Process	Description	Material	Tolerance	Tooling Cost	Parts Cost 100	Parts Cost 1000	Source	Comments
<u>Casting</u>								
Flexible Mold	Urethane/Epoxy	356	± .005	\$750.00	\$3.85	\$3.65	A.L. Johnson	4-Cavity, 3-4 Ws. 125 Finish
Sand Cast	Plaster/Sand	356	.020	\$1,135.00	\$3.55		Alloy Casters	
	"	356	.010	\$1,960.00	\$8.40	\$10.90	Taylor Pohl	
	"	356	.010	\$1,900.00	\$5.00	\$3.00	American Prec.	
Die Cast	Machined Mold	380	.005	\$7,750.00	\$4.84	\$2.30	Wrex	
	"	380	.003	\$10,350.00	\$8.48	\$5.59	SXS	4-Cavity, 10 Ws.
	"	Zn/Al-27	.003	\$8,900.00	\$6.95	\$4.48	SXS	10 Ws., 6 Cores
	"	Stainless	.003	\$3,300.00	\$30.00	\$10.00	Prec. Found.	
	Permanent Mold	356		\$11,500.00	\$8.00	\$5.00	Stahl	110 Days
	"	380		\$9,700.00	\$5.00		El Monte	2 Cavity
	"	380		\$15,400.00	\$5.00	\$4.00	Amptech	
	"	CF3 Stainless		\$2,900.00	\$10.05	\$8.90	Valenite	Long Delivery, No Threads
							<u>Non-Responsive</u>	
							Pioneer	
							American Precision	
							Gries Dymcast	
							Consolidated Metals	
Investment Casting	Transfer Process	356/7075	.010	\$1,500.00	\$12.02	\$8.00	Rex	10 Weeks
		17-4PH		\$1,750.00	\$24.50	\$19.75	Rex	No Small Holes
		17-4PH	.005	\$3,206.00	\$10.00	\$9.70	Prec. Found.	No Threads, Long Del.
<u>Forging</u>								
Powder Metal Forming	High Press. Spec. Dies to 100 Ksi High Temp.	Many Ferrous Alloys O1-Steel 3030 Str	.003					
			.012	\$15,000.00	-	-	Ferralloy	Resin Impreg., 20 Ws.
			.005	\$9,984.00		\$5.97	Cermet	Resin Impreg., Deburr, Partial Holes, 15 Ws.
	Sintered/Pressed	316		\$5,895.00	\$7.14	\$7.01	Wakefield	Offshore, 6 Drill Stops, Resin Impreg.
	Sintered/Pressed	O1-Steel	TBD				Symco	Slab Only, Resin Impreg. Large Quantity Only
	Vac/Sintered	17-4PH		\$4,800.00	\$20.00	\$10.00	Nat. Forge	Demand Larger Quantities

Table 5-5. Metal Processing Survey (Continued)

Process	Description	Material	Tolerance	Tooling Cost	Parts Cost		Source	Comments
					100	1000		
<u>Forging</u>			+/ -					
Metal Injection Molding	Pressed/Vacuum	316/17-4PH	.003-.005	\$1,500.00	\$50.00	\$18.00	Amax	Resin Impreg., With Threads
Hot Isostatic	Special Tooling & Containment Vessel	Most Alloy Powders	.002 .005	\$50,000.00	-	-	IMT	Need Larger Production Quantities
Impact Methods	High Pressure High Speed Deep Drawing Coining Hydraulic Forming Explos. Forming						Non-Responsive Advanced Metals Metal Impact Explos. Fab.	
<u>Machining Operations (Outside Services)</u>								
	Mult. Tooling	6061 3034	.001	\$2,100.00	\$34.40 \$39.70	\$9.13 \$23.30	El Monte "	10 Weeks "
	Turnstone Tooling	7075/T6	.001	\$2,500.00		\$16.00	WERC	

circular forms. This method does not appear to lend itself to the present high-strength aluminum requirement.

- (e) The highest precision in aluminum alloy castings is obtainable with vacuum-assisted castings. The molds are of the permanent type and not considered economical unless large quantities are procured. Vacuum-casting foundries declined to make their services available for moderate quantities.
- (f) Investment and centrifugal castings are also employed for producing stainless steel parts (17-4PH, 316, 304). The cost of the parts (and weight) is relatively high, and no prototype data were taken for this project.

5.5.2. Plastic Injection Molding. The injection molding process depends primarily on selection of a suitable polymer base material for fabrication of the CADPT. With minor design adaptation of the injection dies various polymer materials (both reinforced or homogeneous) may be used to turn out reasonable parts. This is a low-cost production method provided that suitable dies are constructed and production rates are maintained. Mechanical tolerance is equivalent to that obtained with metal casting ($\pm .005$). See, for example, Appendix C, for quantification of the force collector thicknesses and tolerance comparisons.

Secondary operations for threaded holes and force collector thickness dimension is generally required, as well as minor finishing and polishing operations. Secondary threading operations can be avoided if costly die inserts are constructed.

Injection molding of prototypes in high tensile polymers was carried out. See Table 5-6. Aluminum alloy dies with a hard surface treatment were deemed satisfactory for preproduction quantities. The hard coating was considered, because the composite polymers for the CADPT application are of the glass-filled type and would otherwise have a tendency to erode the walls of the mold during production. The steel molds used would not be as vulnerable to such erosion. A photograph of the injection mold is shown as Figure 5-7.

Figure 5-8 is a finished CADPT glass-reinforced body. In addition to the glass-filled materials, consideration has been given to carbon-reinforced elastomerics. The carbon-filled materials, in general, exhibit a somewhat higher tensile strength but have a significant increase in the elastic modulus. This would tend to insure better endurance and lower hysteresis characteristics with thinner sections. As of this writing, sample carbon-reinforced Polyphenylene Sulfide (PPS) has only been made available from one source--Phillips

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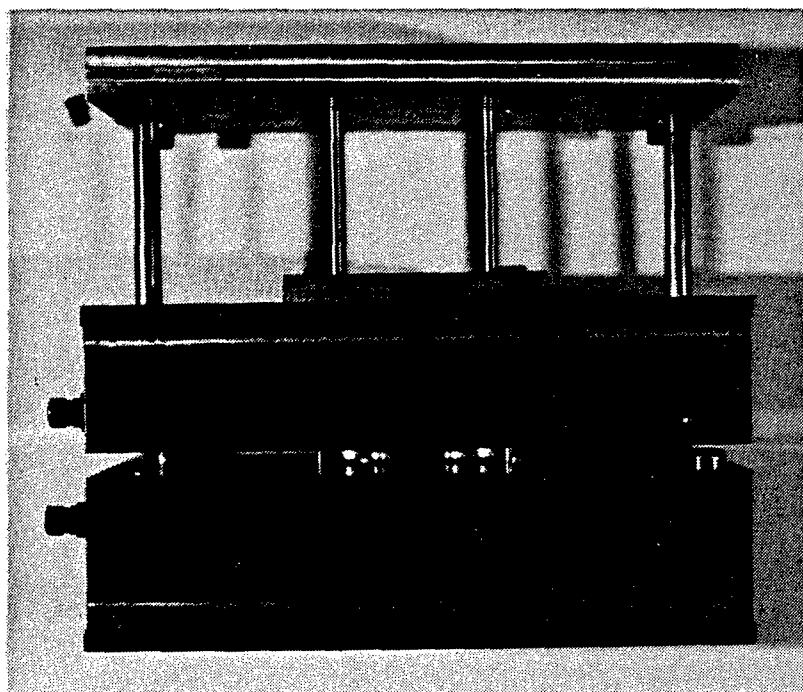


Figure 5-7. Injection Mold

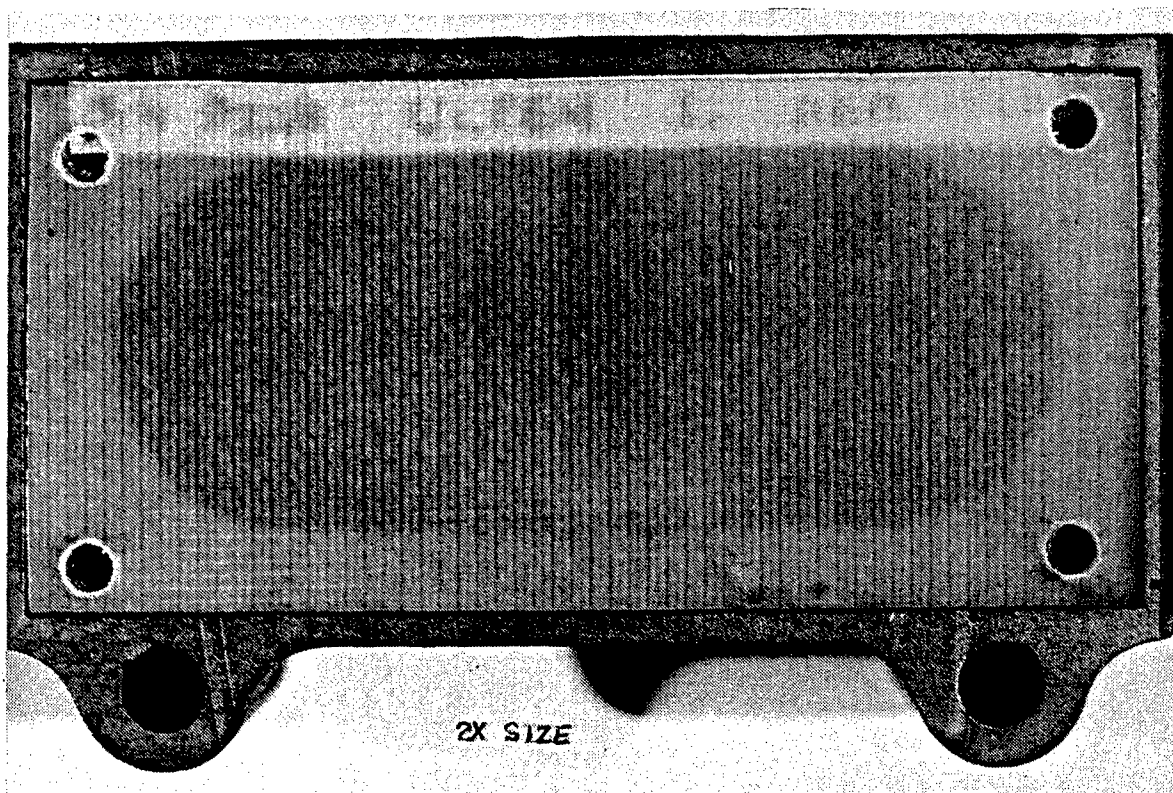


Figure 5-8. Glass-reinforced Polymer CADPT Body

Table 5-6. Injection Molding Survey

Material	Tooling	100	1000	Vendors	Comments
6/6 Nylon-40% Glass	\$25,702.-	\$2.52	\$1.52	Rakar	Single Cavity, All Threads
6/6 Nylon-30% Glass	\$14,300.- \$4,300.-	\$5.00 -	\$3.68 -	ITE Whiting	Each Thickness Mold Only
VespeI	\$4,600.-	\$30.00+	\$19-27	Dupont	Propr. Tooling
Valox	\$4,925.- \$8,750.-	\$3.81 \$7.00	\$4.33	Abtec Lord	1 Cavity
Ryton R-4	\$2,750.-	\$4.00	\$3.45	Plastic Source	
Zytel	\$10,900.-	\$4.00	\$2.79	Amptech	
Reinforced Urethane	\$2,450.-	\$19.00	\$15.95	Polymer Design	Low Modulus
Polymide QF1004	\$3,440.-	\$12.00	\$0.708	Tektronix Plastics	
R-4	\$3,575.-		\$1.10	Lim Plastics	1 Cavity
R-4	\$3,800.-	\$3.75	\$2.50	<u>PRO-ACTION</u> Phillips	
Vectra 150		\$3.50	\$3.00	Phillips	
BR90A/Glass		\$6.00	\$5.00	Phillips	
AC50-30/Carbon		\$18.00	\$5.00	Phillips	
Rynite 555		\$4.00	\$3.00	Dupont	
Ultem 2400		\$4.00	\$3.50	GE	
Ultem 7201/Carbon		\$20.00	\$15.00	GE	
Ultem 7801/Carbon		\$20.00	\$15.00	GE	

Petroleum - Type AC5030. General Electric does not have their carbon-filled PEI, polyetherimide, commercially available without a special order. Dupont is not currently marketing the carbon-filled type for injection processing. Many other manufacturers of polymers were contacted, but the material properties offered were of lesser capabilities than those used for prototyping.

The injection molded parts, similar to the case of cast aluminum parts, may require a secondary machining and polishing operation to bring the force collector dimensions within the tolerance needed for accurate electrical output. Thread elements are best added after molding. This leads to a consideration of a more conventional production method--a complete machining process.

5.5.3. Automatic Machining. It is patently possible to produce high-precision CADPT bodies by conventional machine processing. The trick is to manufacture machined parts at low cost. Automatic machining in quantity production could fulfill the cost requirement. Use of a computer controlled milling center is a means to this end provided that tooling for simultaneous set-up of multiple units can be arranged. Use of CNC machining can be an effective tool in reducing cost, even with high strength, relatively tough materials. In fact there is little restriction on any particular type of materials employed.

In considering the CNC operation, single-shot production was ruled out from the standpoint of efficiency and cost. When the CNC machine is programmed for operating on one part, it is a relatively simple matter to machine a large number of parts in sequence. To evaluate a program for complete finish machining on metal parts, a 3-axis machine program was setup. By appropriately mounting multiple parts on a "4th axis" indexing center, rapid production could be obtained. It was necessary to employ a special milling fixture, known in the trade as a "tombstone." Figure 5-9 shows the setup for Tombstone Machining. The CADPT parts could be mounted on four faces of a rectangular tombstone. By appropriately clamping the transducer bodies and employing a CNC rotary indexing head which is programmed for the job, high speed machining can be performed. All machining required on the prepared rectangular body of the CADPT can be completed in a single set-up. This accelerates the production time interval per unit.

The material cost enters into the evaluation, but materials can be selected from a variety of metals, composites, matrices or polymers to suit the application. The other factors entering the cost estimate include tooling amortization over the anticipated production volume, processing cost, handling

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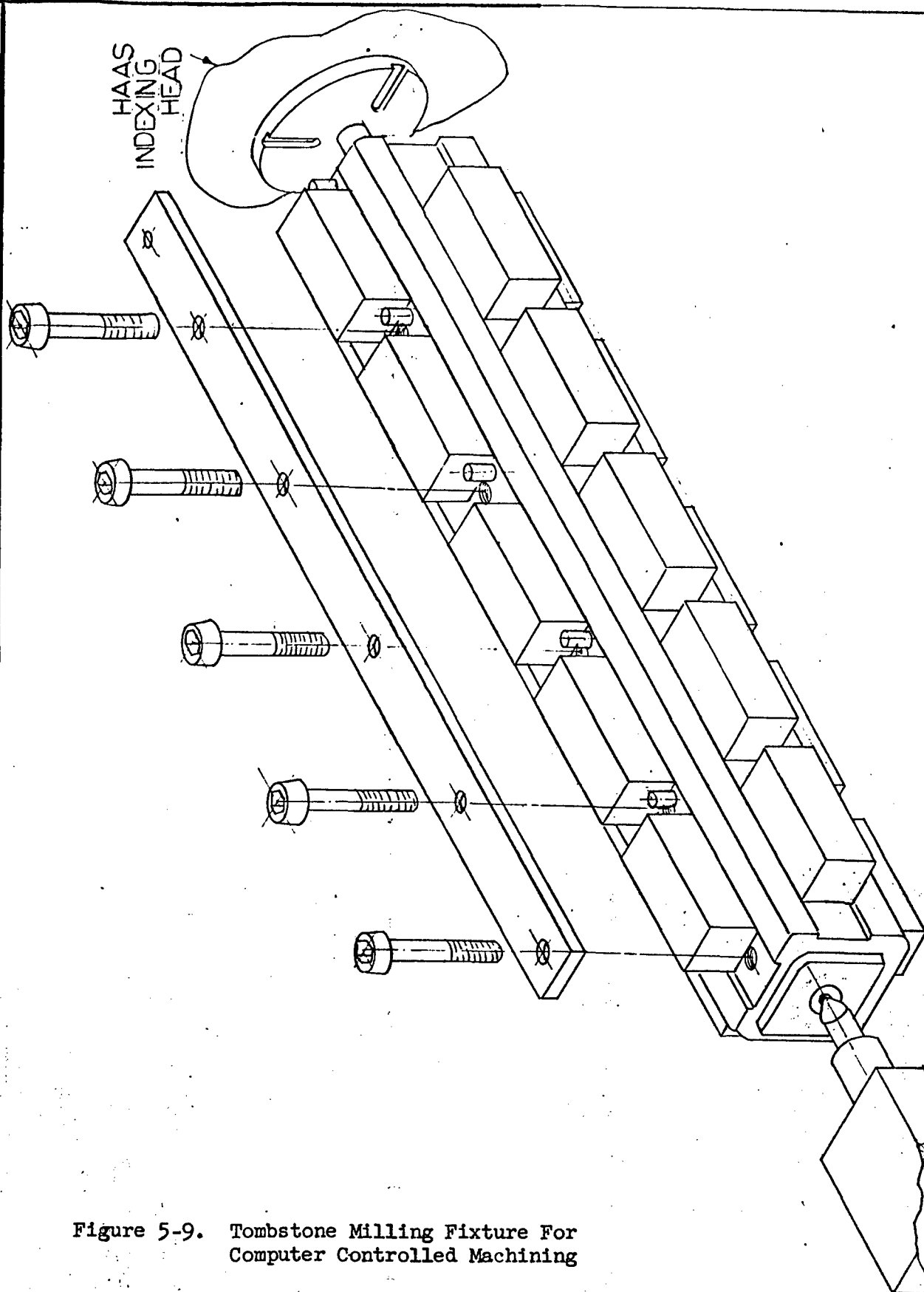


Figure 5-9. Tombstone Milling Fixture For Computer Controlled Machining

operations, sensing element installation, electrical adjustments and testing operations.

Of course, a major advantage of the machined parts is closer tolerance and better finishes without further handling. A comparison of parts cost for labor and material only is shown in the graph of Figure 5-10. Estimates of total costs are based on projections of in-house labor, and subcontract processing quotations are shown in Appendix B. These estimates are to be refined, as more current data is made available.

Another advantage to the CNC method is that any type of metal or composite material can be produced to close tolerance, by use of appropriate cutting tools.

5.5.4. Ceramic Forming. Ceramic transducer elements can be formed from ceramic powders under pressure and high temperature. Such materials as alumina and beryllia are frequently used to form the collectors of transducers. However, more complex assemblies with nonsimple geometry and variation in wall thickness dimensions, such as found in the one-piece CADPT, are difficult to produce. This leaves cylindrical and disk structural elements as the commonly used geometry, which require additional assembly and sealing operations.

Thin disk elements are needed for low-pressure response but are frangible. However, disk-type elements can provide a satisfactory design basis for a transducer, but complications arise in assembly to a housing. It is difficult to cast threaded holes, or even straight holes in the initial forming; therefore, secondary threading is mandatory before firing. Shrinkage in the curing cycle must be considered.

Nevertheless, ceramic materials were investigated for the CADPT force collector. Acceptable results were obtained with a thick film sensing element (D.J. Instruments). This unit incorporated signal conditioning electronics and sealing elements. The associated cost did not encourage serious consideration for a lower-cost production model.

A ceramic sensing element is also available in a piezoceramic material such as PZT. These materials generate a signal in response to applied pressure, but in addition to the assembly of the sensitive disks to an independent housing, the disk must be electrically connected from two sides and sealed against the applied pressure. One side of the sensing element is exposed to the working fluid. On the other hand, thick film techniques have been applied to screen print strain sensitive elements on the protected side of the ceramic disks. Test data has been included on ceramic element performance in

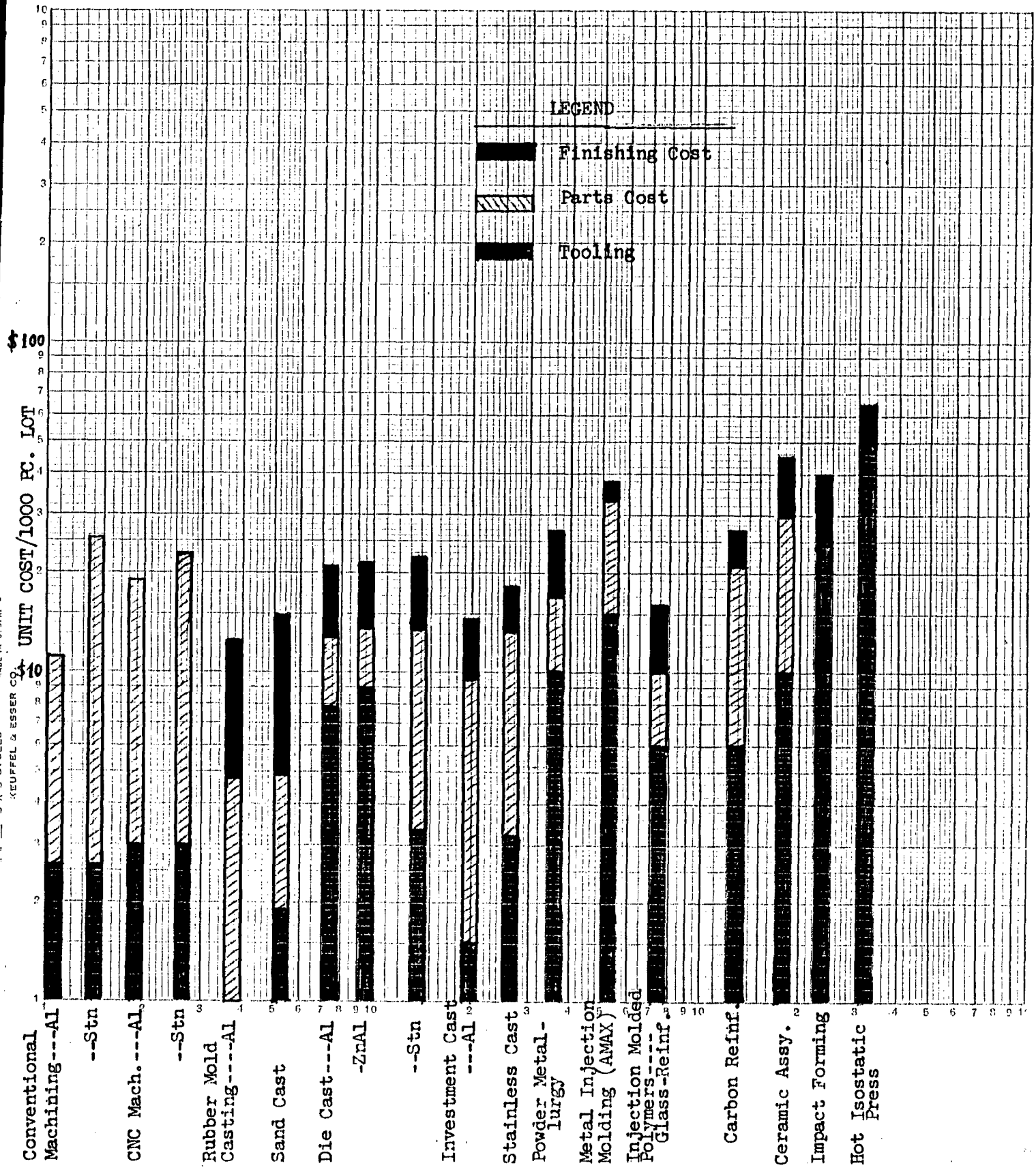


Figure 5-10. Relative Manufacturing Cost* CADPT Body (Various Processes)
 (*1000 Pc. Production Quantity, Excluding Instrumentation)

Figure 5-11 for thick film gages and compared to some piezo-ceramic results.

Of course, a ceramic pad can be used as the base for a strain gage or capacitive sensing element but this introduces an additional stage in the transducer assembly. The ceramic pad must be joined and sealed to the base assembly. For the CADPT, this was regarded as an undesirable complication, and this method was eliminated from further consideration.

5.5.5. Other (Forging Related) Forming. Conventional forging methods generally employ expensive dies and are primarily limited to simple shapes and rough finishes. Inherent requirements include secondary machining operations which are necessary to hold tolerance.

A spectrum of methods have been explored by which the CADPT can be produced efficiently and economically. Consequently, some rather attractive processes have been investigated, as well as others which are not quite so readily applied to the problem for a variety of reasons. Table 5-5 reports the results of a survey of the various processes investigated.

Among the processes considered for production of the CADPT were powder metal forming, hot isostatic pressing, coining, deep drawing, ceramic forming. In each case, either the geometric requirements, or the limitations on production quantities necessary for payback on tooling, prevented proceeding to the prototype stage.

Some modern forging methods utilize impact forming at high pressures, hydraulic forming, explosive forming, and deep drawing (thin enclosures). None of these forging methods appears to be compatible with the CADPT structure drawing. Double-sided cavities are not feasible for forming in a single operation. This is particularly the case for threaded holes and thin center sections (force collector). Uniformity of repeated impacts is limited to produce only rough dimensions in a single shot. Impact tools have a short life.

The negative reasons can be reviewed to put the program in perspective.

- 1) The technology exists to carry out a number of other fabrication procedures, but the interest of existing industrial sources has not been forthcoming. These methods are:

- a. Coining

- Structure of the CADPT too massive for coin press

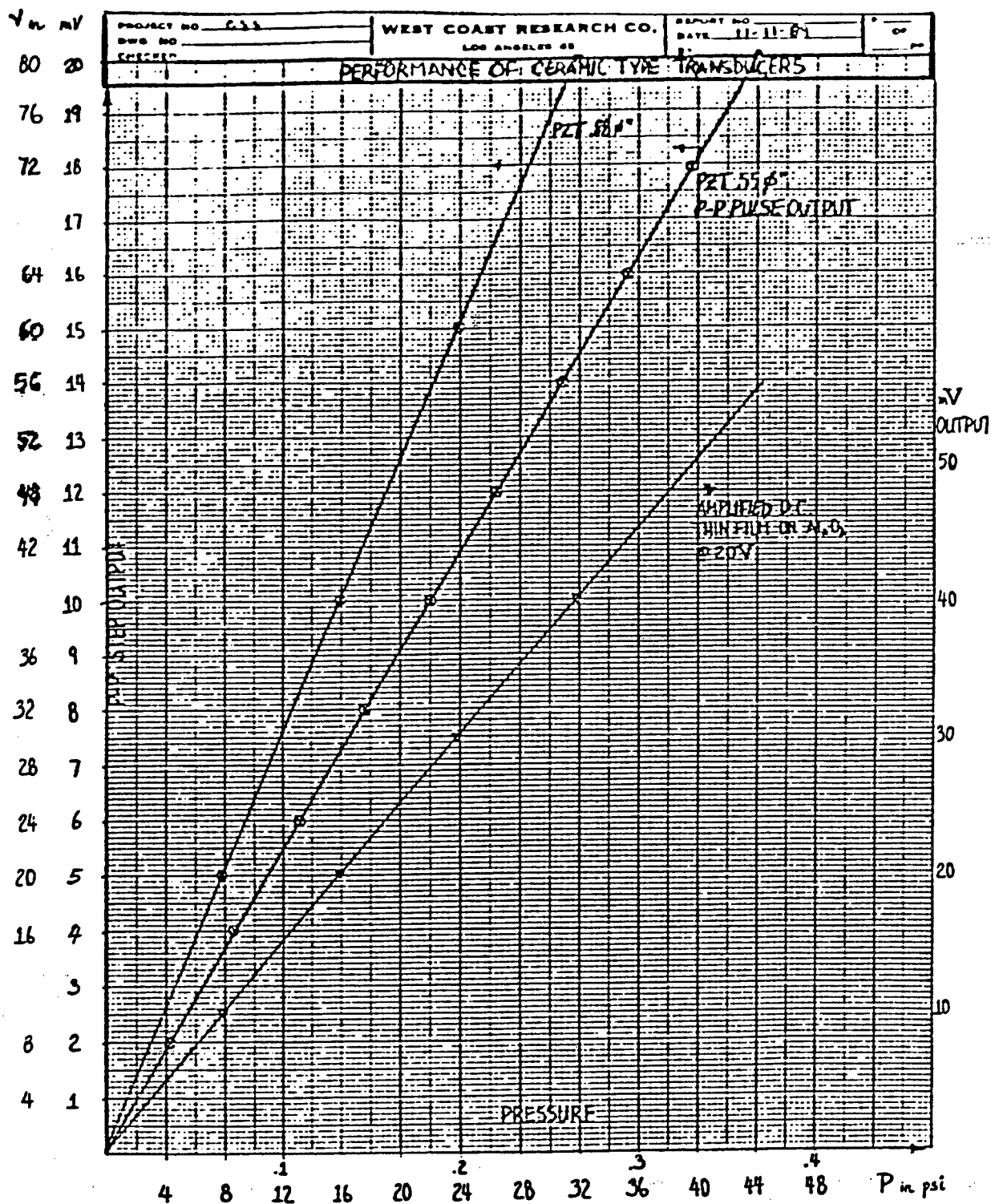


Figure 5-11. Ceramic Type Transducer Performance

forming. Satisfactory only with relatively thin sheet forming or more simple geometries.

b. Deep Drawing

Similar problems to (a) above.

c. Explosive or Hydraulic Forming

May be feasible in theory but requires development testing of high-cost and specialized machines. This is similar to impact forming techniques. Also, hydraulic forming techniques involve complex tooling and is restricted to thin sections.

One newer method of (powder metallurgy) forming is a production process which promises to be suitable for small quantities. In order to take advantage of a new process patented by Advanced Metal Systems of Torrance, Calif., a redesign of the basic one-piece structure of the CADPT would be needed. Some consideration was given to this requirement, but the decision not to proceed was made in conjunction with the other material processes under consideration and the attendant time delay.

5.5.6. Specialized Forming Processes.

5.5.6.1. Powder Metallurgy. The powder metallurgy process has great appeal for a shape such as employed for the CADPT. The metal powder is placed in a mold under pressure and sintered under elevated temperature. To obtain a pressure-tight assembly, epoxy resin impregnation is applied. However, the powder metal processors are reluctant to quote to the tolerance requested. Holding close tolerance on thin sections may not be feasible. The vendors also are more interested in repeat annual production orders of quantities in excess of 25,000 pieces. It has generally not been possible to interest any of a number of sintered metal processors in developing the tooling for the CADPT job.

5.5.6.2. Metal Injection Molding. Metal injection molding is a form of powder metallurgy. The tooling is similar to that used for plastics injection molding. Other companies use the powder metal as a base for pressure compaction, rather than direct injection into the mold.

A late quotation has been obtained from one company (AMAX), and this is currently being pursued. Results should be obtained under a Phase III effort.

5.5.6.3. HIP. Hot isostatic pressing (HIP) is a high temperature and pressure process applied inside a sealed uniform pressure vessel in which the specimen is immersed. The tooling obviously is complicated and expensive; consequently, very large quantities or high-priced parts should only be considered. With high-precision dies, close tolerance is possible. The HIP forming is similar to powder metal pressing except that an inert fluid medium is used to transmit the pressure in a closed hydrostatic vessel. Special sealing is required for the pressure vessels. It is particularly effective for densification of castings, molded parts or ceramics. Tooling involves massive high-temperature presses, and the investment is not economical for quantities of less than, say, 10,000.

5.6. Performance

The ideal transducer should have a perfectly elastic response. This is necessary in order that nonlinearity and hysteresis do not interfere with the pressure signals measured by the transducer.

In the design of the CADPT, a force collector is employed which is in the form of a disk (or diaphragm) integral with the supporting structure (rigidly clamped plate). When the input pressure is applied to the transducer, the force collector undergoes a small but finite deflection. The deflection is governed by the geometry and the applied pressure and is given by the formula (1).

$$\delta = \frac{3}{16} \frac{P m^2}{\pi E m^2 t^3} \left[\frac{(a^2 - r^2)^2}{a^2} \right] \quad \text{Eq. 1}$$

where P = applied pressure
 m = reciprocal of ν , Poisson's Ratio
 E = Modulus of Elasticity
 t = thickness of the diaphragm
 a = Radius of the diaphragm
 δ = deflection of the diaphragm at
 a distance r away from the center

A diagram of the deflection function is shown in Figure 5-12.

So long as we select a design point around which the deflection remains linear with applied pressure, a proportional output signal can be obtained from the transducer. In practice, it is found that good linearity will result when the maximum force collector deflection is less than the thickness. "Perfect" elasticity assumes that hysteresis in the force

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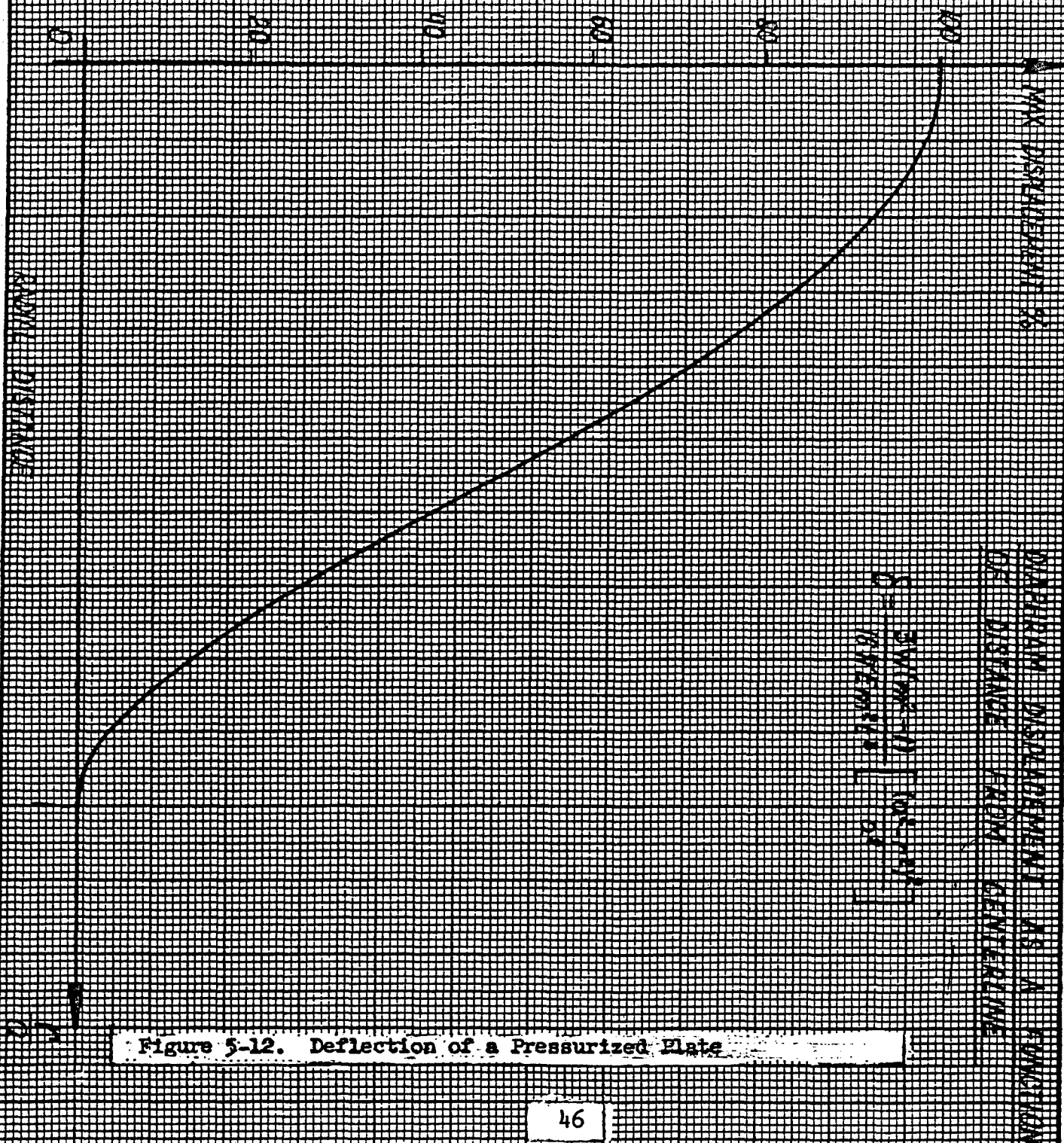


Figure 5-12. Deflection of a Pressurized Plate

collector will have a completely insignificant effect on the output signal. However there are other components of the strain gage assembly which can make a contribution to hysteresis and nonlinearity.

These include the adhesive layer employed to effect a bond of the strain gage, the strain gage elasticity, deformation of the transducer structure, and other characteristics. In addition, a protective sealing coat employed may fall short of pure elastic behavior. Any load imposed by the wiring connection can also be a factor. Thus the total error contribution can be considered as a series of component errors.

$$E_T = e_R + e_h + e_r + e_{ro} + e_a + e_s + e_w + \text{-----} \text{Eq. 2}$$

The subscripts refer to possible error sources which are considered in design of a strain gage system.

Where T = total
 R = resistance
 h = hysteresis
 r = non-repeatability
 ro = zero resistance
 a = adhesive aging
 s = sealing
 w = wiring load

Each of these factors may be taken into account in the design and installation of a strain gage pressure transducer.

Other effects that may be of significance include the sensitivity to temperature, humidity, vibration, shock and other environmental conditions.

5.7. Design Integration

The initial effort in the development involved preliminary testing of raw materials for fabricating the CADPT bodies. Bar stock and plates were procured, and the transducer prototypes were fashioned by conventional machine operation on the solid bars and plates. These prototype bodies are illustrated in Figures 5-13 and 5-14.

Strain gage sensors were installed on the fabricated bodies. Conventional strain gage techniques were employed to measure performance.

Figure 5-15 shows test results on a group of cast aluminum bodies. Here the output from the strain gage bridge is shown over a range of pressures.

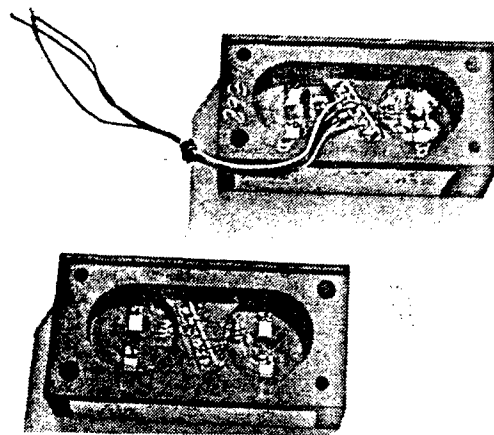


Figure 5-13. Prototype (Photo)

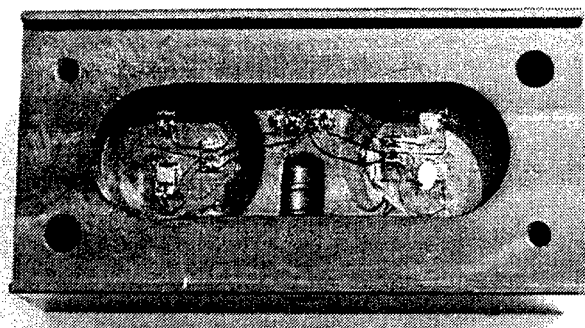


Figure 5-14. Prototype (Photo)

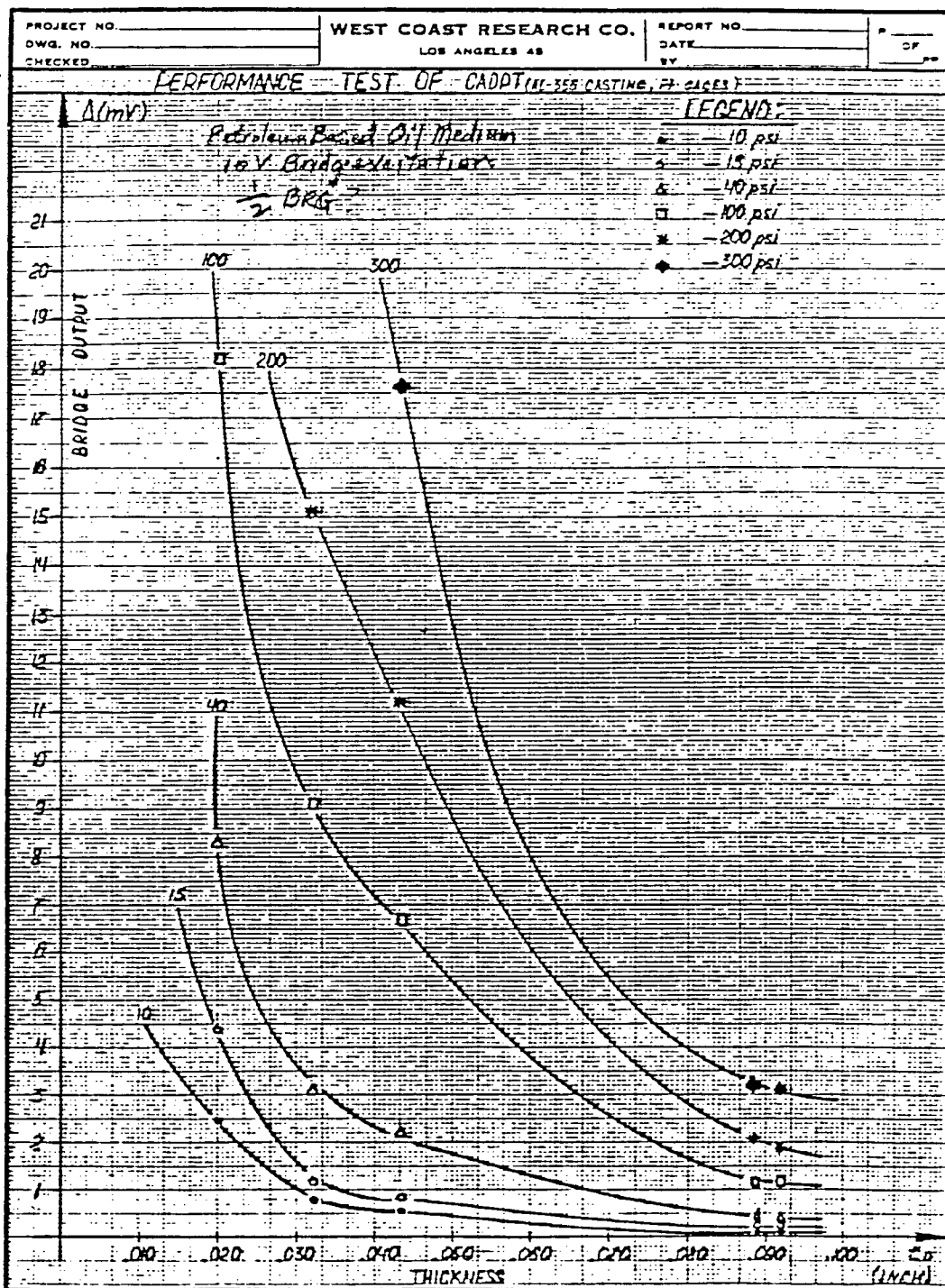


Figure 5-15. Cast Aluminum Transducers - Output Performance as a Function of Applied Pressure

A half bridge arrangement was generally used to obtain preliminary data. The data was used to confirm the requirements for sensitivity as a function of force collector geometry and placement of the strain gage elements. Diameter and thickness of the force collectors was considered.

Figure 5-16 similarly shows output sensitivity for a group of prototype machined polymer bodies as a function of pressure and collector thickness.

The limits of the transducer force collector thicknesses corresponding to estimated pressure ranges were initially determined from bar stock sample tests. It was found that some materials sampled could not be relied on to contain the applied pressure in thin sections. The glass-filled polymers required that minimum force collector thicknesses be determined. The envelope of measured values are indicated in the Figure 5-17.

Final force collector thickness dimensions were then calculated for application of silicon strain gages. The thicknesses used to avoid vulnerability to leakage are shown in Table 5-7. The composite polymers were selected after elimination of several nonperforming samples.

Having established the internal geometry necessary for the glass-filled polymer CADPT, attention was then turned to the output level required for compatibility with the DCA (STE/ICE) system input requirements. The general requirement is to provide a 100mv DC signal and utilize the specified 12VDC excitation. In other words, a full-scale input from the CADPT should provide a signal level of $+8.33\text{mv}/V_{\text{exc}}$. In order to achieve this level consistently, it was decided to investigate the high sensitivity afforded by the silicon chip strain gages. Corresponding thickness for the different pressure ranges is shown in Table 5-7.

Injectable materials were procured, and an injection die mold was constructed. A photograph of the injection die is shown in Figure 5-7. Figure 5-18 (Note 1) is a drawing of the injection molded geometry. We were then in a position to evaluate the injectable CADPT base materials following the same strain gage evaluation procedure used on the bar stock-glass reinforced units. Results are presented in Table 5-8.

For some pressure ranges, it became apparent that a strain gage with lower output sensitivity (and lower thermal response) could also be employed. Low thermal response is an essential characteristic for strain gage installations. Calculations were then made for platinum foil gages which

CALIBRATION OF COMPOSITE POLYMER TRANSDUCERS
(Ambient Temperature)

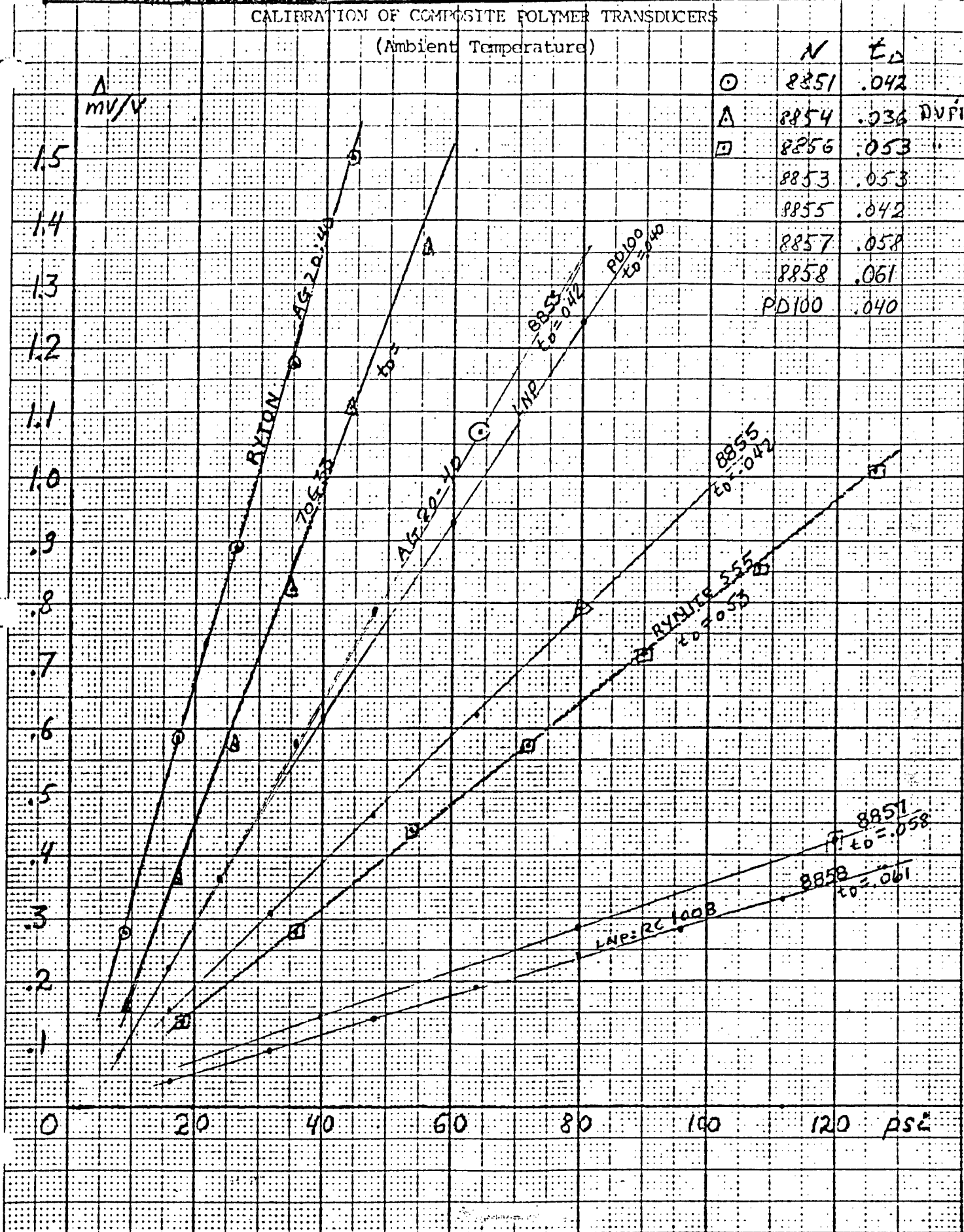


Figure 5-16. Output Sensitivity vs. Pressure on Polymer Force Collector

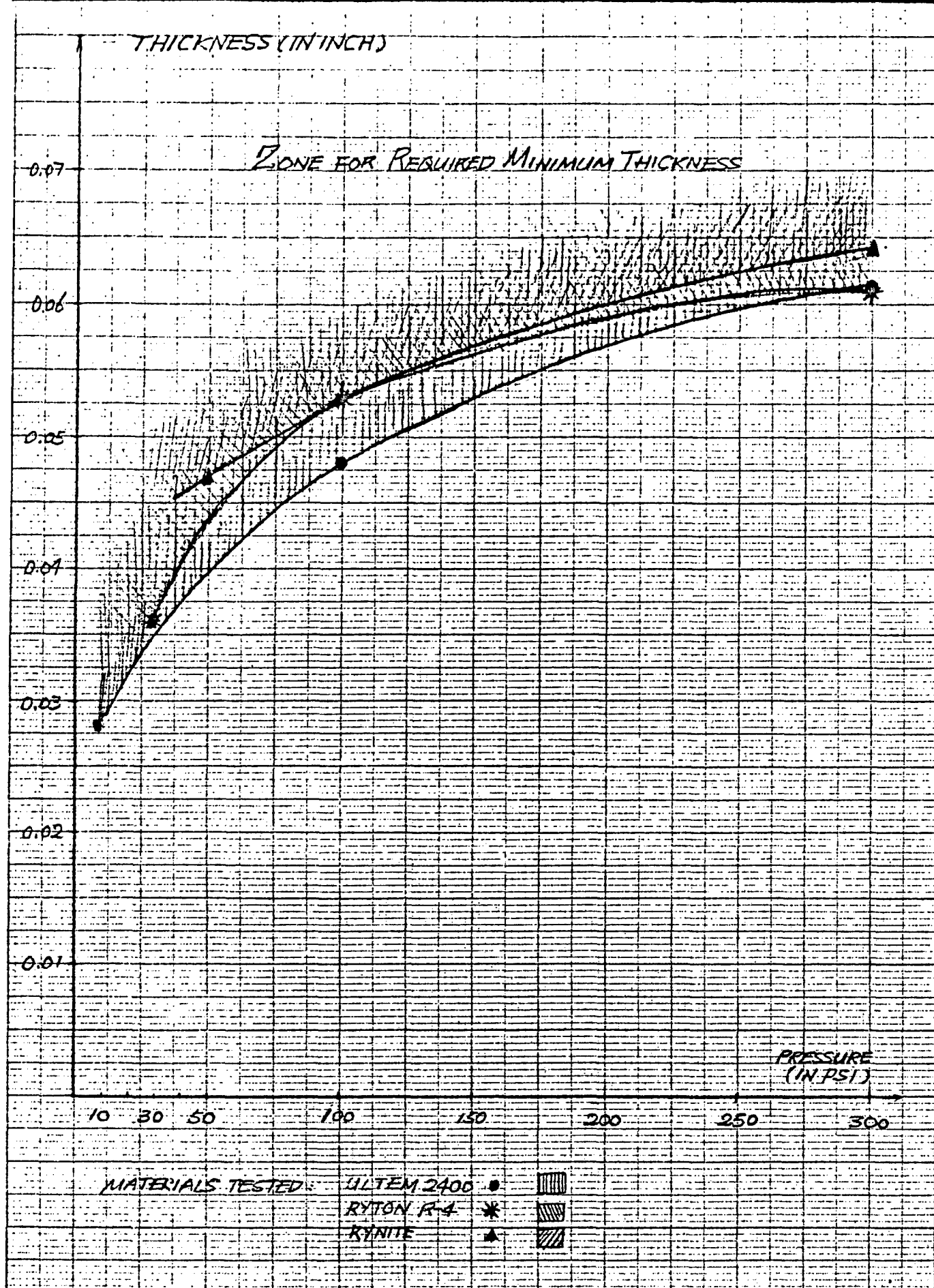


Figure 5-17. Polymer Force Collector Minimum Thickness Envelope

Table 5-7. Required Force Collector Thicknesses for Silicon (Si) Gages Extrapolated from Initial Strain Gage Measurements

Serial No.	Collector Thickness	Material (Gage Type)	Max. Pressure	Conventional Gages mv/V Output	SiGage (1) Output	Necessary Collector Thickness (2)
9142	.049	Ultem 2400 (paper)	100	.104	6.24	.0420
9144	.048	Ultem 2400 (paper)	100	.124	7.44	.0454
9346	.081	Ultem 2400 (paper)	260	.094	5.64	.0667
9288	.080	Ryton (paper)	240	.0816	4.896	.0613
9290	.084	Ryton (foil)	300	.174	10.44	.094
9123	.062	Ryton (paper)	260	.307	18.42	.0922
9124	.061	Ryton (paper)	260	390	23.40	.102
9175	.062	Rynite (paper)	100	.430	25.80	.1091
9175	.065	Rynite (foil)	100	.476	28.56	.120
9176	.060	Rynite (paper)	100	.110	6.62	.053
9141	.061	Rynite (foil)	100	.408	24.48	.105

Notes:

(1) Si Output = 60X Foil Gage Output.

(2) Thickness to Yield 8.33mv/V Full Scale.

Table 5-8. Required Collector Thickness for 100mv Output

Thickness of the Collector (Inches) to Get 8.33mv (= 100mv Full Scale) Sensitivity at 12 Volts Excitation.												
Material	PSI				Platinum Gaged				Silicon Gaged			
	100	300	500	1000	5	10	15	30	50	100	300	
Al Cast 356		.028	.036	.051	.019	.027	.033	.046	.060	.085	.148	
Ultem 2400	.047	.082	.105	.149	.055	.079	.097	.136	.177			
Ryton R-4	.041	.071	.092	.131	.022	.049	.070	.085	.138	.154		
Ryton 50-30C (Carbon-filled)		.046	.059	.083		.044	.054	.076	.099	.142		
Ryton BR90A	.037	.064	.084	.188	.044	.063	.077	.108	.140			

could fulfill this alternative approach. Table 5-8 shows the data calculated for the platinum elements.

The attractiveness of using the composite material construction is reflected in the compliance of basic structure. The relative effectiveness can be estimated from the flexural modulus, elongation, and tensile modulus of the reinforced polymer construction. Selection is based partly on information listed in Table 5-8. See also Appendix C, p. C-5.

5.8. Sensing Elements

The investigation has concentrated on the types of sensing elements known as variable resistance strain gages. These gages are normally employed in a wheatstone bridge configuration, as shown in Figure 5-19. Excitation power is applied across the bridge in one direction (Terminals 1 and 2) and an output signal is extracted from the bridge in the other direction (Terminals 3 and 4).

Other types of sensing elements can be applied to the CADPT configuration, but the techniques and circuitry are sufficiently different to require a separate development effort. It is the opinion, based on extensive experience, that the resistance strain gage bridge applied to a force collector surface, by bonding under elevated temperature conditions, results in superior long term stability, reliability, ruggedness, with reasonable accuracy. The DC circuitry associated with the bonded strain gage is simpler and less subject to the effects of noise, vibration, shock and EMI than sensor systems based on A.C. It is immune to ordinary effects of mechanical handling after bonding (generally with epoxy cements) to the mounting surface. Consequently such other methods as: capacitive sensing; or variable reluctance sensing; which can conceivably be used in this application have been excluded except as referred in a patent application⁽²⁾.

Several types of sensing elements in the resistance strain gage family are shown in Table 5-9.

The number in the third column represents the relative strain sensitivity of the gages. This is expressed in terms of output ratio divided by strain ratio.

$$G.F. = \frac{mv/V}{S/Y}$$

Eq. 3

⁽²⁾ Patent Disclosure

Table 5-9. Strain Sensing Characteristics

	Material	Typical Gage Factor
Wire Grid	Constantan (Advance)	1.9
Etched Foil	Constantan (Advance)	2.1
Etched Foil	Platinum	4.5
Etched Foil	Isoelastic	3.0
Single Filament	Silicon Crystal	135.0
Thin Film	Platinum	5.0*
Thin Film	Special Alloys	40-50*
Thin Film	Polycrystalline Silicon	100*

*Estimate

where G.F. (Gage Factor) = a measure of sensitivity of the gage material

mv = voltage output in millivolts

V = excitation voltage applied to the wheatstone bridge configuration

S = strain, in psi, resulting from a pressure applied to force collector

Y = (Young's) Modulus of Elasticity in psi

The characteristics of the various strain gages available are reviewed.

5.8.1. Wire Grid Gages. Wire grid gages may be applicable to the present project but do not conform as well to the stressed substrate (force collector) on which mounting is performed. Lead attachment to the wire grid introduces an area in which reliability may be affected. These gages are not as compact as the foil grid gages but are useful in some geometric applications and can be prepared in a variety of wire materials. Figure 5-20 shows an installation using wire grid gages. However, these have been largely superseded by foil types.

5.8.2. Etched Foil Gages. Etched foil gages are produced by photolithography and are provided on a laminated backing in compact and miniature envelopes. Having a thin profile, adherence to the mounting substrate is enhanced. Depending on the type of material of the grid, a range of gage factors can be obtained. Currently the G.F. range commercially available is from 2.0 to 4.5. These gages are easiest to manipulate and install. Balancing the bridge circuit and compensating for thermal effects on zero offset and span (sensitivity) is more straightforward than with other gage types. Figure 5-21 shows some foil gage installations on the CADPT.

5.8.3. Silicon Strain Gages. Silicon strain gages constitute a special class which are an outgrowth of semiconductor technology. The gages are generally tiny, being a few millimeters in length and a few mils in width. This represents a small sliver of silicon to which gold lead wires are attached in a typical semiconductor bonding joint. Failure in handling and installation usually occur at the bond between the silicon and the gold leads, although the gage is quite fragile prior to

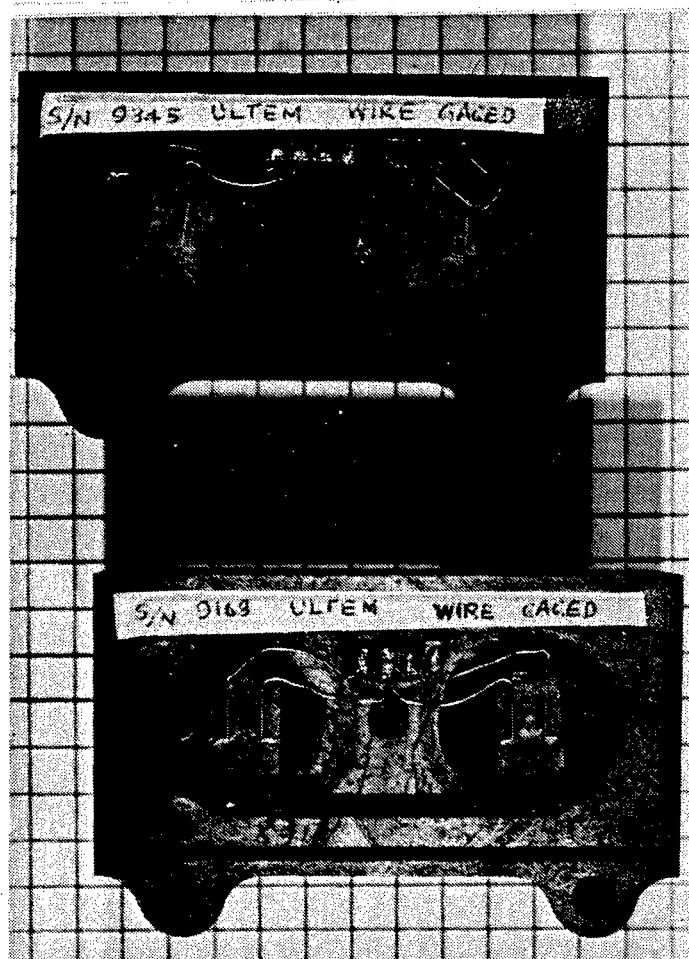


Figure 5-20. Wire Grid, Installation

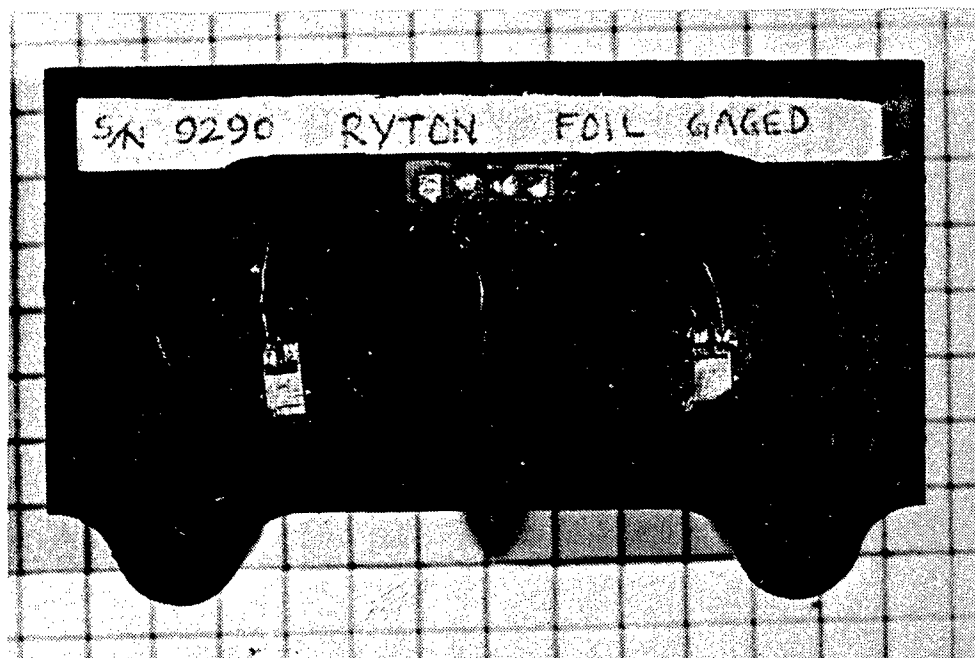


Figure 5-21. Foil Gages Installed on CADPT

installation and may crack or develop a diode fault, if mechanically overstressed before mounting. However, once mounted, the silicon gages are amenable to rugged handling. The silicon gages have an exceptionally high output (G.F. >100) but also have a correspondingly high temperature sensitivity. To minimize changes of output with temperature, sometimes tedious circuit compensation procedures are required. This involves counterbalancing this change with a resistive element with a high T.C. which changes precisely in the opposite sense when connected in the circuit. Figure 5-22 shows several silicon gage installations on the CADPT bodies. The thermal compensation elements are shown as R_5 and R_m in Figure 5-19.

5.8.4. Thin-Film Gages. Thin-film gages represent a relative new technology which requires innovative procedures to obtain the matched, stable, precision performance characteristic of modern strain gage practice. Thin films are deposited on substrates in a high to medium vacuum environment. A beam of ions, electrons, or atoms is directed at a target, causing emission of a beam or plasma of the target material. This beam is deposited on the film substrate to execute a pattern. The pattern is determined by a mask inserted in the path of the particle beam. Calculations show that a simple single grid (similar to the silicon sliver) provides the required geometric characteristic to produce a resistive sensing element. Utilizing the vacuum deposition procedure, copper lead wires can also be laid down, so that electrical connection problems are largely accommodated. This is demonstrated in Figures 5-23 and 5-24 (twice actual size) showing the circuit network.

Special preparation of the substrate is usually necessary, and an insulating layer is laid down if the substrate is electrically conductive. Close tolerance in the masking and lead bonding technique is imperative in attempting to match the resistive and thermal characteristics of the individual deposited film elements.

5.9. Theory of Strain Gage Pressure Transducer

When the strain gages are connected in a wheatstone bridge, the output is given:

$$e = \frac{E}{4R} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \text{ at constant current} \quad \text{Eq. 4}$$

where R is the nominal resistance of a sensing arm of the bridge and

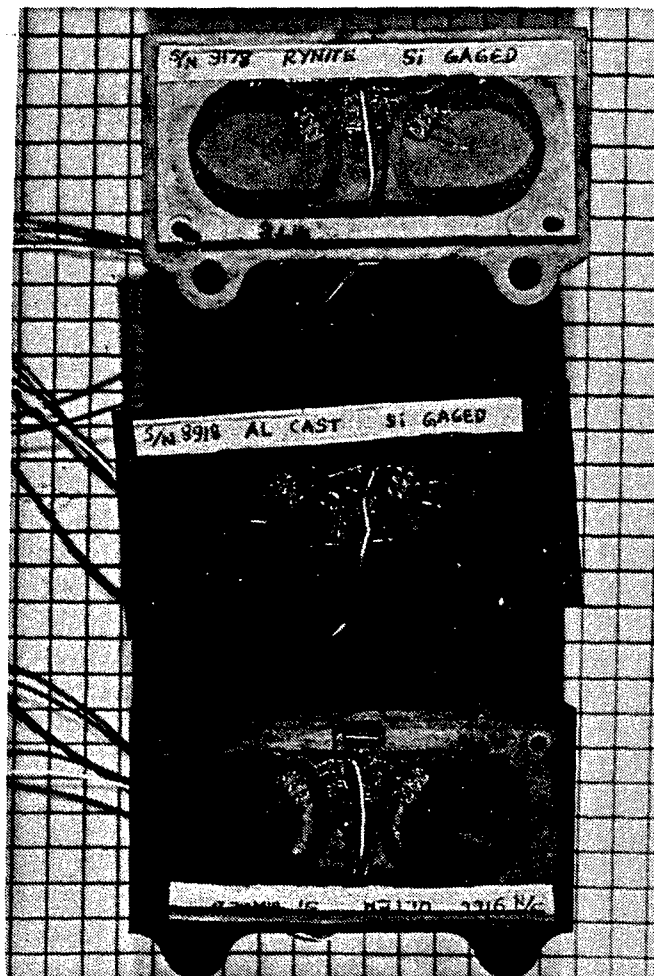


Figure 5-22. Silicon Gage Installations

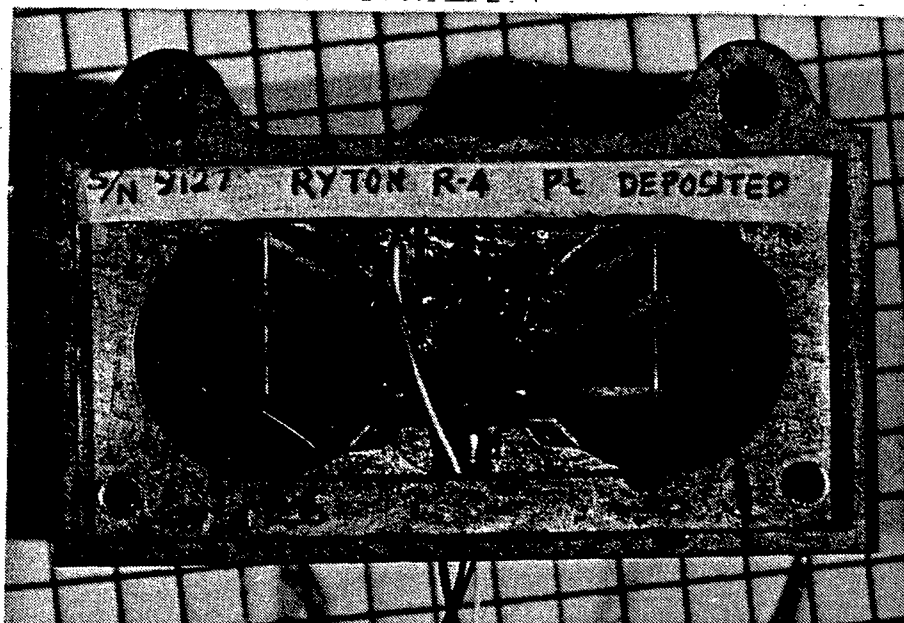


Figure 5-23. Platinum-Deposited Thin-Film Circuit



Figure 5-24. Silicon-Deposited Thin-Film Circuit

R_1, R_2, R_3, R_4 are the strained resistance values
and

$\Delta R_1, \Delta R_2, \Delta R_3, \Delta R_4$ are the change in the corresponding resistance.

Calculations show that when pressure is applied to one side of the force collector, a deflection of minuscule magnitude is caused. Table 5-10 shows some actual deflection measurements of the CADPT force collector. When deflection is small compared to the thickness dimension of the collector, the deflection is proportional to applied pressure. The corresponding strain measured by a strain gage mounted on the surface of the force collector is then relatively linear with applied pressure. The formula for deflection of a cylindrical disk rigidly fixed at the periphery is given by Eq. 1. This was plotted in Figure 5-12.

Sensing elements are aligned in the radial direction of the force collector disk, to obtain maximum signal due to small deflections.

The stresses imposed at the periphery and at the center of the disk are given (in the radial direction) respectively, by:

$$\sigma_{\text{wall}} = \frac{3a^2P}{4t^2} \quad \text{Eq. 5}$$

$$\sigma_{\text{center}} = -\frac{3}{8} \frac{a^2P}{mt^2} (m+1) \quad \text{Eq. 6}$$

where P = applied pressure
 m = reciprocal of μ ,
Poisson's ratio
 a = radius of the disk
 t = thickness

In order for the fabricated unit to behave as predicted by the theoretical equations, the support for the central disk must be rigid. Also the force collector disk thickness must be small compared to the diameter, i.e., a "thin diaphragm," and the deflection under pressure must be much less than the thickness. In order to provide a relatively fixed mounting, the force collector is "built-in" to a "heavy" wall. The wall should have negligible deflection to mechanical installation loads, as well as applied fluid pressure. Figure 5-18 shows the configuration which fits the requirements, within reasonable tolerance, in a compact arrangement.

Table 5-10. Force Collection Deflections

$\frac{P}{t} = \frac{\text{Pressure}}{\text{thickness}} = \frac{\text{psi}}{\text{inches}}$		10 psi	50 psi	90-100 psi	130 psi	200-210 psi	250-300 psi
Material							
Aluminum Cast 356		10/.076 = .0000	50/.076 .0000	90/.076 .0005	130/.076 .0005	210/.076 .0005	250/.076 .0005
Ultem 2400				100/.048 .007		200/.044 .015	300/.062 .011
Ryton R-4		10/.028 = .003	50/.085 .0005	100/.044 .007		200/.061 .006	300/.061 .010
				90/.085 .001		200/.082 .0023	
				90/.104 .0005		200/.078 .003	
				100/.082 .0018			
Rynite 555		10/.047 = .001	50/.047 .004	100/.064 .003		200/.064 .006	200/.062 .010

5.10. Thin-Film Deposition Development

5.10.1. Introduction. The search for advanced methods and materials has led to consideration of innovative sensing techniques. Among these are the direct installation of strain sensing elements utilizing high vacuum deposition coating technology (analogous to semiconductor fabrication processes).

This technique would provide the means for directly installing strain gages on the CADPT force collector surface and would eliminate the need for:

- Time-consuming manual labor in handling delicate elements.
- Offsetting adjustments to the circuit.
- Temperature compensation.
- Internal wiring and the consequent contribution of minor assembly discrepancies to the overall error budget.

The thin-film coating technology, which already exists, is capable of implementing this advanced sensing application, provided specialized equipment, techniques, and material specifications can be fulfilled. The tasks, under this phase of the contract, were to acquire a suitable vacuum system within budget, develop the necessary peripheral equipment, and produce prototype thin-film CADPT units to successfully demonstrate this innovation. The equipment acquired for the purpose is shown in the photograph of Figure D-1 (Appendix D).

The properties of materials required for the vacuum strain gage element included:

- a maximum strain sensitivity,
- reasonable resistivity,
- good mechanical stability,
- low thermal sensitivity,
- compatibility with high vacuum deposition methods, and
- adhesion to the substrate.

The available thin film deposition methods considered filament evaporation, ion plating and electron beam evaporation and

selection of one of various sputtering processes. Theory and analysis of thin-film deposition is presented in Appendix D.

5.10.2. Vacuum Deposition Processes. The methods that can be applied to thin-film deposition in a vacuum system are of interest. One is the generation of a collimated ion beam in an argon atmosphere. Other gases can be used as the medium, depending on the material to be sputtered, the temperature of the target, and of the substrate and the film to be formed. Another deposition source is an electron beam generated in a high-voltage filament. The electron beam alone is most efficiently produced in an E-Beam gun which directs the beam of particles to the target by means of an intense magnetic field. High-speed depositions can also be attained with magnetron guns which are driven by high voltage RF sources or by DC voltages.

The physical vapor deposition processes such as vacuum evaporation and sputtering are proper media for the production of thin films. Advantages of thickness control, good adhesion, and process repeatability, at reasonable costs are available. The process can be scaled up for production. A study of these processes was done to explore optimum production methods for thin film strain gages.

In general, the science of physical vapor deposition has grown exponentially over the last 20 years. The various sputtering and ion plating processes are now well understood (Reference 3), and in use commercially for a wide range of applications. The physics of sputtering are summarized in classic articles by Sigmund⁽³⁾ and by Kaufman⁽⁴⁾. There is a wealth of literature to draw on related to these vacuum coating processes. However, searches of various databases has revealed little information on deposition of strain-sensitive pure metals, alloys, or composites suitable for the present application. It became necessary to review the properties of known materials in the solid form and infer the strain sensitivity characteristics of the deposited state. (Ref. 5 reports the results

⁽³⁾Peter Sigmund, "Theory of Sputtering", Physics Review, Series 2, 184, August 5-15, 1969.

⁽⁴⁾H.R. Kaufman, "Technology of Ion Beam Sources in Sputtering", Journal Vac. Sci. Technol., 15(2) March/April 1978.

⁽⁵⁾Julian Delmonte, Harry Albaugh, Daniel S. Baker, Charles B. Spence, "Advanced Strain-Gage Pressure Transducer", Report No. AFWAL-TR-82-2009, Gould, Inc., March 1983.

of one thin film study, but details on applicable material properties were not available.) Evidently, an extended research and experimental program will be required under a Phase III operation to discover the ideal thin film strain gage material and perfect the process. However, sputtering and evaporation processes are well suited to deposited film investigations. We are currently applying these techniques for in-situ strain element fabrication.

An important part of the vacuum technique is associated with the creation of a precision mask. The purpose of the mask is to interject a selective barrier or path between the substrate and the coating beam. By providing a carefully controlled pattern by means of which the deposited film adheres to the substrate, accurate results may be assured. The configuration of the pattern and the installation of the mask, particularly for a recessed substrate geometry, such as the CADPT, requires meticulous attention to achieve the quality needed for a set of matched strain gage films, with the desired characteristics. Figure 5-25 shows one mask set used in experimental depositions.

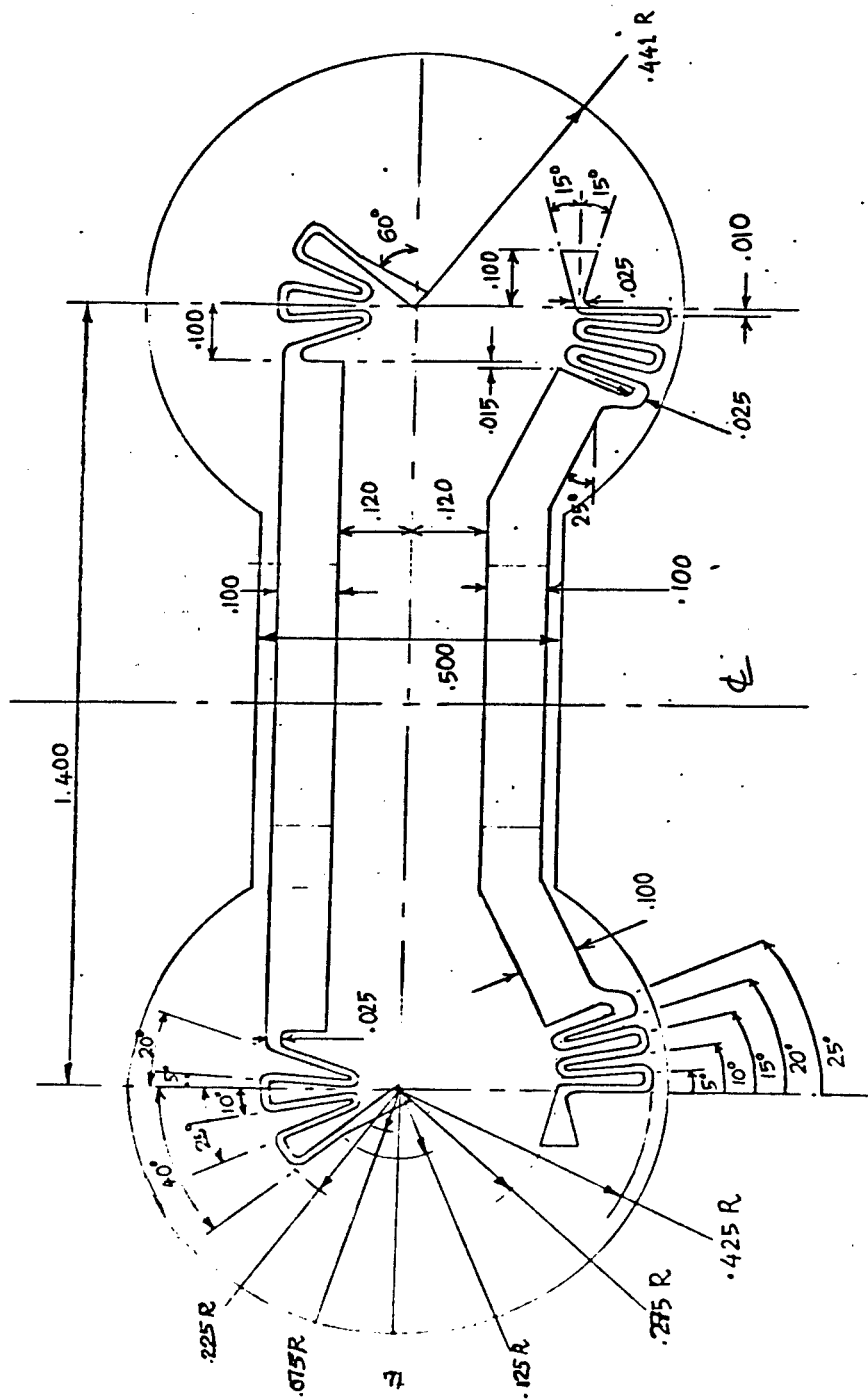
Appendix D provides a discussion of the vacuum evaporation deposition techniques and the classical sputtering technology.

5.11. Test Processing and Calibration

Testing of the instrumented transducers was carried out by applying pressure in a mechanical pressure calibrator and recording readings of the transducer output. See Figure 5-26 Pressure Test Set-up. The next major testing effort was to determine the performance of the transducers in an elevated temperature environment. Temperature cycles were run and data recorded on the final prototypes involved. In each case where the thermal effect was found to exceed $2\%/100^{\circ}\text{F}$ when subjected to a temperature excursion, temperature compensation was employed to reduce the thermal sensitivity to the stated value. Other tests carried out on samples involved effects of shock and vibration.

Since it is intended that the units be sealed at the factory, the effects of sand, dust, oil and water impinging on the outer surface of the CADPT were deemed to be of minor consequence.

In production processing of measuring devices such as the CADPT, it is necessary to carefully collect data on pressure sensitivity, temperature dependence, common-mode deviation of differential ports, linearity, hysteresis, repeatability and creep. Taking of data during the process of measuring and adjusting the wheatstone bridge elements to produce accurate



PL MASK (088)

WEST COAST RESEARCH CORP.

SCALE: 1:4, 10/16/89

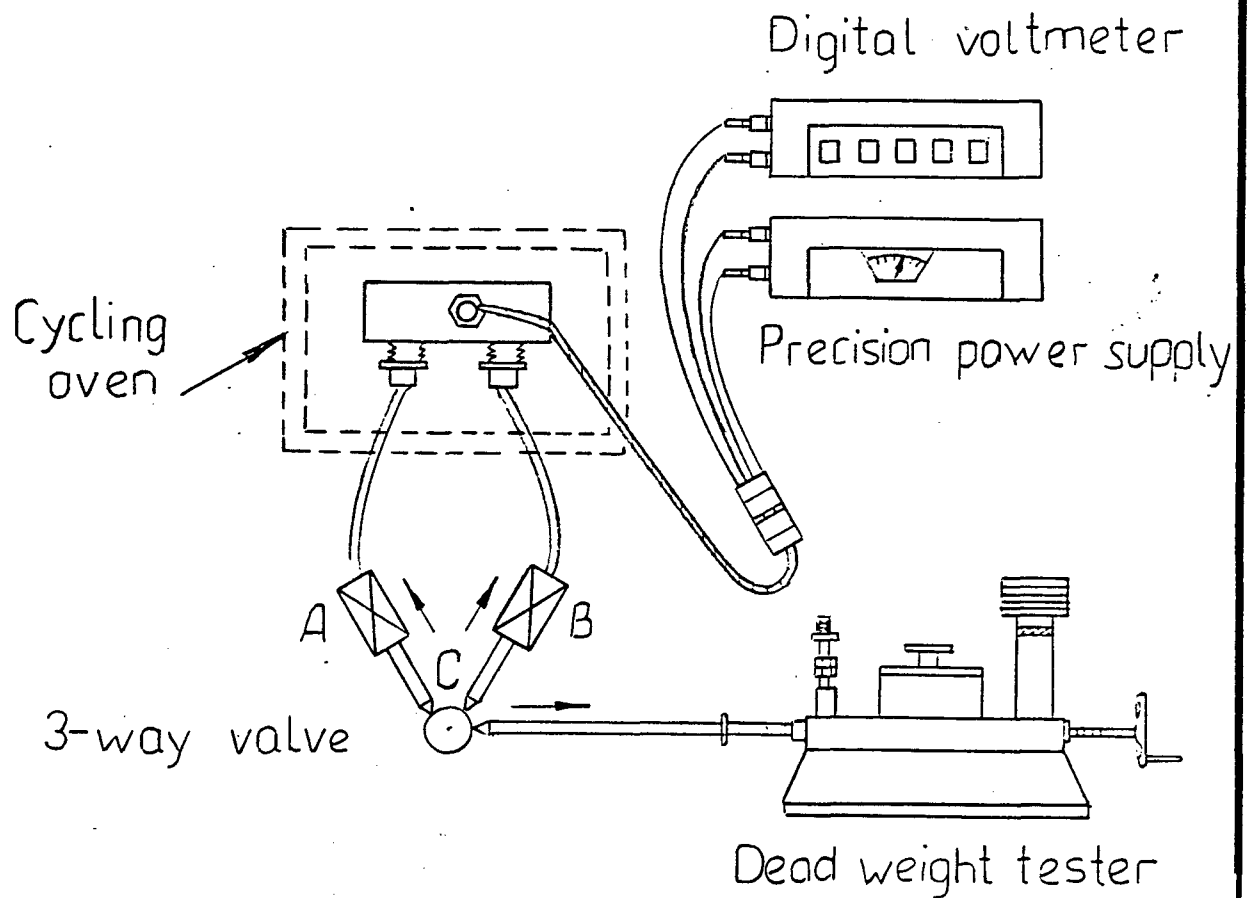
BY: TISSA

NOTES:-

1. ASSUME SYMMETRY ABOUT CL
2. WIDTH OF ALL THIN LINES = .010 (EXCEPT CORNERS)
3. CORNER RADIUS INNER = .010, OUTER = .005

Figure 5-25. Deposition Pattern Mask

PROJECT NO. <u>0088</u>	WEST COAST RESEARCH CO. LOS ANGELES 45	REPORT NO. _____	P. _____
DWG. NO. _____		DATE <u>4.11.90</u>	OF _____
CHECKED _____		BY <u>BALFOUR</u>	PP. _____



- A. Port A pressurized
- B. Port B pressurized
- C. Both ports pressurized

FIGURE 5-26. PRESSURE TEST SET UP (PRELIMINARY)

results is frequently a time-consuming effort. Since this would have a significant effect on unit cost, a more automatic test and calibration procedure was planned. (See Section 5.12.)

Computer-aided testing processing was setup (CAT). See Figure 5-27. In this process, a group of transducers are simultaneously evaluated and the necessary circuit adjustments are calculated by the computer and displayed on a monitor as well as printed out. After the adjustments are performed by the test technician, a final calibration to verify conformance within the prescribed error band is performed. A hard copy document thus can be produced for each transducer, and the operator/technician time is reduced by a large factor.

Software to direct the complete strain gage processing procedure has been written ("strainware"), and with minor input instruction, changes can be applied to other differential pressure measuring devices. The program essentially monitors initial strain gage bridge response and specifies correction values for zero offset, common-mode balance, output sensitivity and temperature compensation over a specified range. If an iteration is indicated to yield higher accuracy, the tolerance on the adjustments are also made available. The reduction in test and adjustment time, compared to a manual operation, is estimated to be at least a factor of 4/1.

The many tests on various materials that have been carried out during the development have been evaluated, screened and presented, as necessary, to illustrate the progress of the R&D cycle on the CADPT.

5.12. Data Acquisition

5.12.1. Calibration System Program Development. A common problem in transducer production is the testing time and manpower for performance measurement, evaluation and compensation. Methods to facilitate the production testing, circuit adjustments needed, and final calibrations were therefore pursued. It was decided to setup a system for automatic programming of multiple transducer tests in a computer controlled procedure.

Methods were followed for both a low and a high pressure range. The high-pressure range employs automatic pressure sequencing operated by a microprocessor control. The control sets a series of pressure levels governed by a servo valve and reference transducer. Actual readings at each pressure level are displayed, and provision is made for connection of multiple transducers and print-out of the measurements.

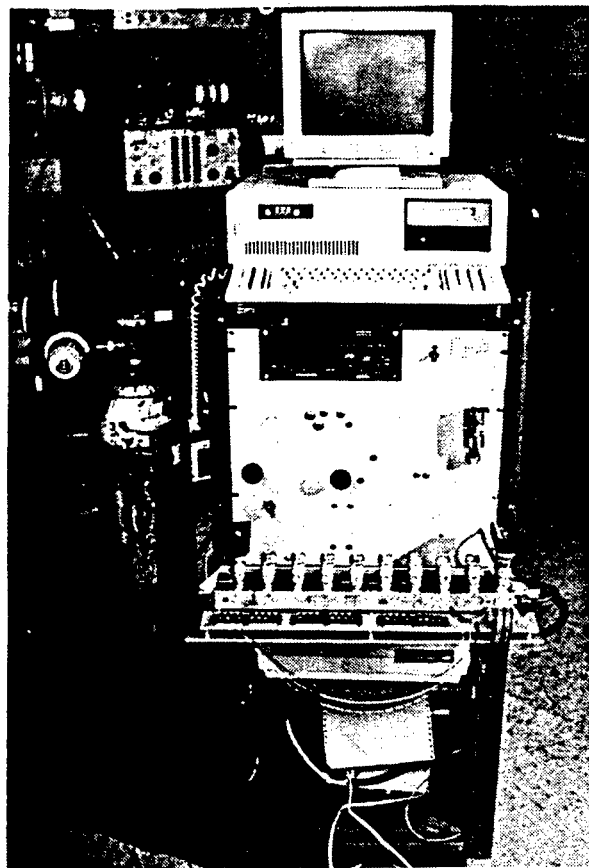


Figure 5-27. Computerized Pressure Calibration System

The low pressure system is operated by a computer driven program and can select from up to 10 differential transducers in or out of sequence. The status of each transducer is displayed on a screen and may be recorded on a printer. To assure system accuracy, a front-end microprocessor based multichannel converter is used to monitor and correct circuit errors exceeding a designated error band. Hardware has been assembled to operate the multichannel calibrator. Solenoid valves are used in a stepping mode to adjust the required pressure applied to a multitransducer manifold. The output from each transducer is indicated and the various error functions displayed.

The software not only allows indication of when the error band is exceeded but provides instructions for correction and compensation elements to be applied to the transducer circuit. This is exceptionally helpful in performing the necessary corrections and, as a result, significantly saves time.

The corrections provided include:

- common mode balance
- thermal drift effects
- span sensitivity adjustment
- null balance

In addition, the software is programmed to print out a record or plot of the final calibration data.

The differential pressure manifold employed and the system controller is shown in Figure 5-27.

The procedure for the calibration system program development may be summarized as follows:

- a) Development of the pressure calibrator control software is composed of the following stages:
 1. Test definitions. This embodies the types and procedural methods for calibration and QA testing of in-process and completed transducers.
 2. Test algorithm development. Formulas to extract transducer performance and derive corrective element values for in-process and QA testing.
 3. Database development. Definition of database for record storage, retrieval, and manipulation.

4. Program coding.
5. Program testing dry. Program components are tested independently of the calibrator hardware.
6. Integrated program test and debug. The program is tested in conjunction with the calibrator hardware.
7. Evaluation and refinement.

5.12.2. Data Acquisition System. The pressure calibration system electronics consists of the following components:

- a) Transducer mounting header. Multiple transducers under test connect at this point.
- b) Transducer multiplexer and signal conditioning board. This board contains:
 1. Transducer selection multiplexer.
 2. Measurement function selection. The following functions are available.
 - Differential bridge A
 - Differential bridge B
 - Full bridge
 - Bridge resistance
 - Amplifier null
 3. Solenoid valve drivers (pressure step input).
- c) Analog data acquisition card for personal computer. This card contains Analog to Digital, Digital to Analog, as well as direct digital interface circuitry.
- d) Host personal computer. The pressure calibration program is run on this device, and resultant data is retained on its mass storage devices.
- e) External pressure loop-controller. This device accepts a pressure command as either a voltage, (the low pressure), or a digital command sequence, (the higher pressure).

Operation of pressure tests follow a linear progression:

- I. The pressure calibration program first sets the solenoid valves via the acquisition card, (3) above, to the signal conditioning board, (2) above. This will establish that regulated high pressure will be applied to either one or both sides of the pressure transducer. (A) or (B) and (A + B).
- II. The program then outputs a pressure command to the external loop controller. The loop controller will drive the system to maintain the selected pressure.
- III. The program then measures both differential and full bridge outputs from each connected transducer in sequence.
- IV. The program loops back to Step II with a new pressure command, until all steps in the test sequence have been completed.

In practice, the program steps the pressure up to full scale in 10% increments and then steps downward to atmosphere in 10% increments. Thus, at the end of Step IV, the pressure system will be fully relaxed at atmosphere.

Certain tests, such as bidirectional differential pressure runs, will require that the process outlined above be followed twice. The first time, the "A" side of the transducer will be connected to pressure, while the "B" side is vented to atmosphere. On the second pass the situation is reversed, with "A" vented and "B" pressurized.

After the test data has been collected, the program then evaluates the data. The type of evaluation depends not only on the type of pressure test but also on whether the fixture is in the Manufacturing or the Quality Assurance modes.

Manufacturing tests take place on raw and in-process transducers. These tests are used to determine optimum compensating elements for the particular parameter being tested. Parameters include: common-mode pressure rejection, temperature coefficient of zero, and room temperature zero. As a transducer which is in-process is likely to be out of the tight tolerances, a finished-goods part will require the manufacturing tests use much more liberal rejection criteria than the QA tests.

QA tests take place on completed units before being placed in finished goods inventory. These tests are used to insure that the transducer now conforms to the product specification requirements. Test reports only log performance of the units

in their current (final) state.

5.12.3. Development Tests. The accuracy to which the data acquisition system can perform is limited by several factors:

- o Accuracy and drift of the electronics on the signal conditioning board.
- o Resolution and accuracy of the data acquisition card.
- o Resolution and accuracy of the pressure controllers.

The data acquisition card originally obtained for this system has a resolution of 12 bits, with -1 lsb accuracy. This implies a resolution and accuracy of 1 part in 4096 or about .025%. While on the surface this would appear adequate to produce transducers to .1% or .2% accuracy, it introduces some limitations.

The range of 4096 counts must include full scale in both directions. This cuts the effective resolution in half. Further, raw transducers and finished products alike are processed by the same system. Since raw transducers have higher sensitivities than compensated transducers, some further loss in resolution results. This is most evident during QA tests.

Further problems arise when consideration is given to certification of transducer performance. Actual transducer performance must be at least as good as the certification data indicates. As such, the uncertainty and errors inherent in the measuring system must be subtracted from the certification limits to arrive at accept/reject limits for the test system.

Given a test system of uncertainty N, in order to certify compliance to a performance standard M, the acceptance limit is given by:

$$T = M - N.$$

Performance spread of actual devices will be equal to:

$$PS = T \pm N.$$

Consequently, $PS_{low} = T - N$, and $PS_{high} = T + N = M$.

In the case of $M = .2\%$ and $N = 1\%$, $T = .1\%$, and $PS_{low} = 0$. Consequently, a .1% accurate test system is not practical for use certifying even .2% components.

To avoid this problem, the basic test system precision can be enhanced. This is done by improving analog to digital resolution and accuracy. Existing product technology has been adapted to realize a solution. It is in the form of a microprocessor based, multichannel converter, which supports up to 14 input channels. The microprocessor constantly corrects for drift in the analog circuitry, allowing a real accuracy of 1 part in 20,000 full scale.

When applied to this test situation, the 20,000 counts are again divided by four to realize the worst-case resolution on either side of zero. The resulting coefficient N is $1/5000$ or .02%. For a required M of .1%, we have $T = M - N = .1\% - .02\% = .08\%$. This results in a spread of PS_{low} to PS_{high} of .06% to .1%.

5.12.4. Program Requirements for Data Acquisition & Control System For Pressure Transducer Processing

a) An automatic sequencing control is required to perform the following functions:

1. Input multiple transducers up to 10 units simultaneously.
2. Read each transducer (in sequence).
3. Identify each by S/N.
4. Display (and print) reading = mv level
5. at each of 10 fixed pressures.
6. Pressure sequence selectable (range selectable) (equal increments).
7. Manual input of temperature excursion.
8. Temperature cycle in oven--manual.
9. Read (and print voltage change vs. temperature.
10. Compute resistance value required to compensate the wheatstone bridge for thermal deviation (display or print) R_{TC} . See Note (R_5).

Insert resistance.

11. Read transducer output @ 70°F.

12. Compute resistance value required to adjust offset of bridge to zero (+100mv) (display or print for each transducer) R_z .

Insert resistance.

13. Recycle to confirm results. If acceptable (i.e. +100 mv) then repeat Steps 7 thru 12.
 14. Perform 10 pt. up and 10 pt. down final calibration.
- b) Interface transducer test system with:
1. Pressure Control (CCC Controller for example).
 2. Computer (or Δp) program.

APPENDIX A

CADPT RESEARCH & DEVELOPMENT ROAD MAP

APPENDIX A. CADPT RESEARCH & DEVELOPMENT ROAD MAP

I. Materials & Processes Research

A. Database Searches

1. Material Laboratory Contacts

- a. U.S. Army
- b. NASA
- c. USC

2. Journal Publications

B. Material Properties--Manufacturers' Data

Composite Polymers

Glass-filled

LNP
GE
Phillips
Dupont
Amoco
Dow

Carbon-filled

Phillips
GE

Metals

Al. Alloys
Zn. Alloys
Powder

C. Sensor Properties

1. Strain Gages

a. Bonded

- (1) Foil--Constantan
- (2) Foil--Pt
- (3) Si
- (4) Wire

b. Deposited Film

- (1) Cu
- (2) Ni
- (3) Pt
- (4) Si
- (5) Alloys

2. Other

- a. Capacitive
- b. Ceramic Types
 - (1) Thick Film
 - (2) Piezo

D. Fabrication Processes

1. Machined Parts

- a. Automatic Machining
 - (1) CNC

2. Castings

- a. Aluminum Alloy
- b. Zn/Al

- c. Stainless
 - d. Sand
 - e. Epoxy
 - f. Die
- 3. Powder Metallurgy
 - a. Metal Injection
 - b. Sintering
- 4. Forging
 - a. Press Forming
- 5. Injection Molding
 - a. Reinforced Polymers
- 6. Finishing
 - a. Secondary Operations

II. Measurements Program

A. Data Acquisition

- 1. Structural Integrity
- 2. Pressure Calibrations
- 3. Geometric Adjustments

<u>Metals</u>	<u>Composites</u>
Machined Units	Injection Molded
Cast Units	
Metal Injection	

B. Analysis

- 1. Define Operating Envelope
- 2. CAD
- 3. Structural Analysis
 - a. Finite Element Program

C. Instrumentation

- 1. Manual Test Procedure
- 2. Automatic Calibration Equipment
- 3. Programmed Machinery
 - a. Remote Programming (CIM)
 - b. RamCam

III. Configuration Management

A. Basic Simplicity

- 1. One-Piece Concept
- 2. Patents

B. Construction

- 1. Casting Dies
- 2. Injection Molding

3. Powder Metallurgy
4. Press Forming

C. Machine Tool Operations

D. Economic Considerations

1. Cost of Materials
 - a. 356 3/#
 - b. Stain Steel 6/#
 - c. Aluminum/Steel Bar 4/#
 - d. GE Ultem 2400 20/#
 - e. Phillips R-4 20/#
 - f. Dupont Ryton 10/#
 - g. Carbon-Filled 48/#
2. Cost of Tooling
 - a. Dies 5,000-10,000
 - b. Tools 4,000-6,000
 - c. Minimal
 - d. Die Charge
 - e. Special Tools 10,000-20,000

IV. Equipment

- A. Computer-Aided Design (CAD)
 1. Automatic Calibration
 2. Automatic Circuit Layout
- B. Computer-Aided Manufacturing (CAM)
 1. CNC Center
 2. Automatic Fabrication
 3. Remote Programming (RAM-CAM, CIM)
- C. Laboratory Aids
 1. Surface Preparation
 2. Lead Bonding
 3. Microscopes
 4. Inspection Equipment
 5. Hand Tools
- D. Vacuum Laboratory
 1. Vacuum Deposition
 2. Electron Beam
 3. Magnetron Sputtering
 4. Ion Gun
 5. Thickness Gage
 6. Laser Trimming
 7. Die Bonding

- E. Other Laboratory & Test Items.
 - 1. Injection Molding Machine
 - 2. CNC Lathe

V. Projections for Phase III

- A. Publicity
- B. Information
- C. Marketing
- D. Drawings
- E. Development Equipment
- F. Joint Venture Sources
- G. Economic Considerations

VI. Recommendations

- A. Follow-on Funding
- B. Equity Capital
- C. Other Financial Arrangements
- D. Projecting Sales
 - 1. Federal
 - 2. Commercial

APPENDIX B
UNIT PRODUCTION/1000 RUN

APPENDIX B. UNIT PRODUCTION ESTIMATES/1000 RUN

<u>Material</u>	<u>Casting</u>	<u>Injection Molding</u>	<u>Automatic Machining</u>
356	2.00		
Polymer		3.00	
Al Bar			2.00
Powder Metals		4.00	
<u>Processing (Outside)</u>	3.00	5.00	12.00 (in- house)
<u>Secondary Operations</u>	2.50	2.00	-0-
<u>*Gaging, Silicon, Pt</u>			
Material	16.00	16.00	16.00
Labor, Gaging	15.00	15.00	15.00
Testing, Adjustment	10.00	10.00	10.00
Final Calibration			
<u>Distribution</u>	1.00	1.00	1.00
<u>Tooling</u>			
Amortization			
1000/Units	2.00	4.00	5.00
(10,000+ Units)	(1.00)	(2.00)	(3.50)
	\$51.50	\$56.00 (\$54.00)	\$61.00
	(\$50.50)	\$57.00 (\$55.00)	(\$59.50)
<u>Overhead</u>	22.50	26.00	26.00
<u>Profit</u>	7.10	8.40	8.70
<u>SELLING PRICE</u>			
Bonded Foil or Silicon	\$81.10	\$91.40	\$95.70
<u>ALTERNATE GAGING</u>			
<u>*Vacuum Deposition</u>			
1000 Units	45.00	45.00	45.00
10,000 Units	40.00	40.00	40.00
<u>SELLING PRICE</u>			
Vacuum Deposited Thin Film Gages			
1000 Units	\$85.10	\$95.40	\$99.70
(10,000 Units)	(\$80.10)	(\$90.40)	(\$94.70)

*Alternate Not Duplicative

APPENDIX C

SEMI-EMPIRICAL PRESSURE TRANSDUCER DESIGN

APPENDIX C. SEMI-EMPIRICAL PRESSURE TRANSDUCER DESIGN

The theory of elasticity applied to a strain gage pressure transducer, generally considers a plate or diaphragm rigidly clamped at the edges with a uniform pressure distribution over a force collector⁽⁶⁾. It is evident from the calculations of Figure C-1 that the higher strength of metallic aluminum permits use of thinner force collector sections. The reinforced polymers all require thicker sections to contain the applied pressures. However very thin sections in both aluminum and polymers are difficult to fabricate and prone to leakage. Therefore the thicker reinforced polymer section may be preferred for low pressure CADPT ratings. (See also Table 5-8, p. 56). Departure from calculated values may arise in:

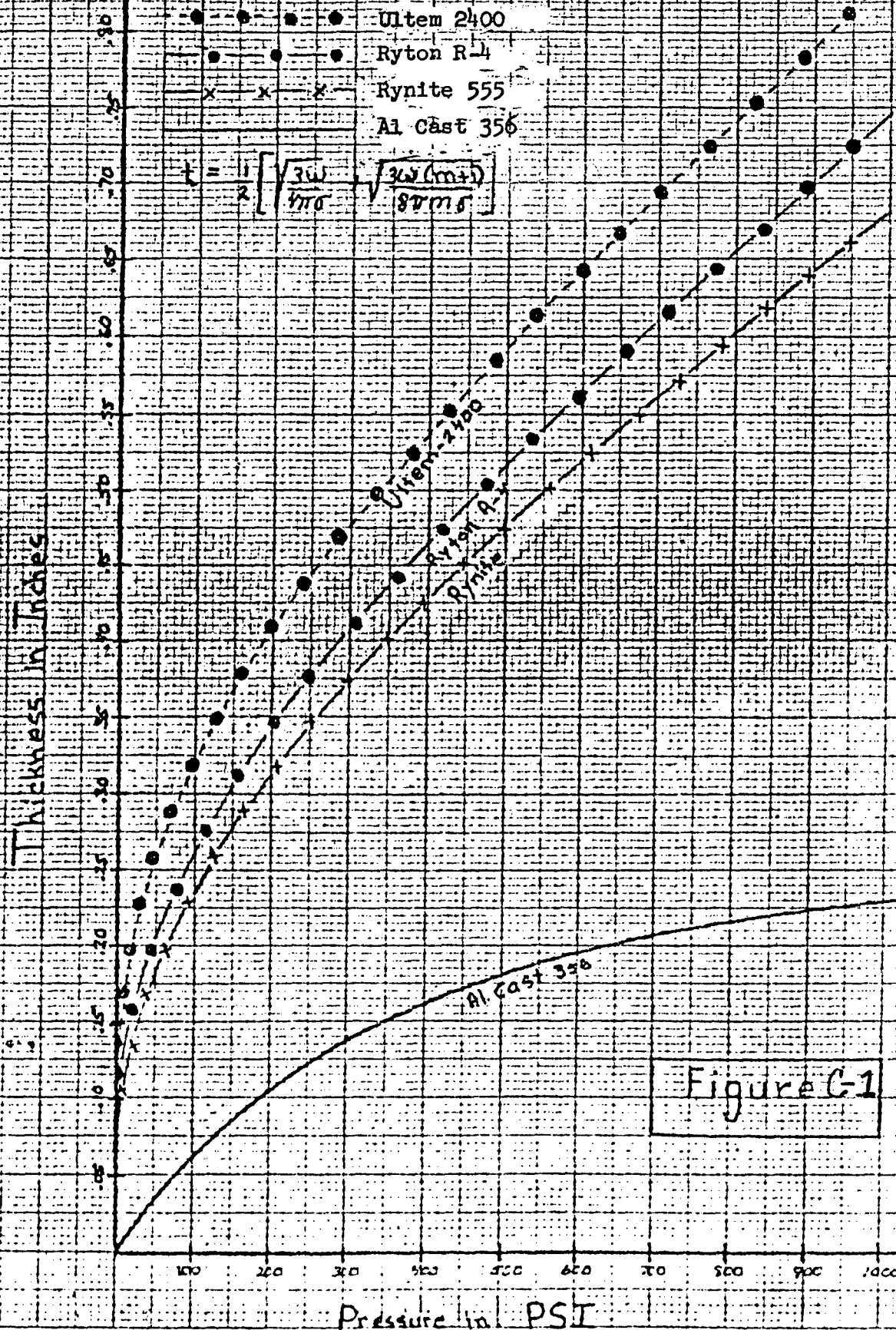
- (a) non-rigidity of the supporting frame,
- (b) imperfect clamping of the force collector,
- (c) non-uniform deflection of the force collector under pressure,
- (d) non-linearity of all but small deflections,
- (e) compliance of the collector material,
- (f) imperfect bonding of the strain gage sensors,
- (g) location of the strain gages as well as
- (h) minor deviations in apparent strain caused by the electrical connections and wiring (as outlined in Eq. 2, p. 47).

Consequently refinement of the calculated output sensitivity of the strain gage bridge installation on a quasi-rigid plate is better served by application of empirical results where such data is available.

Experimental data was collected on a group of prototype strain gage transducers constructed from several different materials. The principal objective of the experimental program was to produce an output signal which matched the existing DCA equipment calibrations. It was therefore necessary to produce a signal which was continuous from 0 to 100mv bidirectionally. The full scale output being ± 100 mv. Since a 12 Volt power

⁽⁶⁾R.J. Roark, Formulas for Stress and Strain (McGraw-Hill), 2nd Edition.

Silicon Strain Gage Calculations Thickness Required to Yield 100 Millivolt of 12 Volt Excitation



source was specified for the DCA, the transducer sensitivity was 8.33mv/V at full range.

Test data was taken on 12 samples and averaged for each material to obtain a representative figure of merit. Earlier tests (Figure C-1) indicated that the required sensitivity could best be achieved utilizing silicon strain gages which have an exceptionally high gage factor (G.F. > 120) (Table 5-9, p. 59).

Table C-1. Summary of Averaged Results

Material	Force Collector Thickness	Sensitivity @100 Psi Applied
Cast Alum. 356	.093 in.	7mv/V
Ultem 2400	.062 in.	139mv/V
Ryton R-4	.082 in.	60mv/V
Rynite 555	.066 in.	92mv/V

Considering a circular force collector integral with the transducer frame, we calculate (from Ref. 6) the radial stress level at a distance r from the centerline.

$$S_r = \frac{3W}{8\pi m t^2} \left[(3m+1) \frac{r^2}{a^2} - (m+1) \right] \quad \text{Eq. C-1}$$

Since the silicon gages are quite small we assume the gage centerline to be displaced by 0.025 in. from the force collector centerline and edge, respectively, i.e. $r = .025$ and $r = .446$. For example in the case of aluminum construction $m = 2.75$, we get from Equation 1:

$$S_t = -1160 \text{ psi (tension) at center}$$

$$S_t = +1406 \text{ psi (compression) at edge}$$

Using the average stress over the sensing elements, Table C-1 shows the results for the several materials.

Table C-2. Stress Calculations

Material	Thickness	Stress Level @ 100 Psi
Aluminum	.093	1283
Ultem 2400	.062	2970
Ryton R-4	.082	1671
Rynite 555	.066	2618

Applying the analytical results, we calculate the output sensitivity for a half active bridge transducer as follows:

$$e/E_0 = 1/2 \text{ Gage Factor} \times S/Y \quad \text{Eq. C-2}$$

where e is the bridge output in Volts

E_0 is excitation voltage in Volts

S is stress level

Y is tensile modulus of elasticity psi

Since the measured values in Table C-1 are available, we can calculate the stress level implied to achieve the prescribed 8.33mv/V sensitivity. Scaling the data we get:

Table C-3. Required Stress Level for Si Gages
 $e/E_0 = 8.33\text{mv/V}$

Material	Required Stress Level
Cast Aluminum 356	1527 psi
Ultem 2400	177 psi
Ryton R-4	231 psi
Rynite 555	237 psi

Evidently we can manipulate the force collector thickness to obtain the required stress under the strain gage. It is apparent that the Table C-3 stresses are extremely low, so by using appropriately higher stress levels, we may avoid the tedious temperature compensation procedure associated with thermal effect correction for the highly temperature dependent silicon gages. For example, Platinum foil gages have a more manageable thermal characteristic and can provide a gage factor as high as: $G.F. = 4.5$.

If we scale the gage factors of $\text{Si/Pt} = 120/4.5$, we arrive at a correspondingly adjusted stress level.

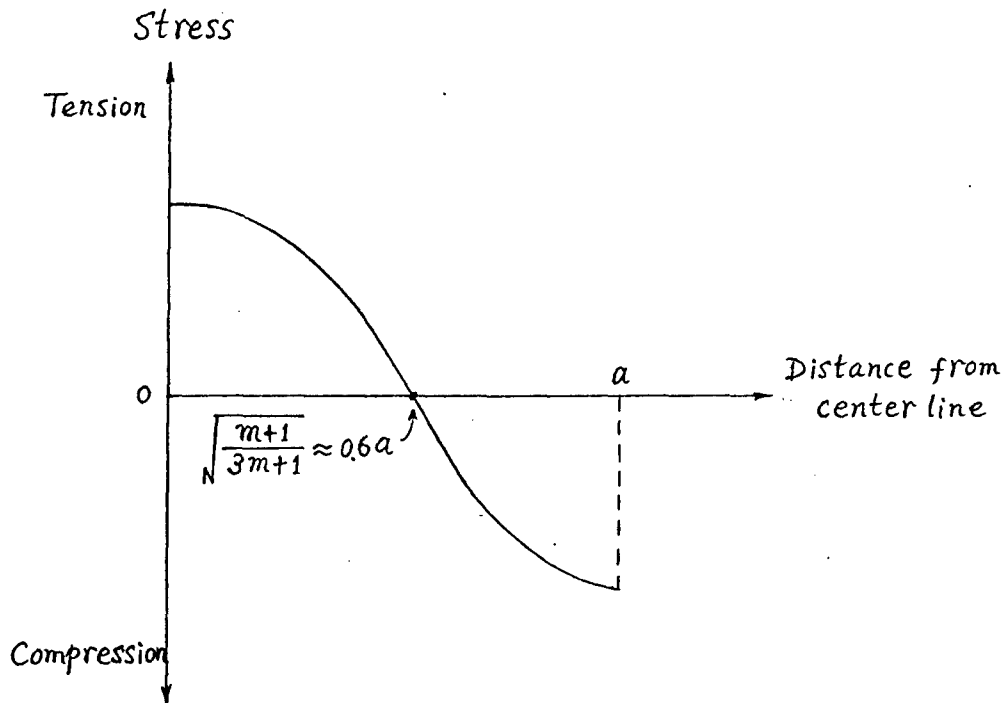
Table C-4. Required Stress Level for Pt Gage
 $e/E_0 = 8.33$

Material	Required Stress Psi
Cast Aluminum	43,622
Ultem	5,058
Ryton	6,628
Rynite 555	6,773

Now we can adjust the collector thicknesses to correspond to the indicated stresses of Table C-4. From Equation 1 we find:

$$t = \sqrt{\frac{3a^2p}{8mS} \left[(3m+1) \frac{r^2}{a^2} - (m+1) \right]} \quad \text{Eq. C-3}$$

The stress distribution on the force collector for a uniform applied pressure is given by Eq. 1 and takes the form shown in Figure C-2.



$m \approx 2.5$ Ultem, Ryton, Rynite

$m \approx 2.75$ Al cast

Figure C-2. Stress Distribution on a Thin Circular Plate With "Built-in" Edges

If we assume that a pair of strain gages are located at stations of equal tension and compression stresses along the radius, by taking the absolute magnitudes in an average we can calculate a specific thickness corresponding to each of the materials employed for a range of applied pressures. We can prepare a table of thickness estimates for various full scale pressure ratings for the Pt strain gages. The value for the platinum installations are compared to the silicon installations as shown in Table 5-8.

Table 5-8 extends the pressure range to lower levels. It is evident, from the thickness calculations, that the cast aluminum is not a suitable selection for low pressures since the rather thin sections needed to reach 8.33mv/V output are not considered practical.

Elastic Modulus

The published physical data for the various glass-reinforced plastics is not complete. However from the experimental measurements available we can estimate the value of the elastic modulus (Young's Modulus) for the various materials considered. From Eq. C-1 we find:

$$Y = 1/2 \text{ Gage Factor} \times \frac{\text{Stress}}{\text{Measured Sensitivity}} \quad \text{Eq. C-4}$$

For the several materials, Table C-5 presents a comparison (at standard temperature)

Table C-5. Elastic Moduli

Material	Y Psi	Published Values
Cast Aluminum	11×10^6	10.99×10^6
Ultem 2400	1.282×10^6	1.7×10^6
Ryton R-4	1.671×10^6	1.9×10^6
Rynite 555	1.707×10^6	2.6×10^6

C-10

APPENDIX D

SUMMARY OF DEVELOPMENT WORK FOR THIN-FILM ELEMENT DEPOSITION

APPENDIX D. SUMMARY OF DEVELOPMENT WORK FOR THIN-FILM ELEMENT DEPOSITION

D.1. Vacuum Technology. The physics of thin-film deposition in vacuum was reviewed (see Ref. 3 and 4), and calculations made for the application to strain gage devices. The vacuum deposition process requires specialized equipment but when all the parameters have been properly developed, it is expected that the resulting strain gage installation will be precise, efficient, will not require manual adjustment and will be more economical to process.

Two basic methods, sputtering and evaporation, were followed. Argon ion beam sputtering was used to deposit copper and platinum thin films. Designs were completed for (a) an improved ion source and (b) an improved electron beam evaporator. Methods for process control were evaluated. In addition, deposited films were produced by E-beam gun evaporation of platinum and polycrystalline silicon*.

D.2. Sputtering Process. Sputtering is the process by which the surface of a negatively biased target disintegrates under bombardment by positive ions of inert gas. Current theories visualize the sputtering process as one of momentum transfer in which the arriving ion produces a primary knock-on atom at the surface of the target. This knock-on atom then penetrates several atomic layers deep into the target, losing energy at each collision until it is brought to rest. In the process a target atom may be ejected. The yield in atoms per ion range typically from 2 to 8 for elements under bombardment by Ar⁺ ions at energies of about 10Kv. Sputtering yield is a function of the mass of the Ar ion and can be increased considerably by using heavier ions such as Kr⁺ or Hg⁺. The angle of incidence of the arriving ions with respect to the target surface also affects the rate of sputtering. The yield is also strongly influenced by the crystallographic orientation of the target, sputtered material being emitted at higher rates along close-packed directions of the lattice.

The technology is implemented by the following procedure:

- (a) A source of ions (ionized gas) or electrons (high voltage filament) is set up in an electromagnetic field and directed as a beam on a target within a vacuum chamber.
- (b) The target contains the material to be deposited. As the beam of energetic particles impinges on the target

*Ed Graper, LeBow Laboratories.

atomic particles are expelled (sputtered) from the target surface.

- (c) The particle beam and target are geometrically arranged so that the material is directed to the surface of a substrate.
- (d) The substrate in the present case is the force collector surface of the CADPT.
- (e) A screen or mask is interposed between the substrate and the beam ejected from the target. The mask is prepared to produce the exact pattern desired for the deposited element (i.e. strain gage). See Figure 5-25, for example.
- (f) If the elements produced by the masking process and deposited film are closely matched, we approach the ideal strain bridge arrangement. In this ideal case no further manipulation or adjustments would obviously be required on the bench.
- (g) Since many substrates (CADPT units) can be sputtered in the same set-up, multiple units can be simultaneously produced. Efficiency of production results in economy of turning out the strain gage sensing elements. The process, of course, must be refined to maintain precision in geometric deposition of the set of elements in a bridge circuit.

D.2.1. Ion Sputtering. For ion energy of several kilovolts, the required ion current for argon or xenon as the vacuum chamber medium for silicon deposition of a variety of metals was estimated. For a typical 20 cm target-to-substrate distance, the required current for a 1.0 A/sec deposition rate is about 40-80 ma for most metals. The semiconductors such as Si or Ge may require several times this current. This current is valid for Ar at 1 kv. It is calculated that for Xe at 5-10 kv (using a biased target) the current may be reduced by a decade.

A laboratory type sputtering system was set-up and used to deposit strain gage materials. These were platinum, tungsten, and silicon elements, and copper for a connection network. Several coatings were run to verify calculations and explore the capabilities of these processes. The size of the equipment, and the low wattage to the cathode allowed only low coating rates. The equipment was subsequently modified and refitted for larger cathodes suitable for higher wattage

needed for significantly higher deposition rates. (The work is to be continued into Phase III.)

In the sputtering system used to deposit Pt and Cu films as shown in Figure D-1, the source is a basic cold cathode parallel plate plasma. Ions emerge from the cathode aperture and are collected onto a biased target. The system may be conceptualized as parallel plates several mm apart with a bias of about 4000 Volts. The target is a flat disk 1 - 2 cm diameter biased negative to the source cathode by about 2000 volts. The target is inclined 45° to the ion beam, with the substrate at 90° to the beam. For gas flow rates compatible with a 6" diffusion pump, currents over 10 ma have been obtained. With addition of a magnetic coil, more source apertures, and improved gas flow distribution in the source, currents over 100 ma should be feasible.

The design and calculations were made for a hot filament, cylindrical anode ion source using a three grid beam formation, Figure D-2. The source uses a solenoidal magnetic field to enhance plasma density and thus beam current density. Such sources are able to produce current densities of up to 100ma/cm^2 with excellent beam uniformity and negligible divergence.

D.2.3 Ion Sputtering Calculations. The implemented ion sputtering scheme is shown in Figure D-1. The theory is well described by Sigmund (Ref. 3) and backed by volumes of data. For low energy ($<1000\text{V}$) the sputtering yield is given by:

$$Y = \frac{3}{4\pi^2} \frac{4 m_1 m_2}{m_1 + m_2} \frac{E}{U_0} \quad \text{Eq. D-1}$$

where, Y = sputtering yield = sputtered atoms/bombarding ions

m_1, m_2 = incident and sputtered species amu

E = energy of bombarding ion

U_0 = surface bonding energy



Figure D-1. Vacuum Deposition Equipment

PROJECT NO. _____
DWG. NO. _____
CHECKED _____

WEST COAST RESEARCH CORP.
P.O. BOX 25061, LOS ANGELES, CA. 90025

REPORT NO. _____
DATE _____
BY _____

P. _____
OF _____
PP. _____

FIGURE D-2. HOT FILAMENT, CYLINDRICAL
ANODE ION SOURCE
3 GRID BEAM FORMATION

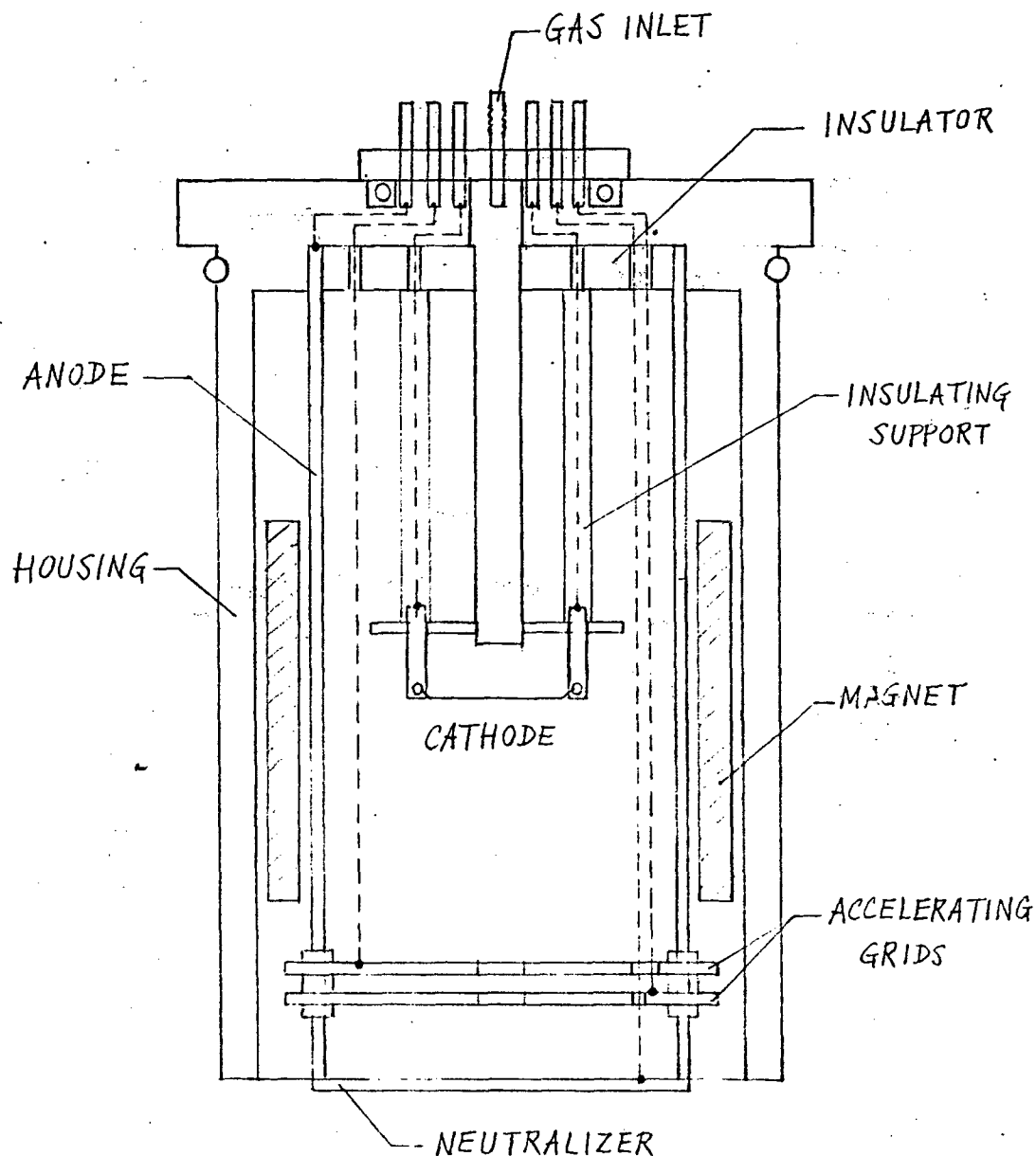


Figure D-2. Hot Filament, Cylindrical Anode Ion Source,
3 Grid Beam Formation

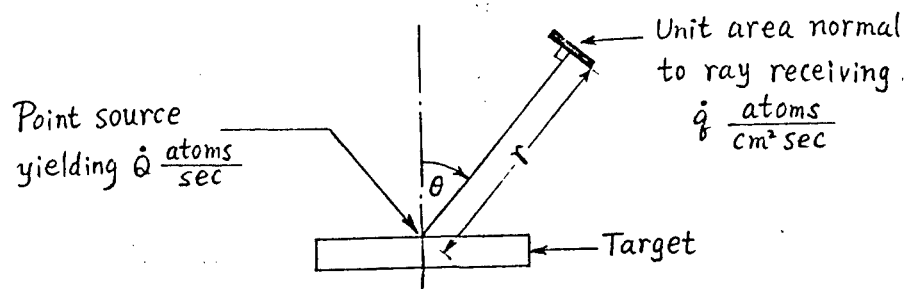
Table D-1. Typical values at 1000 eV are:

	Specie									
	Si	Ga	Al	Pd	Cu	Au	Pt	Ag	Zn	Cd
Yield	0.5	0.5	2.5	3.0	3.0	4.0	5.0	5.0	10.0	12.0
Binding Energy (eV)	7.83	7.63		3.90		3.80		2.96	1.36	1.16

Confidence in theory is good enough that any ion-atom combination may be extrapolated from limited data.

Except for low angles, sputtering yield is independent of beam incidence and the ejected atoms show a typical Cosine pattern.

Thus the relation between incident ions and deposition rate can be derived as follows:



The atoms receiving rate, $\dot{q}$, is given by,

$$\dot{q} = K \dot{Q} \frac{\cos \theta}{r^2} \text{ atom/sec}$$

where, K is the proportionality constant

$$\text{Since } \dot{Q} = \int_0^{\pi/2} \dot{q} 2\pi r \sin \theta r d\theta$$

$$\dot{Q} = K \dot{Q} \int_0^{\pi/2} \frac{\cos \theta}{r^2} 2\pi r \sin \theta r d\theta$$

$$\dot{Q} = 2\pi K \dot{Q} \int_0^{\pi/2} \cos \theta \sin \theta d\theta = 2\pi K \dot{Q} \left(\frac{1}{2}\right) = \pi K \dot{Q}$$

$$\therefore K = \frac{1}{\pi}$$

$$\text{we get, } \dot{q} = \frac{\cos \theta}{\pi r^2} \dot{Q} \frac{\text{atoms}}{\text{cm}^2 \text{sec}}$$

$$\dot{q} = \frac{\cos \theta}{\pi r^2} \dot{Q}$$

D.2.4. Ion Current Requirement.

e.g. deposition rate = $1 \text{ \AA}^0/\text{sec}$

target-substrate distance = 20cm (normal to ray)

tilt of the ray from the target = 45°

$$\dot{q} = \frac{\cos \theta}{\pi r^2} \dot{Q} = \frac{0.707}{3.14 \times 20^2} \dot{Q} = 5.6 \times 10^{-4} \dot{Q} \frac{\text{atom}}{\text{cm}^2 \text{sec}} \quad \text{Eq. D-2}$$

where $\dot{q}$ = atoms/cm²sec falling onto substrate
 $\dot{Q}$ = atoms/sec sputtered out from target

The following data is available as published information.

Material	No. of Atoms $1 \text{ \AA}^0 \text{ Thick/cm}^2$
Si	0.5×10^{15}
Pt	0.66×10^{15}
Cu	0.85×10^{15}

To achieve a deposition rate of $1 \text{ \AA}^0/\text{sec}$ we can calculate the value for $\dot{Q}$:

$$\text{for Si; } \dot{Q} = \frac{\dot{q}}{5.6 \times 10^{-4}} \frac{\text{atoms}}{\text{sec}} = \frac{0.5 \times 10^{15}}{5.6 \times 10^{-4}} \frac{\text{atoms}}{\text{sec}} = 0.89 \times 10^{18} \frac{\text{atoms}}{\text{sec}} \quad \text{Eq. D-3}$$

$$\text{for Pt; } \dot{Q} = 1.16 \text{ atoms/sec.}$$

$$\text{for Cu; } \dot{Q} = 1.54 \text{ atoms/sec.}$$

Then the Ar^+ current can be calculated using the formula:

$$\text{Ar}^+ \text{ current} = \frac{\dot{Q}}{Y} e$$

where $e = 1.6 \times 10^{-19}$
 and Y = Yield for Si

where $\dot{Q}/Y$ gives the no. of Ar^+ atoms/sec required to achieve $1 \text{ \AA}^0/\text{sec}$ deposition rate, and e conversion factor = 1.6×10^{-19} e per ion.

Y values for Si = 0.5
Pt = 5
Cu = 3

Ar⁺ current for Si deposition = $.89 \times 10^{18} \times 1.6 \times 10^{-19} \text{ A} = 285 \text{ mA}$.

Similarly for Pt = 37mA
and for Cu = 82mA

D.2.5. Conclusion. The results from the ion deposition study shows that the practical resistances of the sensing elements obtained are much higher than the calculated values. The calculations were made assuming the bulk properties of the target material is present in the deposited film.

The observations by current researchers (Ref. 7) shows that the calculations made are valid only if the substrate temperature is at least 80% of the melting point of the target material. Otherwise the deposited film has a columnar structure instead of a crystalline structure. The columnar structure has special defects and tends to give reduced mechanical properties. At the same time local discontinuities in the pattern produce much higher resistivity. It is therefore recommended that the substrate be operated at a higher temperature to assure achieving a crystalline structured film. (See Ref. 7.) This will improve the Quality Control of the sensing element.

In general the mechanical properties such as elastic constants, tensile strength, fracture toughness, fatigue strength, hardness, diffusion rates, friction and wear properties and corrosion resistance are affected by the quality of the sputtered film. Electrical property largely depend on the crystalline structure is the electrical resistance. This can be significantly higher from the bulk value in the case of columnar structure.

D.3. Evaporation. The deposition of thin films by evaporation was also studied for rate of $1.0 \text{ A}^0/\text{sec}$ at a 20 cm range. It was found that for sources of a practical size and power, the evaporated metal must be molten to achieve sufficient evaporation rate. When platinum is the highest sublimation temperature element employed, an evaporator using less than

(7) R.F. Bunshah and D.M. Mattox, "Applications of Metallurgical Coatings", Physics Today, May 1980.

100 watts is practical. The stability of evaporation rate from a small boat heated by an electron beam was found adequate by using a constant filament-to-crucible voltage with the filament heating current controlled by a feedback signal proportional to the filament emission. The theory for resistance heated evaporation can be summarized as follows.

D.3.1. Principle of Operation. Most of the metals and therm-alloy compounds begin to evaporate rapidly in vacuum systems when their temperatures have been sufficiently raised from their vapor pressure to have reached a value in excess of 10 microns Hg (1 atm = 760mm Hg). Some substances such as Mg, Cd, Zn, and ZnS can be evaporated from the solid state (sublimation process), but the majority of metals and dielectrics deposited as thin films evaporate from the liquid phase.

Under conditions of high vacuum and where the vapor pressure of the substance is less than about 1mm Hg, the vapor molecules can be assumed to leave the emitting surface relatively unimpeded. The mass of substance removed as vapor from unit area at a given temperature and in unit time will then be the same as that evaporating from the surface of the substance in equilibrium with its saturated vapor.

For equilibrium the rate at which molecules evaporate must be equal to the rate at which they condense on the emitting surface. The number of molecules impinging in unit time is given by the relation $0.25nv$, where n is the number of molecules per unit volume and v is their average velocity. If only a fraction, a , of the molecules arriving at the surface are condensed, then for equilibrium the number of molecules evaporating from unit area in unit time will be $0.25anv$. From which Langmuir derived the following equation for the rate of resistance-heated evaporation in vacuum.

$$5.85 \times 10^{-5} a P_u \sqrt{\frac{M}{T}} \text{ g cm}^{-2} \text{ sec}^{-1}$$

Eq. D-4

Where P_u is the vapor pressure in microns Hg at $T^\circ\text{K}$ and M a mol of the substance being evaporated. Most of the metal are mon-atomic in the vapor phase with a few exceptions which evaporate mainly in the form of molecules (for example Sb_2). The condensation coefficient, a , has been found to be equal to unit for most metals.

D.3.2. Rate of Evaporation. The molecular evaporation rate $dN_e/(A dt)$, at a specified vapor pressure, could not exceed an upper limit equal to the impingement rate. The impingement rate, $dN_i/(A dt)$ is the number of molecules in a gas at rest that strike a unit surface in a unit time. Because some of the particles in the evaporant flux may have been reflected back into the gas, therefore a modification is needed to account these effects. If the gas obeys Maxwell-Boltzmann statistics and the ideal gas relation, the impingement rate is:

$$R_{ev} = \frac{1}{A} \frac{dN_e}{dt} = \frac{\alpha_v(p^* - p)}{\sqrt{2\pi m k T}} \quad \text{Eq. D-5}$$

Where N_i is the number of particles striking the surface of area A , P^* is the vapor pressure of the material at the temperature of the surface, m is the mass of the molecules, α_v is the fraction of evaporant flux that makes the transition from condensed to the vapor phase, p is the hydrostatic pressure of the return flux, and N_e is the number of particles evaporating.

D.3.3. Filament Heaters. The metals used for filament heaters are those which combine the properties of high melting point and low volatility. Typical heater material are refractory metals such as tungsten, tantalum, molybdenum, columbium, platinum, nickel, and chromel. Of these materials, the most commonly used material is tungsten. In order for a metal to be satisfactorily evaporated from a filament, the following conditions must be fulfilled.

- (a) The metal must adhere to the filament;
- (b) it must have sufficient vapor pressure to evaporate while still at a temperature below the melting point of the filament material; and
- (c) it must not form an alloy with the filament which has a melting point below the temperature required for evaporation.

D.3.4. Evaporation System Configuration. A simple resistance-heated evaporation apparatus, shown schematically in Figure D-3, is basically a thermal process emitting from a metal flowing upwards over filament legs or crucible.

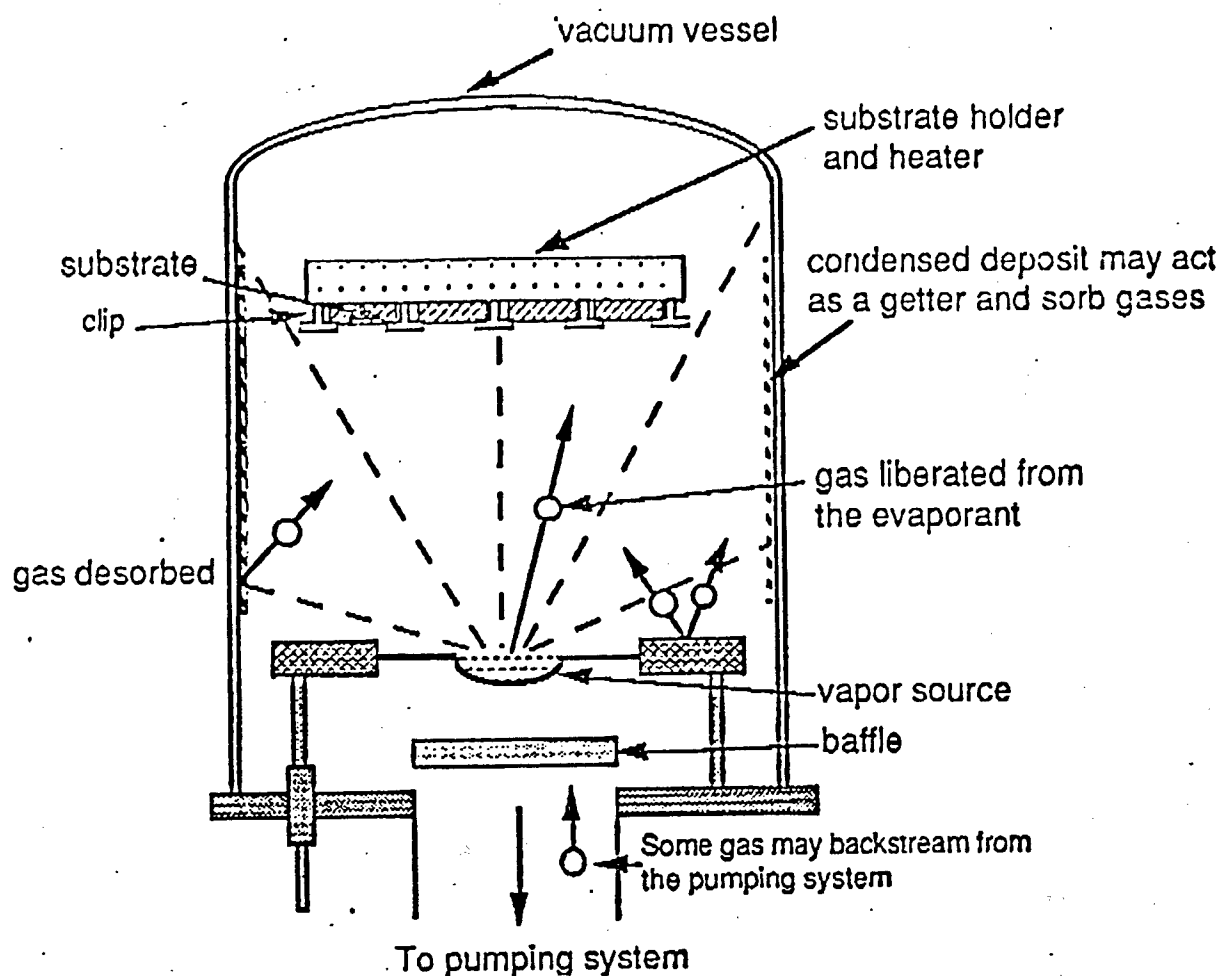


Figure D-3. Schematic Diagram of a Thermal Evaporation Used for Strain Gage Element Deposition

APPENDIX E

BONDED FOIL INSTALLATION PROCEDURE

APPENDIX E. BONDED FOIL INSTALLATION PROCEDURE

The bonded strain gage technology is well-established. Procedures which have been refined over a long period of time are summarized as follows.

The technique can be described in a few succinct steps as follows:

(a) Surface Preparation

A smooth uniform finish to form the base for gage installation.

(b) A fine scale roughness is abraded on the surface to enhance adhesion.

(c) A thin adhesive coating is deposited on the surface.

(d) Strain gage elements (on which an adhesive coat has been brushed) are placed on the surface and restrained from motion.

(e) Compliant pressure pads are applied to assure a positive bond, free of air bubbles.

(f) The assembly is cured at elevated temperature to permanently set the bond.

(g) When the bond is effected, lead wire are attached to join the set of individual gages in the wheatstone bridge circuit. Figure 5-19.

(i) It is important that the resistance of the gage elements are carefully matched both for resistivity and the thermal variation of resistance. This frequently requires addition of compensating elements to the bridge circuit.

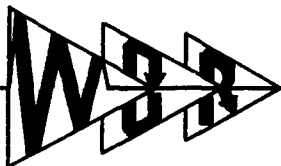
This appears to be a relatively straightforward process but it involves manual attention to the detailed assembly and circuit adjustment.

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