Air Products

Air Products and Chemicals, Inc.
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NRW10-018
Cont 414

30 April 1984

Director, Advanced Research
Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209

Attention: Program Management

Gentlemen:

SUBJECT:	Contract	N00014-83-C-0394
	Item No. 0002	Data
	Sub-Item A001	R&D Status Report #3

Attached is R&D Status Report #3 for the subject contract covering the period from 1 January 1984 to 31 March 1984. A request to change the effective date of the contract to 1 October 1983 has been dropped, leaving the start and completion dates as specified in the contract.

Very truly yours,

Ralph C Longsworth

Ralph C. Longsworth
Program Manager

sk

cc: Scientific Officer
DCASMA - Reading, Pa.
Director, Naval Research Laboratory
Defense Technical Information Center

Enclosures

Air Products

R&D STATUS REPORT

DARPA ORDER NO.: 4746 PROGRAM CODE NO.: --

CONTRACTOR: Air Products and Chemicals, Inc.

CONTRACT NO.: N00014-83-C-0394 CONTRACT AMOUNT: $594,000

EFFECTIVE DATE OF CONTRACT: '83 July 01

EXPIRATION OF CONTRACT: '84 June 30

PRINCIPAL INVESTIGATOR: W. A. Steyert PHONE NO.: (215) 481-3700

PROGRAM MANAGER: R. C. Longsworth PHONE NO.: (215) 481-3708

SHORT TITLE OF WORK: Solid State Compressor

REPORTING PERIOD: '84 January 01 - '84 March 31

- PROGRESS:

  Progress Report is attached.

- KEY PERSONNEL: No changes

- SPECIAL EVENTS: None

- PROBLEMS ENCOUNTERED AND/OR ANTICIPATED: None

- ACTION REQUIRED BY THE GOVERNMENT:

  The request to change the effective date of the contract from '83 July 01 to '83 October 01 has been dropped. The schedule has been adjusted to complete all work by the original date of '85 June 30.

- FISCAL STATUS:

  (1) Amount currently provided on contract: $175,000

  (2) Expenditure and commitments to date: Per separate report

  (3) Funds required to complete work: Per contract

Air Products

1.0 SUMMARY

Subcontracts were signed with CeramPhysics, Inc. and Pennsylvania State University in January. Penn State University, PSU, has been exploring tape casting of long narrow ribbons of PMN:PT and PLZT type ceramic materials which will serve as the drivers. CeramPhysics, Inc., CPI, has started work on a computer model of the multistage compressor system and has completed a layout of a three cell simulator. APCI completed design and fabrication of a material testing device and has been getting dynamic property data on several different elastomers.

2.0 TASK 1.1 DRIVERS FOR PROTOTYPE UNITS

Two configurations are possible for the internally electroded electrostrictive actuators. The first (Figure 2.1a) arranges the electrodes longitudinally along the length of the actuator and makes use of the transverse electrostriction, given by

$$\Delta l/l = Q_{12}P_I^2 = M_{12}E_I^2$$

where $\Delta l/l$ is the induced strain, Q_{12} and M_{12} the transverse electrostriction constants in polarization and in field notations respectively and P_I and E_I the induced polarization and the inducing transverse E field. In the second configuration (Figure 2.1b, the field is applied longitudinally along the length of the actuator and the electrodes run transversely across the system.

Obviously for the 10 cm long actuators required, the first configuration is much easier to realize practically than the second, since many fewer internal electrodes are required and the possibility of delamination and failure is correspondingly reduced.

In the lead magnesium niobate:lead titanate system originally proposed for this work, the realizable strain at 20 kV/cm E field is of order 1.0×10^{-3} for the longitudinal effect, but only 0.4×10^{-3} with the transverse field configuration (Figures 2.2a and 2.2b). A brief search for alternative electrostrictors has revealed very high transverse effects in the lead lanthanum zirconate titanate family of ceramics. For the PLZT with the mole ratio 9.5:65:35, the transverse strain is almost equivalent to the longitudinal, and a magnitude of 0.9×10^{-4} can be obtained at a field level of 20 kV/cm (Figure 2.3). We are currently exploring both PMN:PT and PLZT compositions. Large batches of the required lead magnesium niobate material 0.9 $Pb(Mg_{1/3}Nb_{2/3})O_3$:0.1 $PbTiO_3$ have been prepared using the precursor reactions

$$MgO + Nb_2O_5 \xrightarrow{1000°C} MgNb_2O_6$$

$$3PbO + MgNb_2O_6 \xrightarrow{870°C} Pb_3MgNb_2O_9$$

$$PbO + TiO_2 \xrightarrow{870°C} PbTiO_3$$

formation of the magnesium niobate phase, and later reaction with PbO is essential to avoid the formation of a pyrochlore structure phase which is most delaterious to the electrostrictive properties.

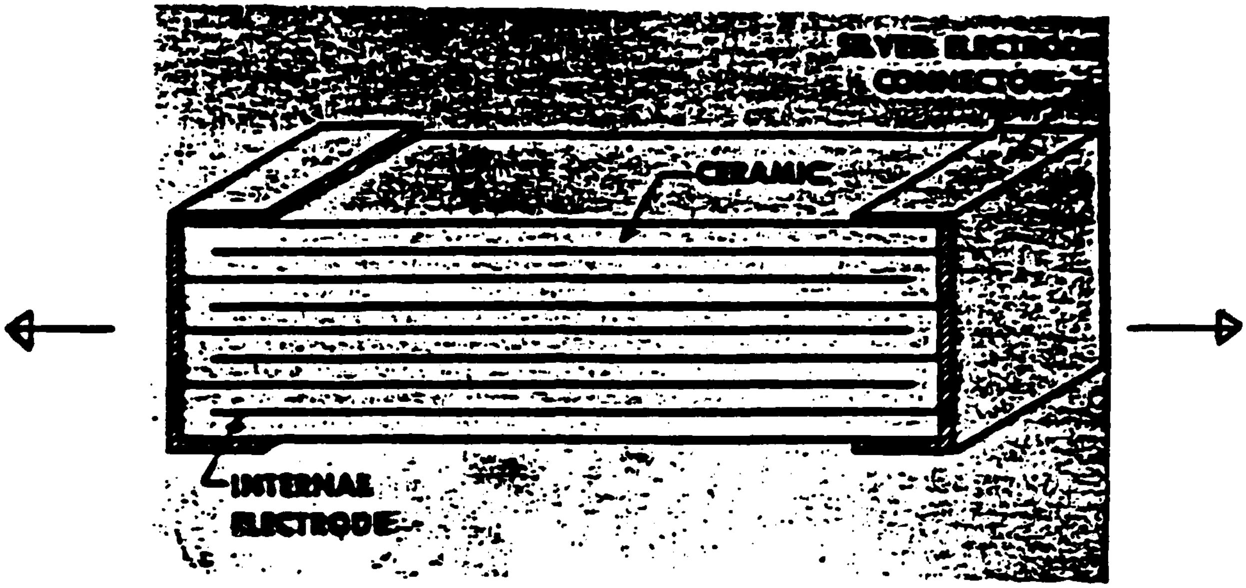


Figure 2.1a Transverse Field Configuration

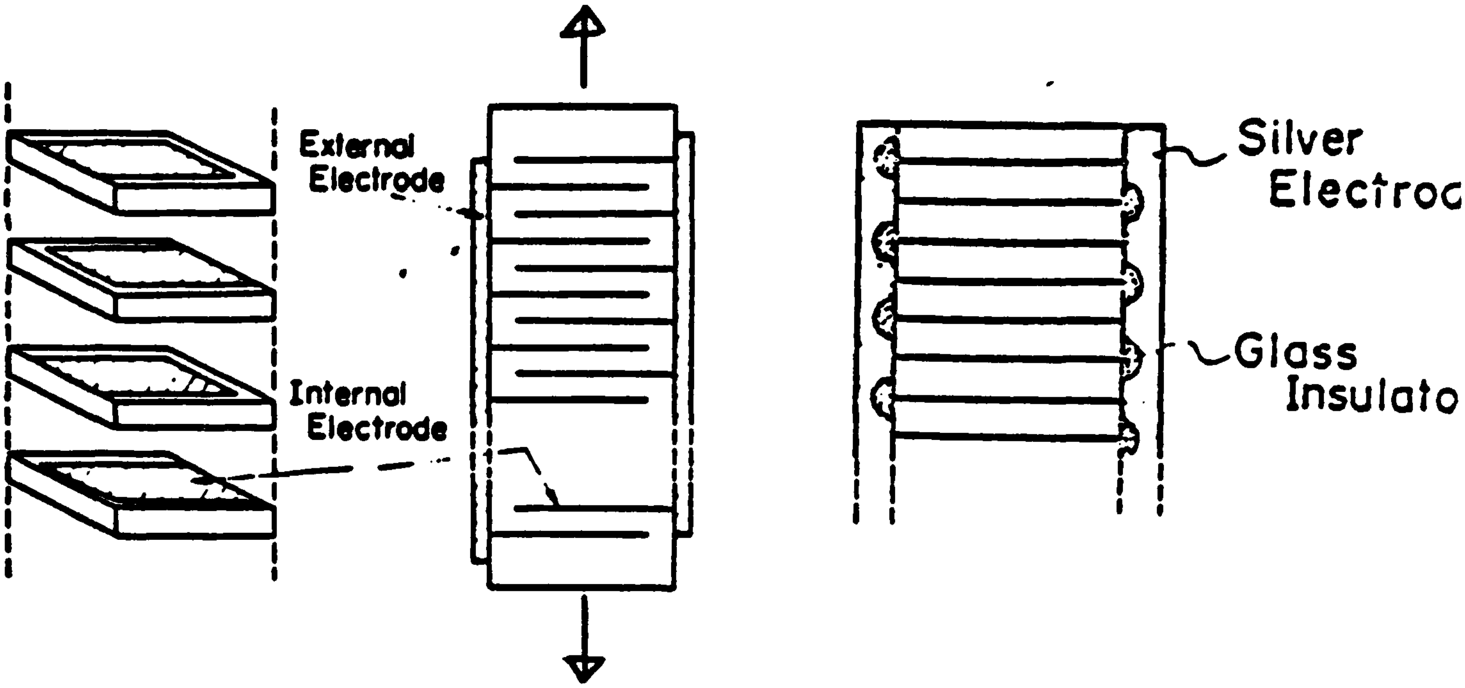


Figure 2.1b Longitudinal Field Configuration

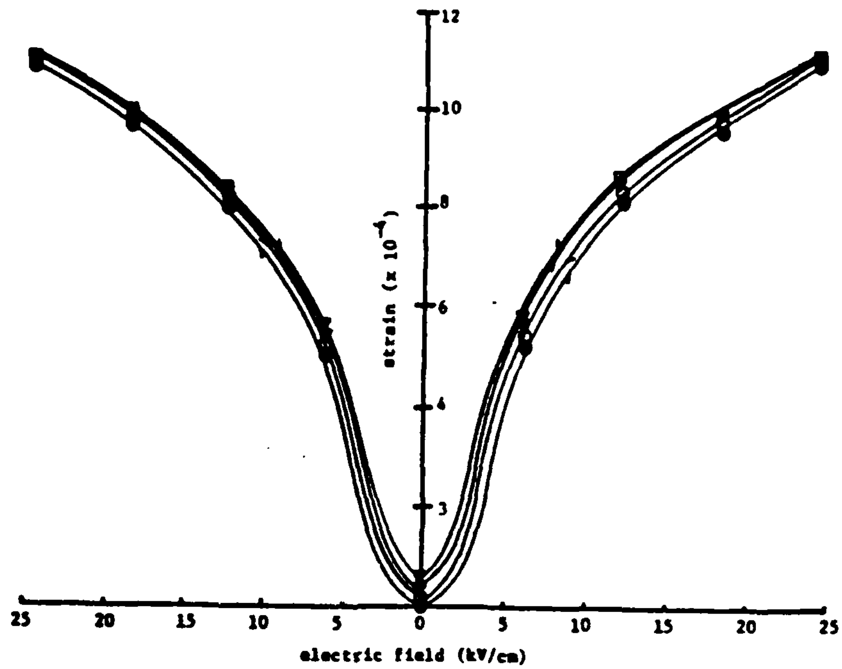


Figure 2.2a Strain Due to Longitudinal Field in PMN:10% PT

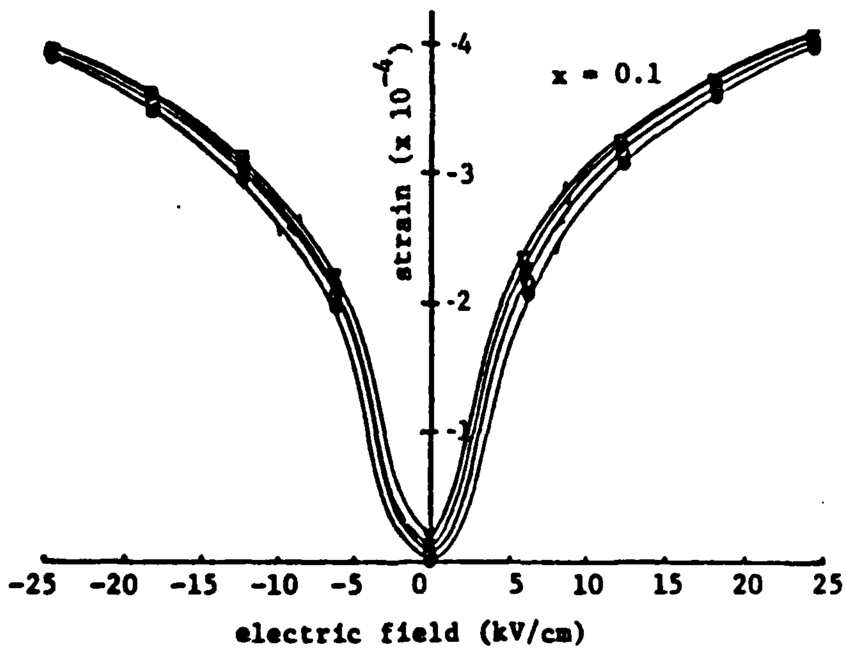


Figure 2.2b Strain Due to Transverse Field in PMN:10% PT

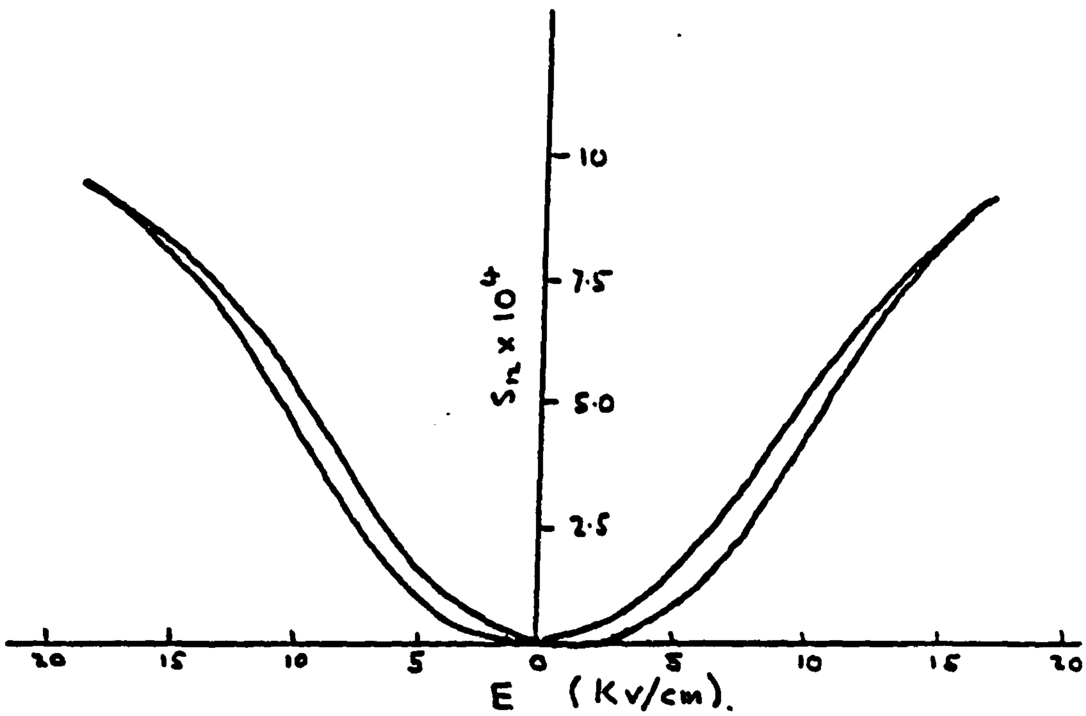


Figure 2.3 Strain Due to Transverse Field in PLZT 9.5:65:35

For the PLZT material, a simple mixed oxide processing appears adequate from the starting components, La_2O_3, PbO, ZrO_2, and TiO_2. Since optical homogeneity is not required, the expense of the organic precursor formation can be avoided.

Initial tape casting is being performed using a standard Cladan binder system and a pure platinum electrode ink.

3.0 TASK 2.1 ONE CELL SIMULATOR (APCI)

3.1 Design, Construction

Figure 3.1 is a schematic of the hydraulic system that was designed and fabricated to test elastomer samples and later on in the program a one cell simulator. An oil reservoir vented to ambient pressure maintains a pressure of about 0 psig at the inlet to the hydraulic pump. The pump is capable of delivering .5 gpm at 1,500 psi. Discharge pressure is controlled by an adjustable relief valve that bypasses excess flow. Pressure to the test cell is cycled between high and low pressure by a rotary valve driven by a variable speed motor. Pulse frequency can be set over the range from 0 to 3,400 rpm (0 to 56 Hz).

A cross sectional view of the test cell is shown in Figure 3.2. The oil line is connected to the port in the base, Item 2, and pressure is monitored by the pressure transducer, Item 10. Three samples, Item 7, separated by two spacers, Item 6, can be tested at one time. Displacement is monitored by a displacement transducer, Item 11. Both the pressure and displacement transducers are connected to a Tektronic 468 dual mode storage oscilloscope.

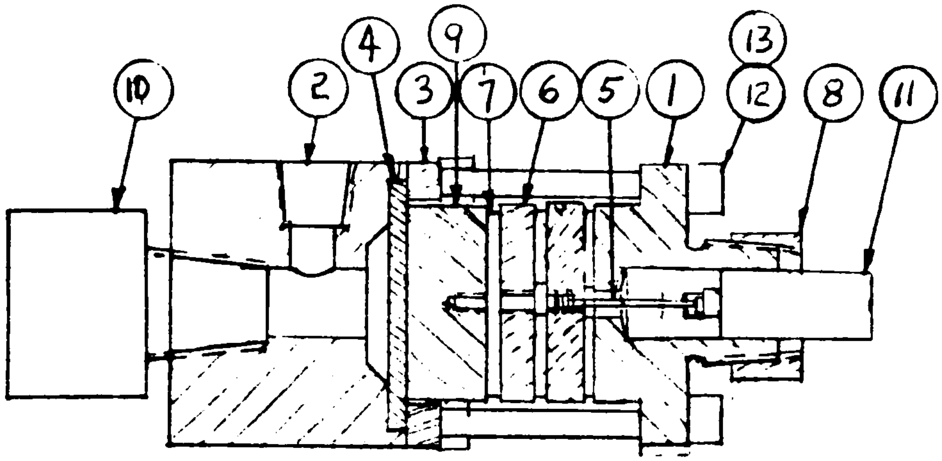
3.2 Elastomer Studies

Piezoelectric elements can be operated at a high speed. We are planning on 200 Hz to 1,000 Hz operation in the final compressor. The elastomer test facilities being built at CeramPhysics and the ones being used at APCI can not be operated at such high speeds. This is because they operate mechanically and hydraulically, rather than piezoelectrically. Fortunately, the well established concepts and experimental techniques of viscoelasticity are simply that an elastomer operated at high frequency at one temperature behaves the same as it does at lower frequency and a lower temperature. This correspondence is valid both for linear properties and for failure properties.

The extreme of this correspondence is easy to see. If we cool an elastomer to its glass transition temperature, it will have a Young's modulus of 10^5 psi (pretty much independent of which elastomer is chosen) even in a static test. Similarly, if we test the elastomer at a sufficiently high frequency, it will exhibit a modulus of 10^5 psi.

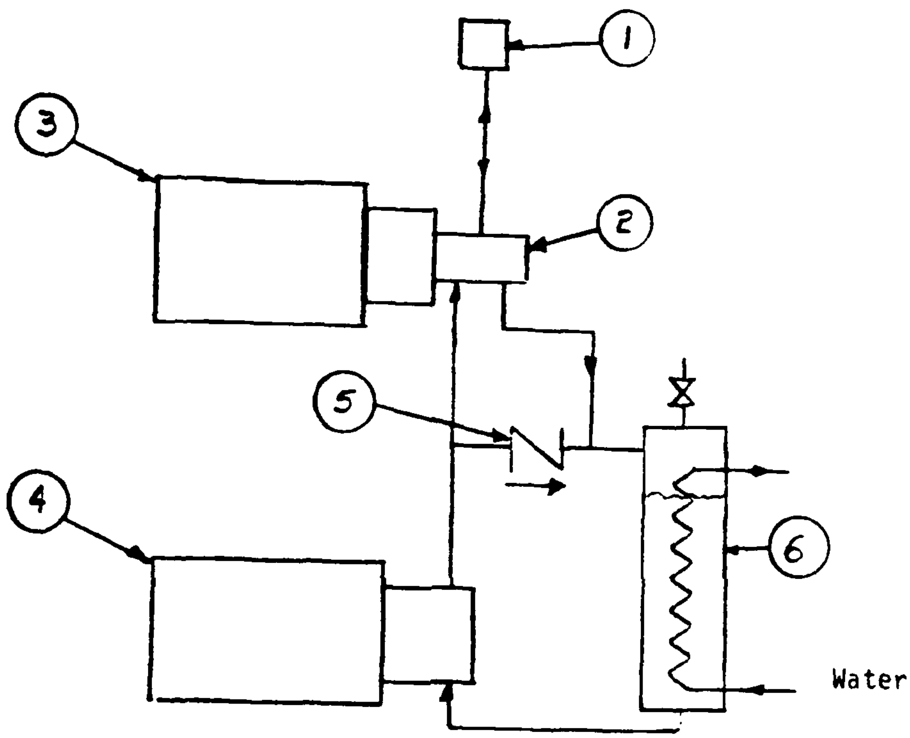
On the other hand, if we warm an elastomer up, it will show its rated modulus corresponding to its durometer even at high frequencies.

Figure 3.3 shows the Maxwell-Wiechert model of an elastomer. Each combination of spring E (representing the elastic modulus in psi) is connected to a dash pot N (representing the vicious behavior). However, E_∞ representing the static modulus is connected to an infinitely stiff dash pot. (In a noncross-linked polymer E_∞ would be absent. Of course, at high frequencies the modulus is given by all the E's in parallel.



Item	Description
1	Top
2	Base
3	Diaphragm Retainer
4	Diaphragm, Neoprene, 1.32 dia.x1/8 thk.
5	Transducer Stem
6	Sample Spacer
7	Elastomer Samples
8	Retainer Nut
9	Piston
10	Pressure Transducer, 1,500 psi Barksdale 302HI-11CG-04-J (10 Vdc, 100 mV/V)
11	Displacement Transducer, Schaevitz 050 MHR LVDT
12	Screws
13	Nuts

Figure 3.1 Elastomer Test Cell



1. Elastomer Test Cell or Single Cell Compressor
2. Rotary Valve, Two Pulses per Revolution
3. Variable Speed Motor 0-1,700 rpm
4. Oil Pump, .5 gpm, 1,500 psi
5. Adjustable Relief Valve
6. Oil Cooler/Reservoir

Figure 3.2 Hydraulic System for Elastomer Testing and Single Cell Compressor

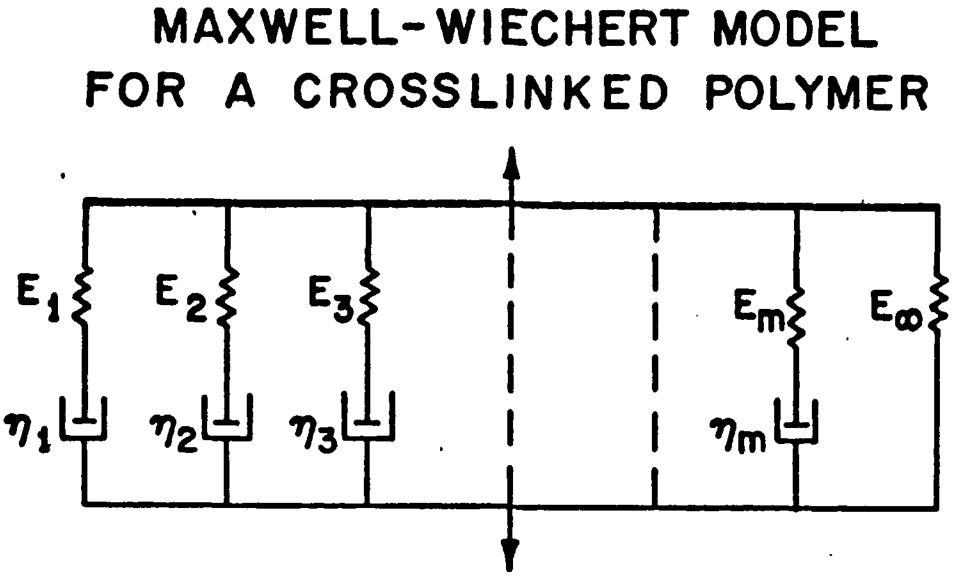


Figure 3.3 Standard Elastomer Model. (This is used to describe elastomer performance over a range of frequencies.)

The time constant for each of these units is given by $\tau = \eta/E$; η is a function of temperature. We are gathering the data to allow a discription of our elastomers performance in terms of this model. Some of the results are described in Section 3.4.

3.3 Static Elastomer Testing

In the previous progress report, Figures 4 and 5 show the static force required for compression of 80 and 73 Durometer elastomers confined in the circular geometry, shown in Figure 3 of that report and reproduced here as Figure 3.4. These tests have been continued. Figure 3.5 shows the test results for a 1/8" thick sheet of Neoprene. This material was listed as 30 Durometer by the manufacturer but tested at 40 durometer on our standard Durometer tester.

Figure 3.6 shows the results for various Durometer Monothanes* as well as a 15 Durometer Neoprene disk.

The results in general indicate that the measured compressions for a given force are somewhat less than those expected from Eq. 17 of our January 1984 progress report.

3.4 Dynamic Elastomer Testing

The dynamic test unit described in Section 3.1 was used to characterize the elastomer force versus compression characteristic at frequencies between 0.6 and 66.7 Hz. A number of elastomers have been tested. Tests were made at 1°C, 22°C, and 40°C. Figure 3.7 is typical data showing the testing of 10 Durometer Monothane at 40°C for three different frequencies. The test is done on two stacked elastomer disks (each like Figure 3.4). Load, in pounds, is calibrated against fluid pressure, as measured by a pressure transducer, using a load cell. Displacement (of the cell pair) is calibrated against load cell output using simple static measurements. It is clear from these results that at the highest frequency there is less compression for the same amount of force.

Currently, we are analyzing the results of 30 individual tests carried out on 30 Durometer Neoprene and 10 Durometer Monothane. The elastomer modulus as a function of frequency and temperature is being compared with the viscoelastic behavior discussed in Section 3.2. This will allow us to extrapolate the results of the hydraulic and mechanical tests at lower frequencies to the higher frequencies of the piezoelectric compressor.

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*One component castable polyurethane resin manufactured by Indpol Division of Synair Corporation, 2003 Amnicola Highway, Chatanooga, TN 37406.

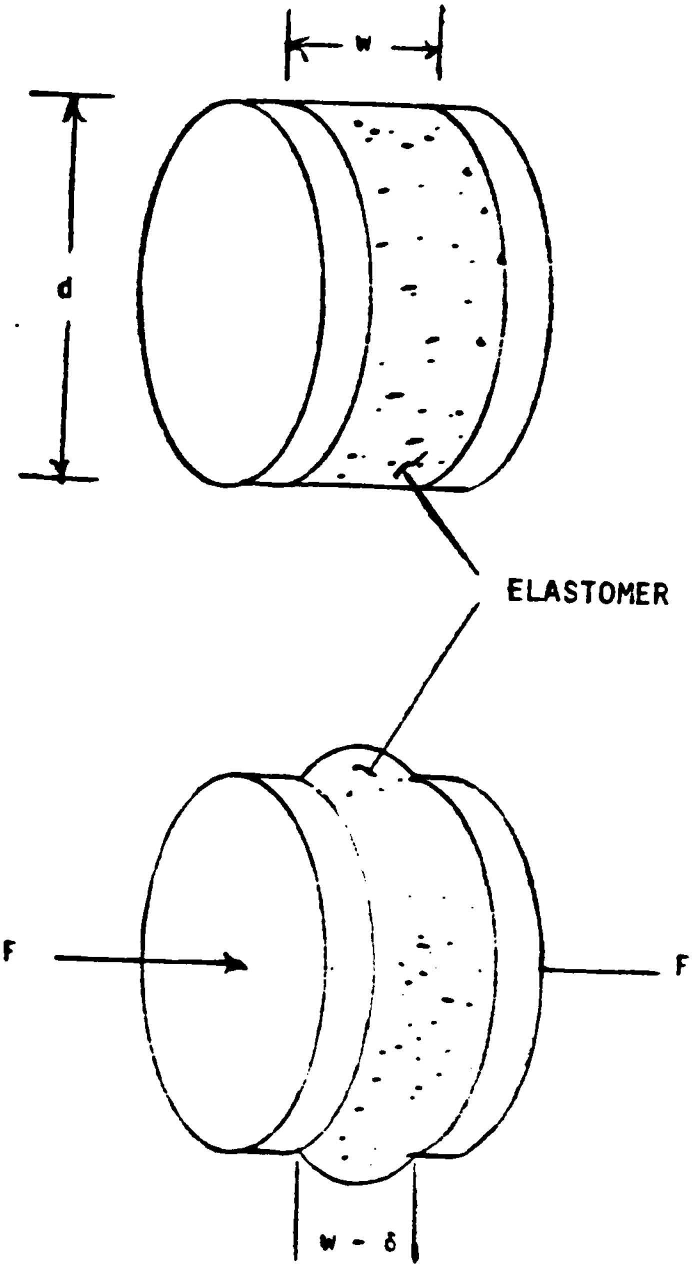

Figure 3.4 Elastomer Confined in a Circular Geometry

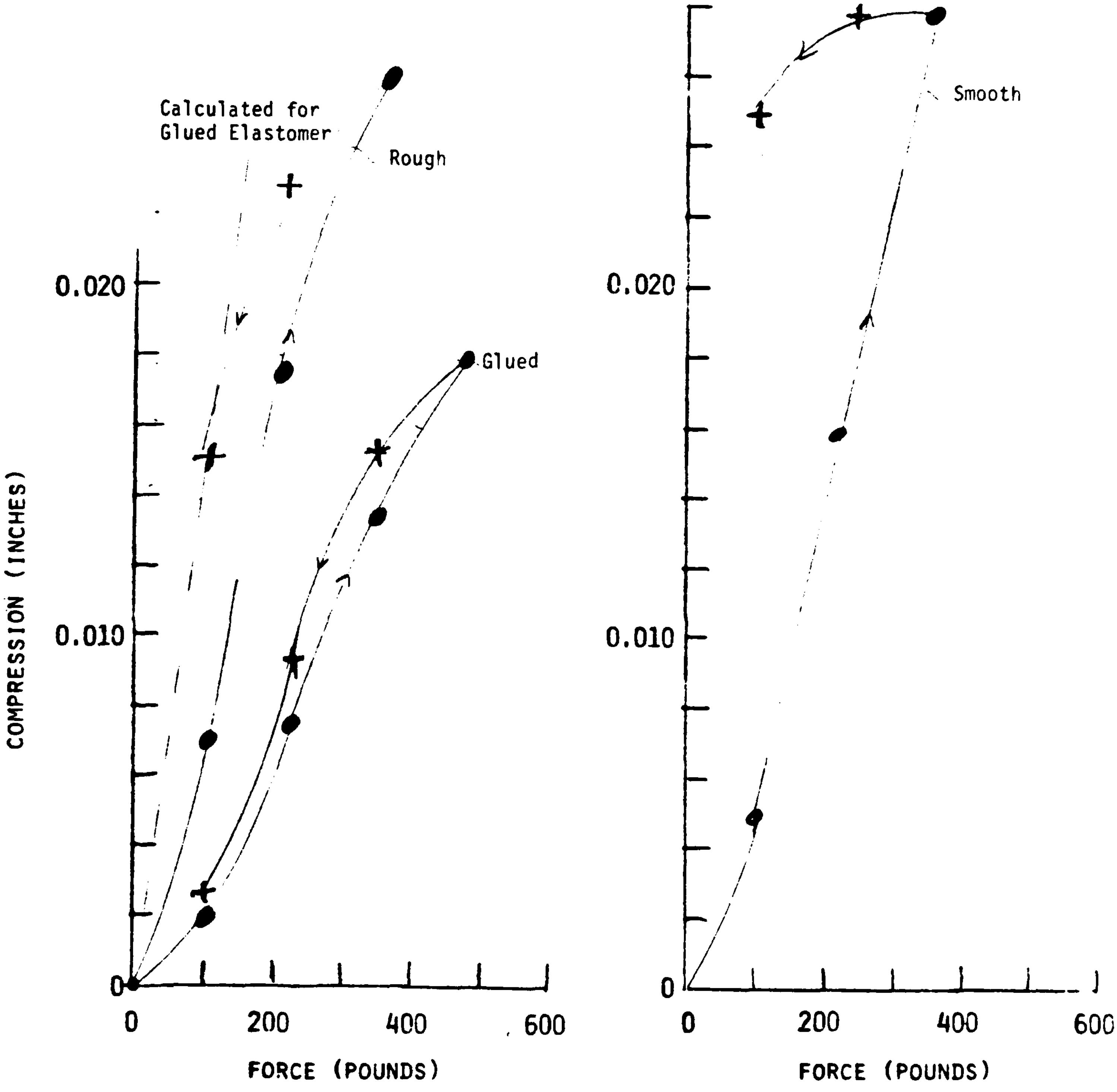

Figure 3.5 Force Required to Compress a 1/8" Thick Sheet of Nominal 30 Durometer between Two 1" Brass Disks of Indicated Surface Finish and When the Disk was Glued to Brass.

The Young's modulus of the elastomer was measured as 190 psi.

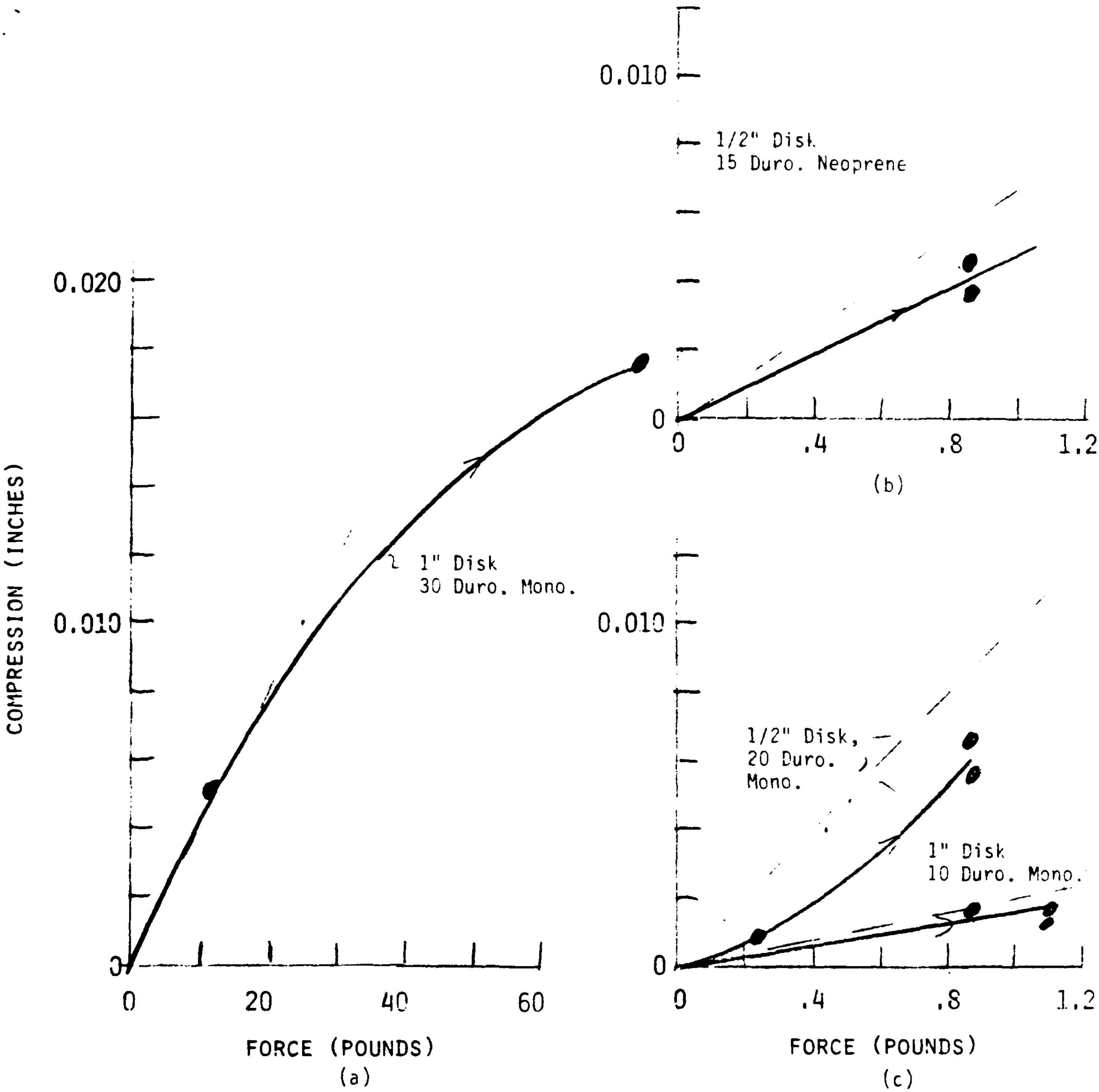

Figure 3.6 Force Required to Compress Elastomers Glued to Brass Disks

Dashed lines are calculated values. (a) Force required to compress a 0.16" thick 30 Durometer Monothane disk between two 1" diameter disks. The Young's modulus, E, was measured as 100 psi. (b) Data for a 0.13" thick 15 Durometer Neoprene disk between two 1/2" diameter disks. (c) Data for a 0.16" thick 20 Durometer Monothane disk between two 1/2" diameter disks. E was measured as 66.7 psi. Also in c is data for a 0.18" 10 Durometer Monothane disk between two 1" disks. Modulus was measured as 30 psi. Dashed lines are values calculated.

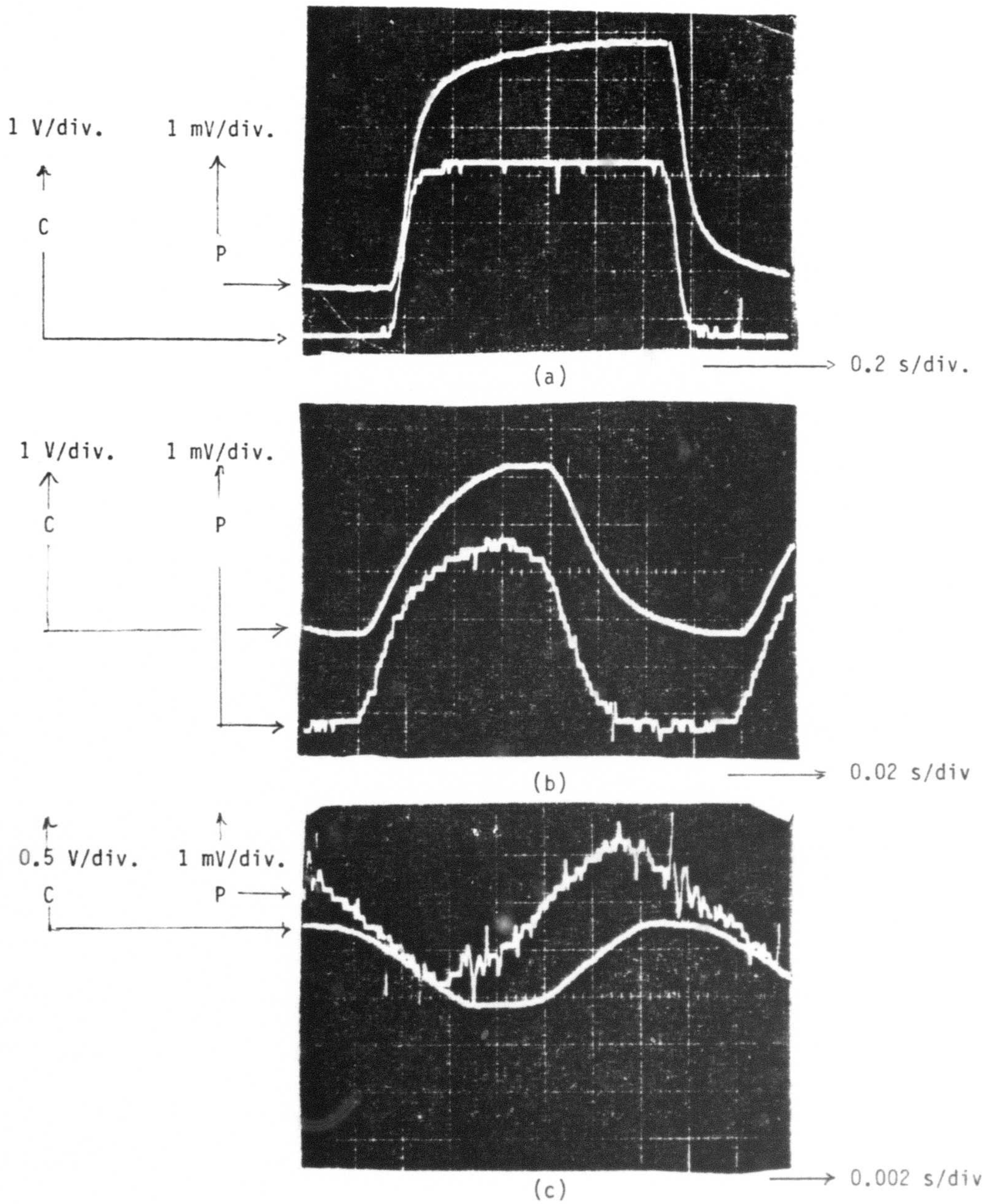

Figure 3.7 Typical Dynamic Test Results. Photographs of Storage Scope.

A fraction of one cycle is displayed. P is output of a pressure transducer on the hydraulic fluid; 1 mV corresponds to 8.3 pounds force on the elastomer. C is the output of the linear transducer; 1 V corresponds to 5.44 mil compression of the two elastomers.

4.0 TASK 2.2 THREE CELL SIMULATOR CPI

Engineering design studies for a mechanical, three cell simulator have been performed. An assembly view of the gas compressor mode is shown in Figure 4.1, and the assembly of the molded test elastomer is shown in Figure 4.2.

4.1 Theory of Operation

1. Test elastomer is molded to fit simulator.
   (a) Thin-wall s.s. tube is cast into elastomer to form inlet and outlet ports.

2. Molded elastomer is glued/epoxied to s.s. force member and to stationary frame, and mounting bolts (6) inserted into stationary frame.
   (a) All metal surfaces to be glued/epoxied are first striated perpendicular to gas flow.
   (b) Gas tightness of seals may be improved with nickel felt.

3. Assembly placed on guide rails in base plate, and micrometer positioners used to bring assembly in tight closing arrangement with drive cams as registered on load cells. Bolts in stationary frame tightened to secure position.

4. Crank head on motor shaft used to check static alignment and self-valving at 150-210° and 270-330° (See Figure 4.3). Solenoid cam operation also checked.

5. With shaft angle at 0=60° (all cells open, Figure 4.3) and inlet and outlet valves open, a helium leak detector is connected to inlet line for leak checking. Alternately, inlet line is pressurized with helium gas and leak detector used to check for overpressure leaks.

6. A pressure gauge (not shown) is attached to the surge tank on the outlet. The surge tank is pressurized with the gas of interest (air, N_2, He); the outlet solenoid valve is closed, and the pressure gauge monitored as a function of time. This calibrates the surge tank leak rate, if any.

7. With the shaft angle at 0=60° and inlet and outlet valves open, the system is brought to 1 atmos. pressure. The dc motor activates the system, and the following are monitored:
   (a) The surge tank pressure gauge as a function of time
   (b) Thermocouples (3) mounted on channel plate
   (c) Load cells

8. Referring to Figure 4.3, the inlet valve is always open, but the solenoid cam is set such that the outlet solenoid valve opens at 0> 270° and closes at 0> 330°. The solenoid cam activates a microswitch.

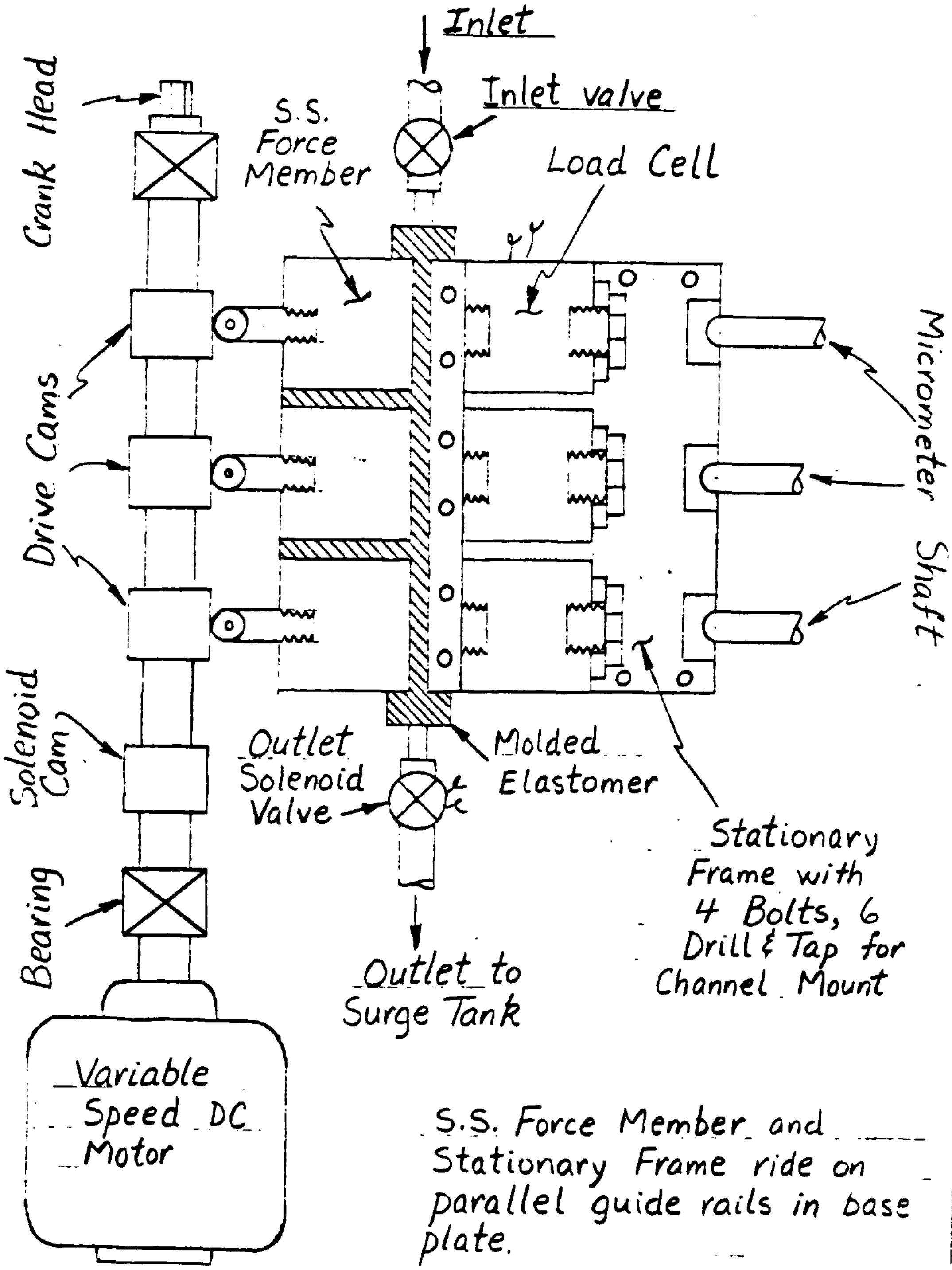

Figure 4.1 Three Cell Simulator

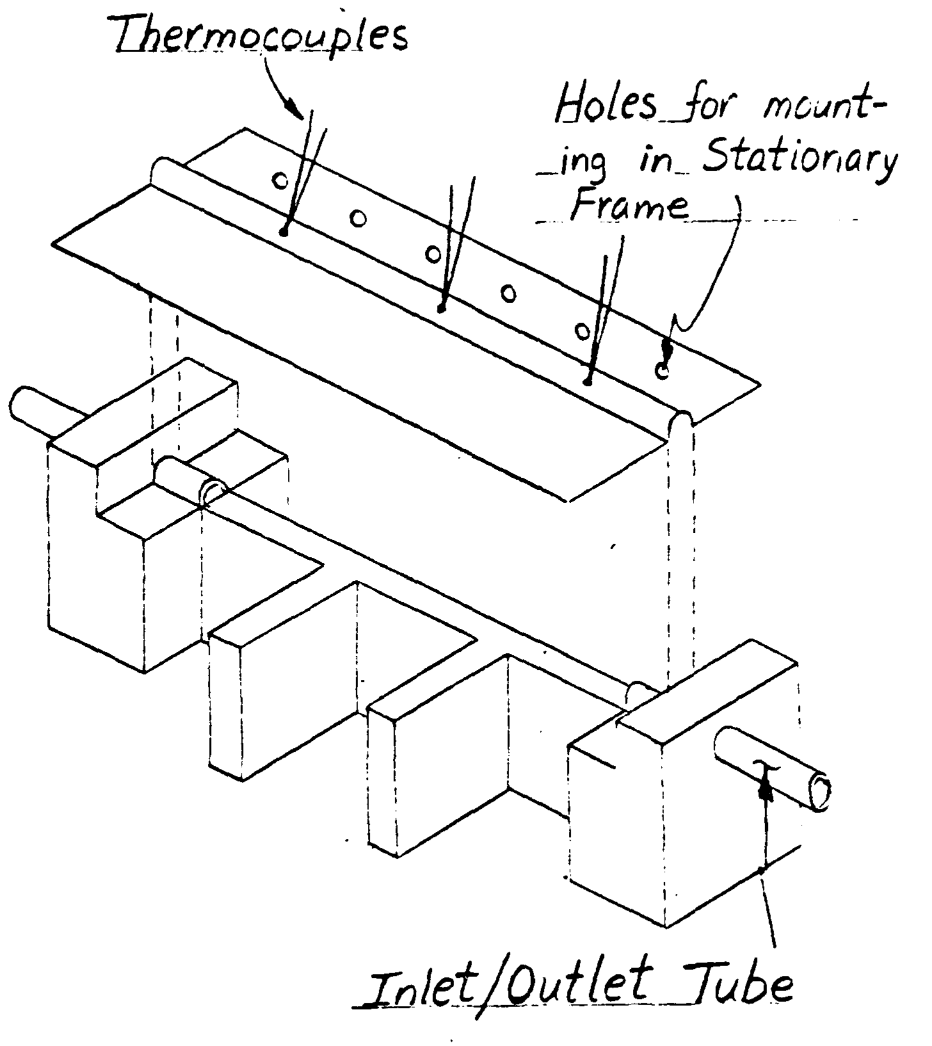

Figure 4.2 Molded Elastomer and Channel Plate

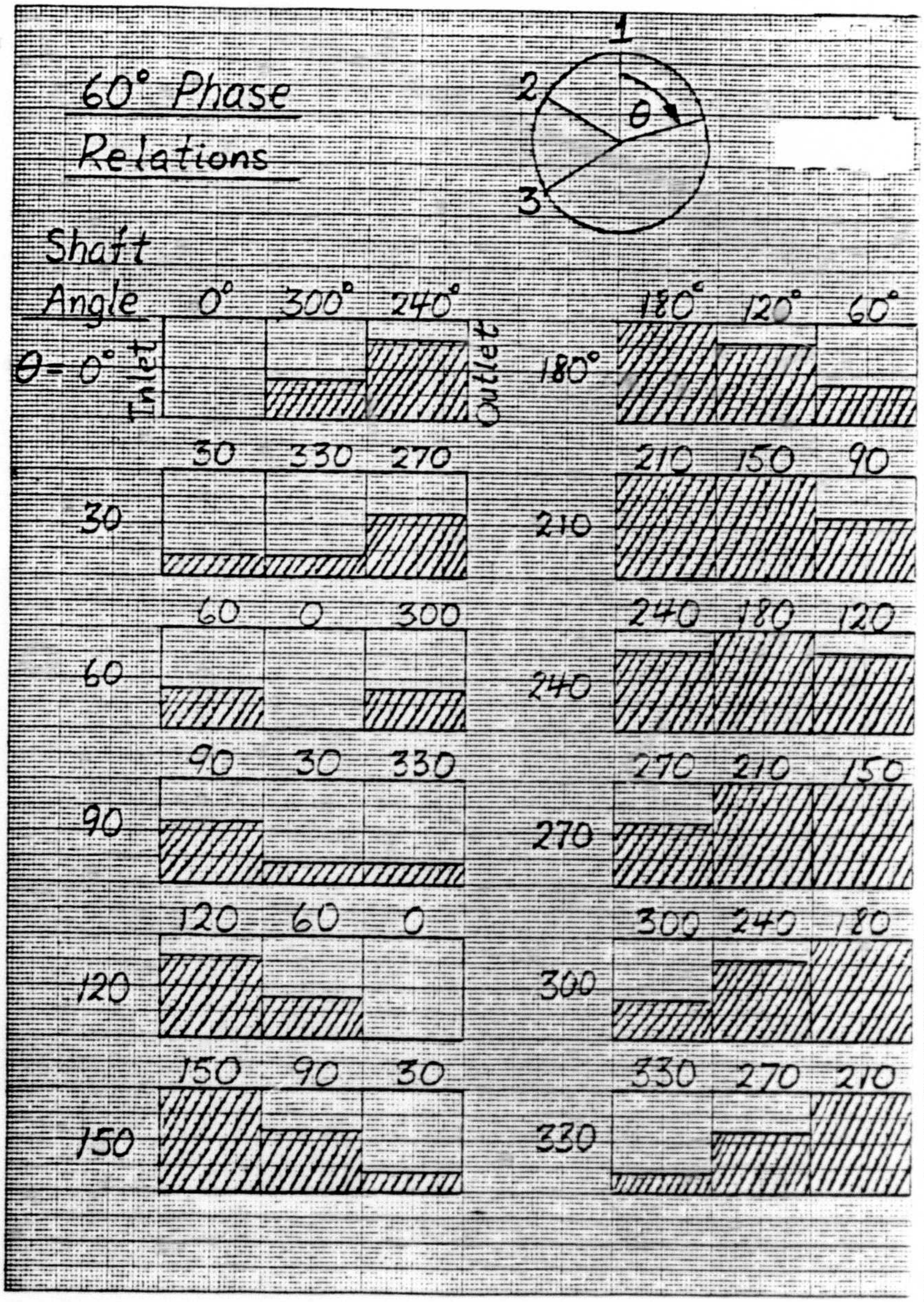

Figure 4.3 Elastomer Position in Each Cell at 30° Shaft Angle Increments

9. Example Operation

(a) System initially at 1 atmos. pressure $P_oV = N_oRT$, V = volume of surge tank

(b) "Puff" volume per cycle = v
$P_ov = nRT$, n = # gas molecules per puff

(c) Pressure buildup in surge tank, $P_iV = (N_o + jn)\ RT$, j = # cycles, $j = \omega t$, ω = shaft rpm, t = time (min.)
Solving,

$$P_t/P_o = 1 + \omega t\ (v/V)$$

(d) Numerical example:

Channel diam. = 0.0125", 1" cell length

$$v = (3)(\pi/8)(.0125)^2(1) \times \underbrace{60\%}_{} \cong 1.8 \times 10^{-3}\ cm^3$$

c.f. Fig. 4.3 at $\theta = 120°$

Assume surge tank diam. = 7 cm → $V = 180\ cm^3$

$\therefore\ v/V \cong 10^{-5}$

P_t/P_o

t(hr)	1000 rpm	3000 rpm	5000 rpm
1	1.61	2.81	4.02
2	2.24	4.63	7.05
3	2.81	6.44	10.1
4	3.42	8.26	13.1
5	4.02	10.1	16.1

(e) Conclusion: Reasonable dimensions and P_t/P_o values for typical running times.

10. For long-time running tests, a pressure-relief valve is mounted in wall of surge tank.

11. Testing diagnostics:
   (a) Proper operation gives $P_t \propto t$.
   (b) Thermocouples and load cells should stabilize.
   (c) After long running times, test stopped, restarted.
   (d) Test gases are He, N_2, Freon, air.

5.0 TASK 4.1 COMPRESSOR SYSTEM ANALYSES (CPI)

To date, work has been devoted to developing a computer program which will allow the evolution of a complete, yet versatile, mathematical model of the solid-state compressor system. This structure at present is being written in Fortran 77 and utilizes subroutines organized in a "top-down" manner. This organization might be likened to a hierachy of labor beginning with the "top" executive giving generalized directions which pass "down" through an increasingly specific chain of foremen and specialized laborers. Our program thus consists of an "executive" main program which calls upon three generalized parts--input, simulation, and output--each of which in turn calls upon chains of "underlying", specialized subroutines, each of which mathematically represents some particular physical aspect of a hypothetical solid-state compressor system.

This organization allows relative ease in making program refinements and other modifications. The final program envisioned will have a variety of input and output options, including terminal and disk input, and disk, terminal, printed paper, and graphical output. The final simulation will likely need such flexibility that it can handle a wide variety of compressor configurations and operating parameters and answer a large number of questions such as the effects of gas turbulence or heat production in the compressor. However, these sophistications may be made in stages; utilizing the subroutine structure would correspond to the addition or refinement of particular subroutines with few changes to other subroutines in that structure.

Work has been begun upon a first iteration of our framework with the goal of obtaining a computer-mathematical representation duplicating the model sketched in the invention disclosure. This particularization utilizes mathematical arrays of dimension corresponding to the number of electrostrictive cells in a hypothetical compressor configuration. Each different array corresponds to some physically measurable parameter such as pressure, temperature, or applied electric field. The number stored in each element of each array corresponds to a measure of that parameter. A series of equations describing physical processes links these parameter arrays together in a chain of dependency; the main simulation program increments compressor operation in time and steps through this chain for each point in time.

As an example of future program refinement, one might consider "feedback" effects--that is, how the dependent parameter chain actually changes itself. For example, one might consider how temperature changes within the compressor as it operates might change electrostrictor or elastomer properties which in turn might change compression and temperature generation properties. This would correspond to an interaction between subroutines toward the bottom of the structure.

3-30-84

DARPA TASK SCHEDULE - START 10/1/83

CONTRACT N00014-83-C-0394

	Task	By
1.1	Drivers for Prototype Units	
.1	Develop Type I Ceramics	PSU
.2	Define Design Parameter	PSU
.3	Specify Driver Design	CPI
.4	Fabricate 4 Sets, Deliver	PSU
1.2	Drivers for Final Unit	
.1	Research Type II Ceramics	PSU
.2	Define Design Parameters	PSU
.3	Specify Driver Design	CPI
.4	Fabricate 10 Sets, Deliver	PSU
2.1	One Cell Simulator	
.1	Design One Cell Simulator	APCI
.2	Fabricate One Cell Simulator	APCI
.3	Test Materials	APCI
2.2	Three Cell Simulator	
.1	Design 3 Cell Simulator	CPI
.2	Fabricate 3 Cell Simulator	CPI
.3	Test Pumping Action	CPI
3.	Driver Electronics	
.1	Specify Driver Elec. Charter.	CPI
.2	Design & Fab. Driver Elec./3 Cell	CPI
.3	" " " " /1 Cell	APCI
4.1	System Analysis	
.1	Elastomer Stress, System Design	APCI
.2	Compressor/Driver Analysis	CPI
4.2	Prototype Compressors	
.1	Design, Fab.&Test 1 Cell Proto.	APCI
.2	" " " 3 Cell Proto.	CPI
4.3	Final Compressor	
.1	Design Multicell Compressor	APCI
.2	Fabricate Multicell Compressor	APCI
.3	Test Multicell Compressor	APCI
4.4	Design, Fab. & Test Cryostat	APCI
4.5	Test Final System	APCI
5.1	Status Reports	
.1	Subcontractor Reports, Mo.-15th	PSU
.2	" " " "	CPI
.3	Report to DARPA, Quarterly-30th	APCI
5.2	Interim Technical Reports	
.1	Driver Research	PSU
.2	One Cell Simulator	APCI
.3	Three Cell Simulator	CPI
.4	One Cell Prototype	APCI
.5	Three Cell Prototype	CPI
.6	Mid-Term	APCI
5.3	Final Report	APCI