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A REVIEW OF PRESSURE-TOLERANT ELECTRONICS (PTE)

NAVAL RESEARCH LABORATORY

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A Review of Pressure-Tolerant Electronics (PTE)

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Pressure-tolerant electronics (PTE) are those electrical or electronics components or equipments which are capable of proper operation in a pressurized environment. The environment may be gaseous or liquid. This review is intended to summarize the efforts which have been given to PTE in the past 20 years. Organizations presently active in PTE are listed. Some ideas are presented which may be used to develop candidate PTE of the future.

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A REVIEW OF PRESSURE-TOLERANT ELECTRONICS (PTE)

INTRODUCTION

Pressure-Tolerant Electronics (PTE) refers to electronic components or systems developed or modified so that they can satisfactorily operate in a hyperbaric or hydrostatic medium without the benefit of pressure-resisting housings enveloping them. Implicit in the definition of pressure-tolerance is the technique of utilizing an intermediary fluid, immediately surrounding the components, which is maintained in equilibrium with ambient pressure.

If every piece of equipment in a submarine could be installed outside of the pressure hull there obviously would be considerable benefits accrued from such an arrangement. Just as obvious is the fact that it is neither feasible nor desirable to have all the equipment inaccesible to the submarine operators. What proportion of equipment should or could be candidates for pressure-tolerant application would depend upon what type of vehicle are being considered.

Systems which have little or no space or weight problems are poor candidates for PTE. Vital or life-support systems in manned submersibles which require a high degree of reliability would also be non-candidates for PTE. On the other hand, manned, underwater habitats and personnel transfer capsules for saturation diving are prime candidates.

BACKGROUND TECHNOLOGY

The advent of the era of oceanography caused a large number of people to become interested in the mysteries of the sea. Each year more and more instruments and vehicles probed the depths of the oceans. By 1960 the bathyscaph, TRIESTE, (which was built in 1953), descended 11000 meters into the Marianas Trench. The propulsion system of the TRIESTE was probably one of the first examples of the application of pressure-tolerant equipment. Not only was the system successful, but it remains essentially of the same design even today.

Along with batteries and electric motors is the wiring which must interconnect them. This wiring, of course, must be watertight, and must also be fed through watertight bulkheads by use of easily detachable connectors. For this development the oceanographic community is

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indebted to the oil-well drilling industry. Their need for such wiring and bulkhead connectors predated that of oceanography's. Today, there is little need for any further research into water-tight wiring or bulkhead connectors. Almost any desired configuration is commercially available. Interest next turned to the more complex items which made up electronic systems - resistors, capacitors, diodes and transistors. How well could these items live in the ocean environment without enveloping them in pressure resistant housings.

Around 1961, interest in PTE was developing in several industrial organizations as well as universities. This interest gave birth to the first meeting on PTE ever held. The meeting was sponsored by and held at the Naval Research Laboratory (NRL). The object of the meeting was to exchange ideas on the merits of and applications for PTE. The meeting was well attended. For various reasons, there never was a follow-on meeting called to ascertain direction of or further interest in PTE. Everyone, apparently pursued his own interest and course - alone. Occasionally, reports of activity in PTE surfaced in various journals. This report will attempt to present a bibliography of all known or published literature on the subject of PTE.

PAST EFFORT

Early in 1960 NRL built a portable high pressure system Figure 1 (1) capable of hydrostatically pressurizing small items of equipment up to 100 MPa. Built into a standard-size electronic relay rack, the system had provisions for automatic temperature and pressure control. The temperature could be maintained at any level between -5^{o} and $+75^{o}$ Celsius. The cylindrical pressure vessel measured 127 mm I.D. and was 500 mm long. The system was built specifically for measuring the temperature and pressure tolerance of electronic components.

The desire for the test facility was motivated principally by the need for a power amplifier to drive a deeply-submerged acoustic transducer. The amplifier which was being used was housed in a 550 kg spherical pressure vessel. The desire to eliminate the excessive weight of the pressure vessel spawned the idea of utilizing pressure-tolerant components in the construction of the amplifier. This, was NRL's first instance for the need of PTE. No attempt was made to build the high-power amplifier - instead, a 30 db gain preamplifier was undertaken. A productive bonus, as a result of the undertaking, was the technique developed for making water-tight, electrically-insulated connectors between amplifier and transducer. One of the first systems to be built incorporating PTE was the Remote Underwater Manipulator (RUM) built by Scripps Institute of Oceanography. The first version of this vehicle in 1958 had two 5.6 kW electric motors and a General Mills Model 500 manipulator exposed to the ambient pressure. The second model, made by Scripps in 1968, had a 70 channel telemetry system with time and frequency multiplexing, eight channels of A-D conversion, a 125 kHz scanning sonar, transponders, magnetic compass, up and down echo sounders, a current meter, and roll and pitch sensors - all PTE. Also, part of the 400 kHz scanning sonar was PTE. Operation has been about 7,500 feet, 2300 m.

Another project making use of PTE was Sea Lab. The components here were exposed to a diving gas environment equivalent to a pressure of about 150 m of sea water. Incandescent lamps, a food warmer for the Hyperbaric Chamber, a space heater for the Personnel Transfer Capsule, and a flame detector and control amplifier for the Deck Decompression Chamber were all made by General Dynamics. In addition, Victor electrowriters were modified for use at 300 m. Scripps contributed PTE relays, amplifiers, and switching circuits to Sea Lab II. Dolphin, AGSS 555, has 15% of its passive sonar system in PTE. This comprises 728 op-amps for the delay and sum amplifiers and 16 voltage regulators.

Several manufacturers have built transponders using PTE techniques. Bendix-Pacific was perhaps the first with its Ship Tended Acoustic Relay (STAR), built in 1964 for the Air Force and good to 4900 m. General Electric also made a deep ocean transponder as did Ametek/Straza. Digicourse has produced a pressure-compensated compass designed for 6100 m depths.

From the earliest days of research submersibles, motors, controllers, wiring harnesses, junction boxes, and batteries have been outside the ship's hull exposed to the ambient pressure. Yardney Electric Corporation, among others, has been concerned with batteries for some years. Franklin, and others, have done extensive work on flooded motors. Delta Electronics has made converters and inverters in PTE. TRW Subsea Systems has developed a pressure-balanced electrohydraulic subsea control system for the petroleum industry. Owners and operators of deep ocean submersibles have also developed motors. batteries, controllers and wiring systems. General Dynamics with their STAR III is an example. Others are ALVIN, TURTLE, SEA CLIFF, MAKAKAI, and DEEP VIEW.

Present applications of PTE include RUM II with its extensive telemetry system. Bunker-Ramo is building an Expandable Reliable Acoustic Path Sonar (ERAPS) with signal conditioning, power amplifers, multiplexers, and battery as PTE. In addition to batteries, Yardney is making motor-driven, battery-cell scanners exposed to pressure. Lockheed has reported prototype solid-state switching devices and multiplexing systems for deep submergence applications.

Naval Underwater Systems Center (NUSC) has built a Small Diameter Line Array with depth sensors, accelerometers, inclinometers, hydrophones, tensiometers, voltage-controlled oscillators, and FM multiplex telemetry. This system is usable to 180 m. Their Weiner Hydrophone Array consists of 25 mm diameter hydrophones connected by cables laid in grooves of the spacing thermal plastic rubber cores. The 25 mm diameter cores, with the .38 m length hydrophones and cables are contained within braided Kevlar rope. The free-flooded electronics is capable of flexing to the curvature of hoisting sheaves.

Since the early days of PTE there has been considerable effort expended in testing various electronic components for pressure tolerance. By judicious selection one may find resistors, capacitors, inductors, diodes and even transitors which are pressure tolerant, to some degree, as off-the-shelf items. Devices with ceramic, plastic and epoxy packages are suitable for use at hydrostatic pressures up to 100 MPa. Solid-state devices with voids, TO-type cans, and DIP flat packs with metal lids fail at very low pressures due to package deformation or manufacturing techniques. Passive components with voids, carbon composition resistors, electrolytic capacitors, and ferrite core inductors exhibit large value changes with pressure. Semiconductors, metals, and insulation materials are relatively insensitive to the pressure environment (2).

The effect of pressure on resistors varies widely depending on the type Figure 2 (3). Those of carbon composition exhibit a direct relationship with hydrostatic pressure, and are adaptable to pressure transducer applications, since they have a repeatable performance in percent changes in resistance when pressure cycled Figure 3 (4). The fixed film and wire wound are pressure insensitive.

When transitors were tested in a pressurized-oil medium, first, as normally-cased and then with the top case removed - the results were similar Figure 4 (4). An improvement in performance results with epoxy incapsulation. Test data for diode indicate that the zener type exhitited very small changes in characteristics and that all-metal-encases type diodes failed Figure 5 (4).

The configuration and materials used in the manufacturing of semiconductor cases influence their capacity to withstand hydrostatic pressure. Figure 6 (2) compares the increased strength of a hemispherically-domed shaped TO-type case with that of a flat-topped type. When kovar is used in the construction of semiconductors an increased water depth capability is realized.

Figure 7 establishes that the values of polystrene, mylar, solid tantalum and ceramic capacitors are insensitive to pressure. The paper and tantalum foil types showed a less-promising performance; and the greatest percent change in capacitance is exhibited by the wet-slug tantalum type (4).

Six electrical contactors were cycled three times to a pressure of 69 MPa, after being pressure-relieved and silicone-oil filled Figure 8 (4). The variation of percent change in open/close time for four of the 100 A size was from less than 40 percent up to 1000 percent. The two samples of the 50 A rating exhibited the least change with increasing pressure.

The above are but a few of the devices which have been modified to determine reactions to pressure. The bibliography appended to this review is supplied for those interested in obtaining details of the scope and type of test data available on PTE.

REQUIREMENTS FOR PRESSURE TOLERANCE

Infinite reliability is the unattainable goal which users of equipments hope to reach. Reliability specifications are found throughout industry and especially in the military. In submarines, vital circuitry and systems must possess the highest degree of reliability possible. For this principle reason, any PTE used in conjunction with manned submersibles must achieve at least similar degrees of reliability as their inboard competitors.

PTE utilize two general methods of achieving pressure tolerance: the item is either hard-coated or is placed in a pressure-compensated container of good dielectric fluid. In some cases the item is first soft-coated, then hard overcoated. The hard coats may be castings, moldings or merely dippings. Hard coated items are not considered reparable. Tables 1, 2a, 2b, and 3 (5) show various characteristics of fluids which could be used in conjunction with fluid-compensation. Table 4 lists desirable properties of containers holding the compensating fluid.

One of the best examples of fluid-compensation PTE is EG&G's 12 kHz pinger transformer. A cylindrical, lucite tube houses the transformer and the pressure-compensating transformer oil. The two open ends of the tube are sealed with close-fitting rubber stoppers. The four lead-in wires are forced through holes in one of the rubber stoppers. These stoppers effectively seal the wires, the tube openings and the slide in and out of the tubing in an amount proportional to the ambient pressure. Inspection of the transformer and wiring internally is afforded because of the transparency of the container. This technique should find wide acceptance in many applications of fluid-compensation PTE.

For reparable items, it would be desirable if the fluid selected would leave the electronic item clean and ready to work on when taken from the fluid bath. This selection indicates a low viscosity, high vapor pressure fluid having good dielectric properties. It would also be desirable that the fluid be non-flammable, non-toxic and non-corrosive-but always, compromises must be made.

ACTIVE RESEARCH IN PTE

The amount of activity in PTE at the present time is apparently less than that of five years ago. This is principally due to the fact that the need for PTE did not materialize to the expected extent. In order to gain some insight as to the present effort being devoted to

PTE, letters were sent to all those organizations known to have been active in some area of PTE. The response was somewhat disappointing. None the less, a goodly amount of information was collected so as to make the finding worth reporting. The below listing indicates organizations with their areas of interest.

A. GOVERNMENT INSTALLATION

1. U. S. Naval Ship Research Development Center (NSRDC): Under the D.O.T. program, work is being done on AC and DC motors and their accessories. Equipment for variable ballast and trim systems.

2. U. S. Naval Underwater Systems (NUSC): Small diameter, acoustic, line arrays for 6 km depths.

B. INDUSTRIAL ORGANIZATIONS

1. Yardney:
   Batteries and battery cell scanners. May be working on brushless DC motors

2. Franklin:
   Electric motor-flooded

3. Delta Electronics:
   Electrical converters and inverters

4. Digicourse:
   Compasses

5. Bendix-Pacific:
   Transponders

6. Ametec-Straza:
   Transponders

7. TRW:
   Electro-hydraulic subsea control systems

8. Bunker-Ramo
   Sonar signal processors, amplifiers and multiplexers

THE FUTURE - PLANS AND NEEDS

Exploration and exploitation of the oceans will definitely increase. How much of the equipment needed in these tasks will utilize PTE will be up to the designer of the vehicles or instrumentation packages. He must demonstrate that PTE is cost effective. This effectiveness may be in terms of internal volume reduction of manned submersibles, cooling load reduction or other tangible considerations (6). One aspect that PTE will always have - is the excellent heat sink which the ocean waters provide.

Future research into PTE will be generated if the Navy's planned expenditure of $2300K, for the periods FY-78-FY-82, become a reality. These funds should be distributed outside as well as in-house. The practical maximum number of people should be brought into this area so that their ideas and ingenuity may be developed. One cannot expect industry to research this field with their own resources unless a salable commodity may be realized.

While general interest in PTE does not appear to be high, there are some areas into which some research or development could bear real dividends. One item, especially, which should be investigated is the D.C. motor. What is needed is a D.C. motor without brushes and capable of operating when flooded with sea water. Secondary, electric batteries work quite well under pressure. The technique of utilizing an intermediary fluid between the electrolyte and the sea water is well known. However, some research would be beneficial on the plate construction of a battery subjected to pressure. The ion transfer rate between plates, when subjected to pressure, should be investigated.

Devices and equipment used in hyperbaric gaseous environment as experienced in manned habitats and personnel transfer capsules is a promising area for further development effort. An understanding of the various effects of the high helium atmosphere on devices and equipment needs more effort in order to overcome their shortcomings in this hyperbaric environment.

With the shortage of funds being experienced in the research community, any effort devoted PTE by an investigator should be directed towards a specific item rather than attacking the general aspects of PTE. This approach may not be the ideally organized method of investigating the general area of PTE, but from a user's viewpoint it would be more cost effective. In time the specific application techniques developed in utilizing pressure-tolerant components would be accumulated and used to form a bank of knowledge as the basis for a PTE handbook. A lead laboratory should be selected and made responsible for the preparation of the handbook.

Fluid	Base Composition	Relative Compress-ibility 69MPa 25°C (%)	Specific Gravity 0 MPa 25°C (k kg/m³)	Kinematic Viscosity 0 MPa 38°C (μm²/s)	Dielectric Breakdown 1.3 mm gap 25°C (kV)	Electrical Resistivity 25°C (GΩ·m)
Bayol 72	Petroleum		.83	13		
Brayco 460	Petroleum	3.4	.86	10	20	64
Brayco 717	Petroleum		.86	27	23	8
Brayco 730	Petroleum	3.2	.88	10	25	500
Castor Oil	Vegetable	2.9	.95	300		
FC-43	Fluorocarbon		1.88	3	28	
FC-77	Fluorocarbon		1.78	1	22	
Kerosene	Petroleum	4.1	.80	2		
Marcol 52	Petroleum		.82	8		
Micronic 756E	Petroleum	[illegible].6	.85	12	24	30
Micronic 762	Petroleum	[illegible].2	.85	4		
MPO-30	Polymer		.87	120		
MIL-S-21568A	Silicone	6.8	.81	1	26	200
Paraffin Oil	Petroleum	3.2	.86	25		
Primol 205	Petroleum		.87	44	28	13000
Polyvis O SH	Polybutene		.84	23	18	8000
SF-1143	Silicone			1	26	5
Submersible No. 2	Petroleum	3.8	.83	5	27	300
Tellus 11	Petroleum		.83	5	30	500
Tellus 15	Petroleum	3.5	.87	11	30	800
Tellus 27	Petroleum		.87	34		
Trichloroethylene	Hydrocarbon	3.6	1.46			
Turbine Oil	Petroleum	3.2	.87	36	15	40
VV-D-00178	Silicone	5.7	.94	9	26	1000

TABLE 1

PRESSURE COMPENSATING FLUIDS FOR PRESSURE-TOLERANT ELECTRONICS

PROPERTIES	EFFECTS
Chemical	
Chemically stable and inert	Maintains compability with system's metals, coatings, insulations, seals and elastomers
Protects system from galvanic corrosion	Retards degradation of system integrity
Neutral pH (neither acid nor alkaline)	Reduces corrosion
Volatile	Easily removed from components for repair or inspection
Not oily; does not stick to electronics	Readily removed
Low foaming tendencies	Easier gas removal when vacuum pumped during filling of container
Insoluble in water	Emulsion reduces electrical resistivity
Does not emulsify	Reduces the loss of electrical resistivity
Electrical	
Good dielectric	Reduces high voltage arcing which causes carbonization
Resists carbonization due to sparking	Carbonization reduces electrical resistivity
High dielectric breakdown voltage (15 kV minimum for 1.3 mm gap)	Reduces loss of electrical resistivity
High electrical resistivity (3 GΩ·m minimum)	Protects electronic components from failure
Low dissipation factor (2% maximum of polar and water-soluble additives)	Reduces voltage breakdown

TABLE 2A

DESIRABLE PROPERTIES OF PRESSURE-COMPENSATING FLUIDS FOR PRESSURE-TOLERANT ELECTRONICS

PROPERTIES	EFFECTS
Mechanical	
High bulk modulus (low isothermal compressibility)	Reduces volume required for pressure compensation
Low specific gravity (1.0k kg/m^3)	Produces neutrally or positively buoyant system
Low thermal coefficient of expansion	Pressure compensation fluid volume reduced
Low viscosity	Increases heat dissipation through greater thermal conductivity; prevents formation of solid "clinkers" on electrical contacts; less affected by pressure
High thermal conductivity	Better heat sink for power components
Temperature stability (-2 to 150°C)	Lessens deterioration of components
High flash point (150°C minimum)	Hazardous, if sparking present
Low vapor pressure	More easily evaporated from electronic components
Low gas solubility	Reduces volume increase when pressure reduced, with possible hazardous rupture of container walls
Resists percolation of container and components under pressure	Reduces degradation of components
Miscellaneous	
Inhibits fouling and bacteria growth	Electronic components become inoperable
Low toxicity	Reduces bodily irritation; tissue destruction
No objectionable odor	May be irritating to persons handling system
Leaves no residue on components	Does not hinder repairing by soldering
Transparent; has low index of refraction	More easily inspected when viewed through wall of transparent container
Commercially available at low cost	Produces an economical system
Capable of cycling to pressures of 100 MPa	Maintains original characteristics by reducing physical breakdown

TABLE 2B

DESIRABLE PROPERTIES OF PRESSURE-COMPENSATING FLUIDS FOR PRESSURE-TOLERANT ELECTRONICS

FLUID	ABS	ACR	CAB	CEA	CEP	CET	DIL	EPOX	EVA	ION	PCB	PHOX	PPO	PSU	PVCE	STY
Butyl acetate	4	4	4	4	4	4	0	2	1	0	4	4	2	-	4	0
Carbon disulfide	4	2	3	3	3	4	4	1	2	0	4	4	3	4	4	4
Carbon tetrachloride	4	3	3	3	3	3	3	0	2	0	4	4	3	4	4	4
Castor oil	0	1	4	4	4	2	0	1	0	0	0	-	1	1	0	1
Cyclohexane	4	-	4	4	4	4	1	1	4	1	1	4	2	4	4	-
Ethyl alcohol	0	3	3	4	4	3	0	0	1	0	0	3	0	1	1	0
Ethylene glycol	0	1	4	4	4	4	1	0	0	1	-	3	4	-	0	4
Formaldehyde	2	4	4	4	4	4	3	1	4	1	4	4	1	-	2	4
Gasoline	2	1	3	3	3	3	2	1	3	1	1	3	4	3	1	4
Glycerin	1	0	4	4	4	4	1	1	-	1	1	1	0	0	0	-
JP-4	1	1	4	4	4	4	0	1	4	1	0	1	4	-	1	2
Kerosene	4	0	2	4	3	3	1	1	4	1	0	1	3	-	0	3
Methyl alcohol	4	0	3	3	3	3	0	0	1	0	1	4	0	-	0	0
Mineral oil	1	0	1	1	1	1	0	0	4	1	0	1	1	1	1	2
Silicone oil	1	0	1	1	1	1	0	0	1	1	0	1	1	1	1	2
Trichloroethylene	4	4	4	4	4	4	3	1	4	1	4	4	4	-	4	4
Turpentine	4	-	4	4	4	4	4	1	4	1	-	1	3	4	3	4
Water, fresh	0	3	1	2	1	1	1	0	0	1	0	1	0	1	0	0
Water, sea	0	0	3	3	3	3	0	1	1	1	0	1	0	1	0	1

CODE	MATERIAL
ABS	Acrylonitrile, butadiene and styrene
ACR	Acrylics
CAB	Cellulose acetate butyrate
CEA	Cellulose acetate
CEP	Cellulose acetate propionate
CET	Ethyl cellulose
DIL	Dillyl phthalate (allylics)
EVA	Ethylene vinyl acetate
ION	Ionomers
PCB	Polycarbonates
PHOX	Phenoxies
PPO	Polyphenylene oxides
PSU	Polysulfones
PVCE	Polyvinyl chloride elastomer
STY	Polystyrene

ENVIRONMENTAL RATING	
0	Excellent
1	Good
2	Fair
3	Poor
4	Do not use

TABLE 3

PRESSURE COMPENSATING FLUID COMPATIBILITY WITH TRANSPARENT PLASTIC CONTAINER MATERIALS

TABLE 4

DESIRABLE PROPERTIES OF CONTAINERS FOR DEEP-OCEAN ELECTRONICS AND ITS PRESSURE-COMPENSATING FLUID

1. Transparent enough to inspect components
2. Low density
3. Satisfactory fracture and notch toughness
4. High low-cycle fatigue resistance under pressure cycling to great depths
5. Sufficiently elastic to accommodate pressure-induced volumetric changes in the dielectric fluid, thus eliminating a piston or bladder arrangement
6. Easily installed aboard instrumented vehicles
7. Provide easy access of components and feedthroughs
8. Inert to both external and internal gases and liquids used in the pressurizing process
9. Galvanically stable
10. Good stress corrosion cracking properties
11. Provide water-tight O-ring sealing

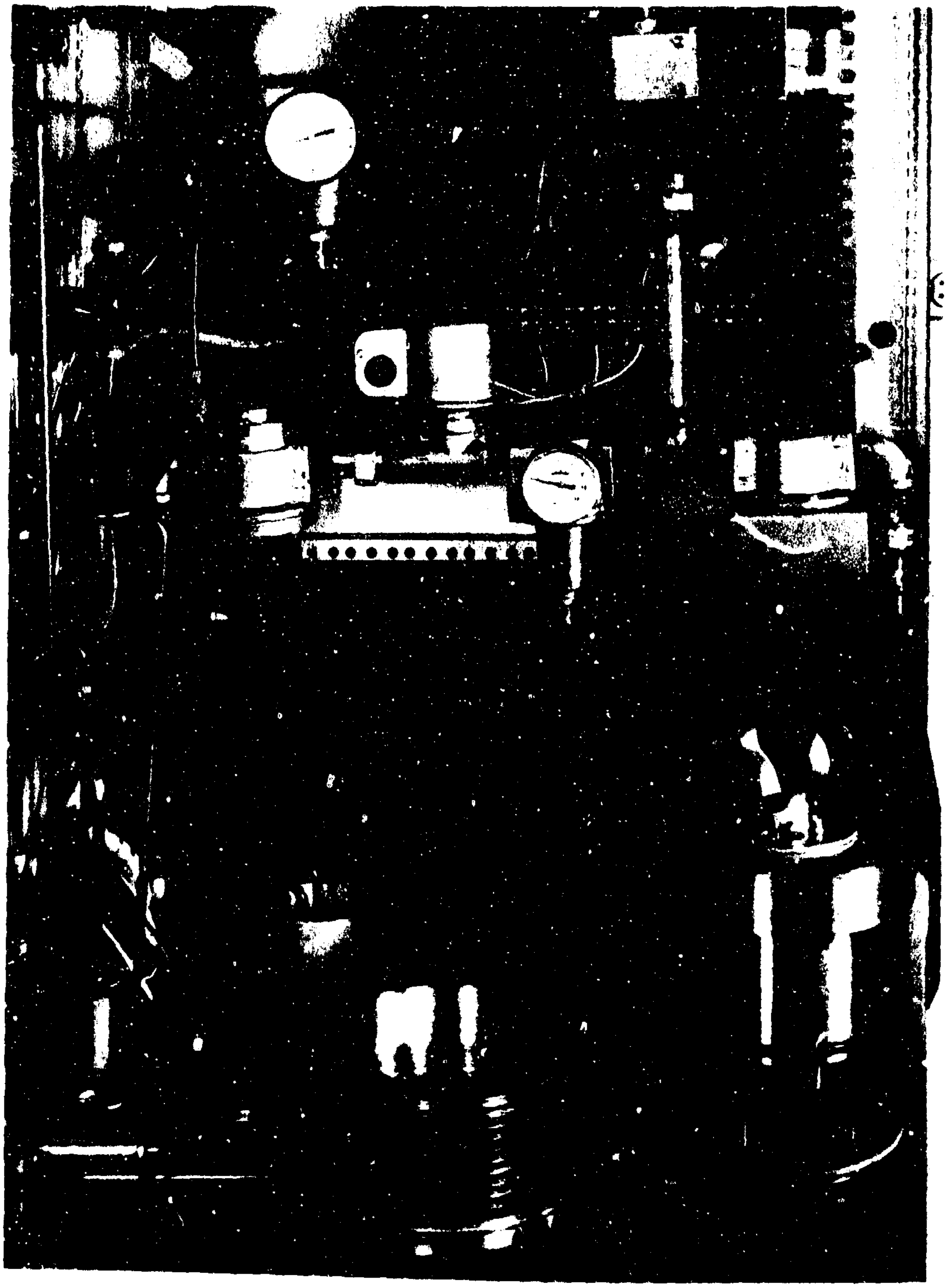

Fig. 1 — NRL portable 100-MPa pressure testing facility

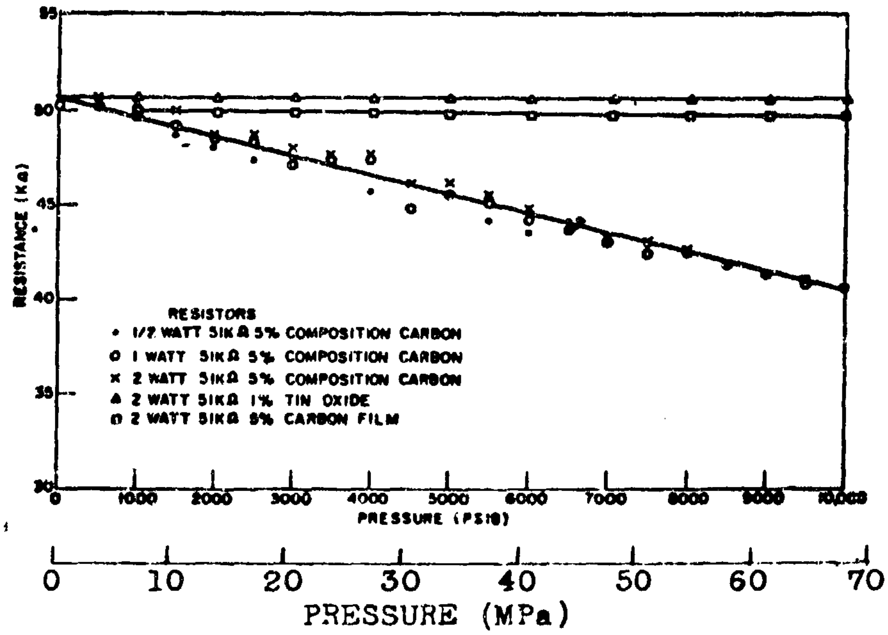

Fig. 2 — Effect of hydrostatic pressure on three types of resistors

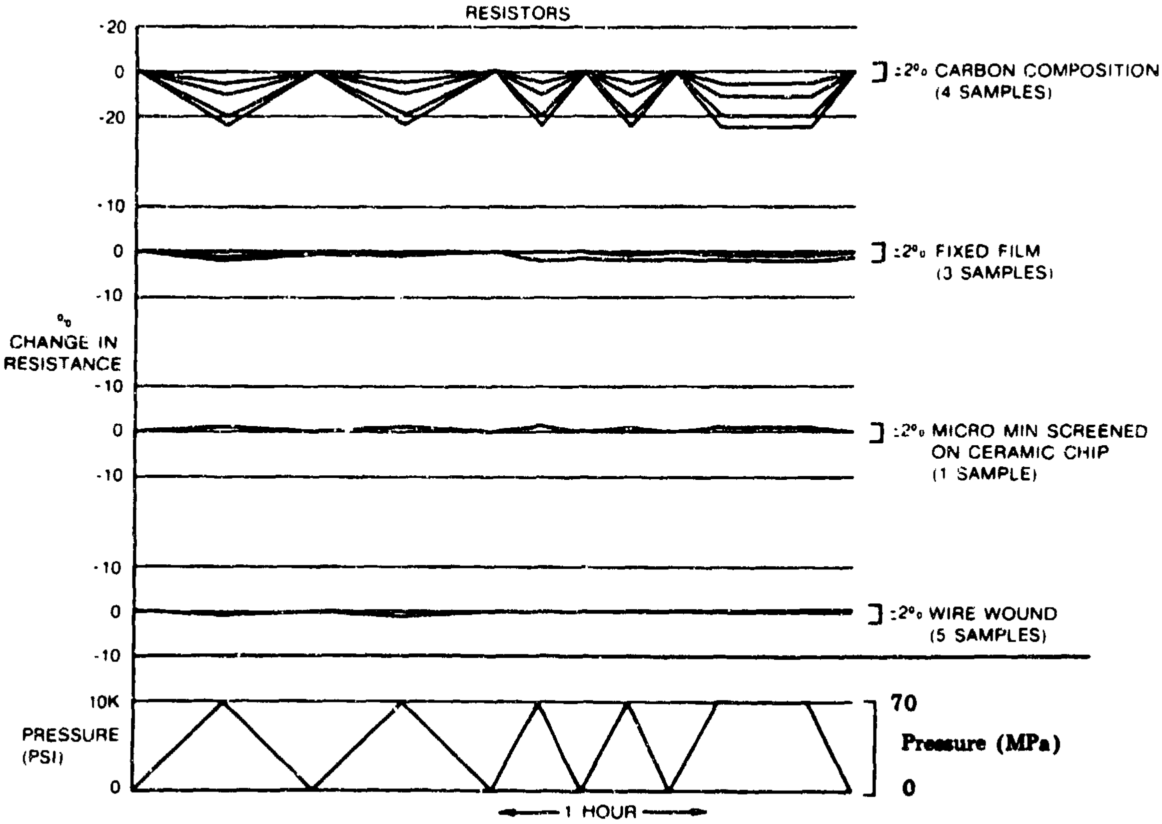

Fig. 3 — Results of resistor tests

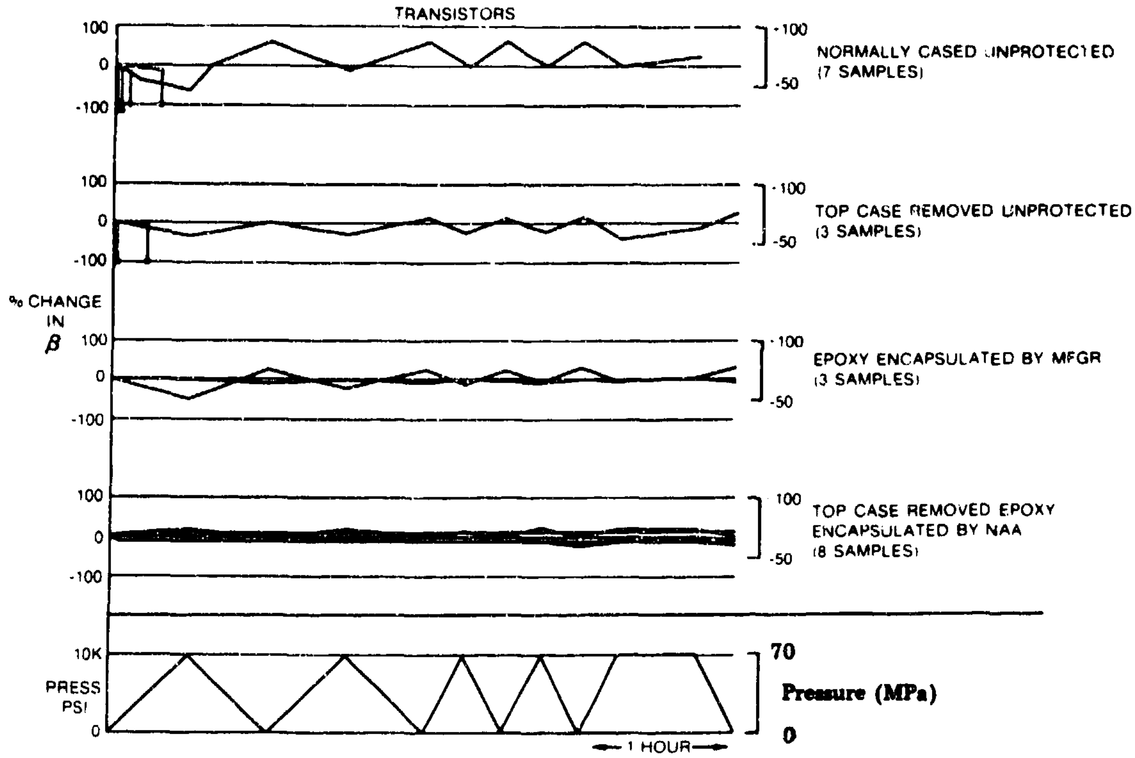

Fig. 4 — Results of transistor tests

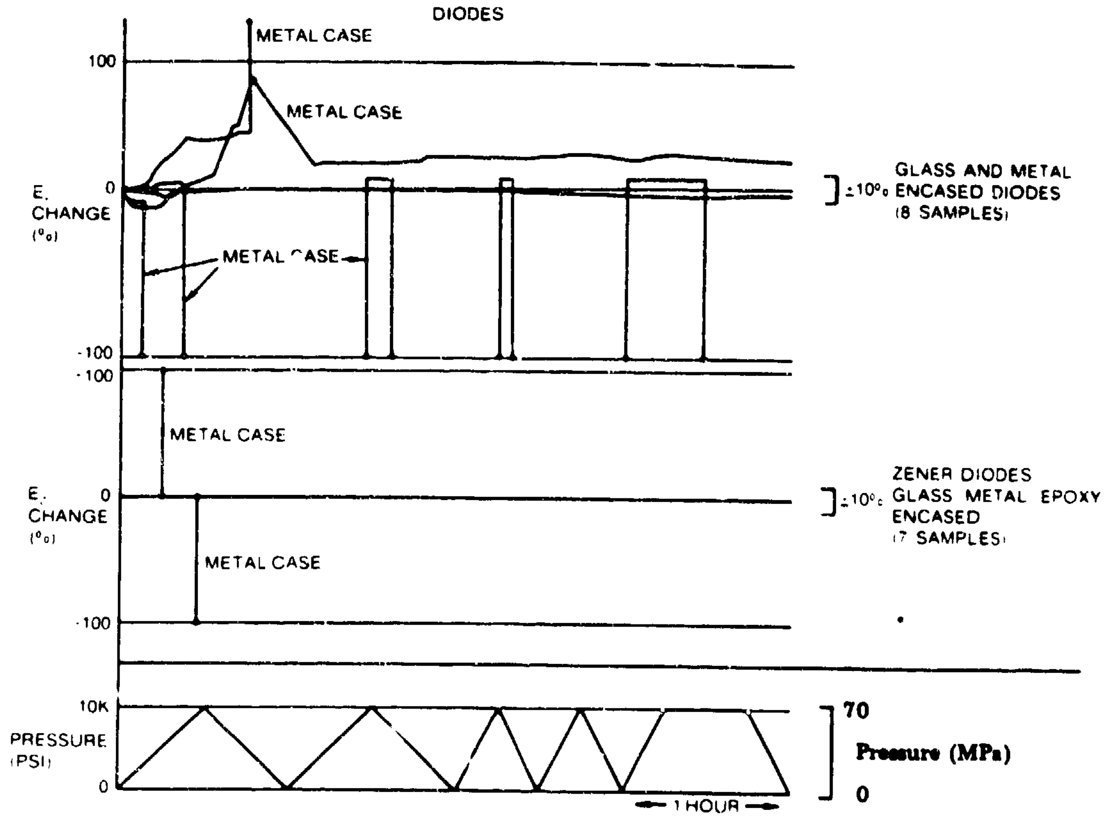

Fig. 5 — Results of diode tests

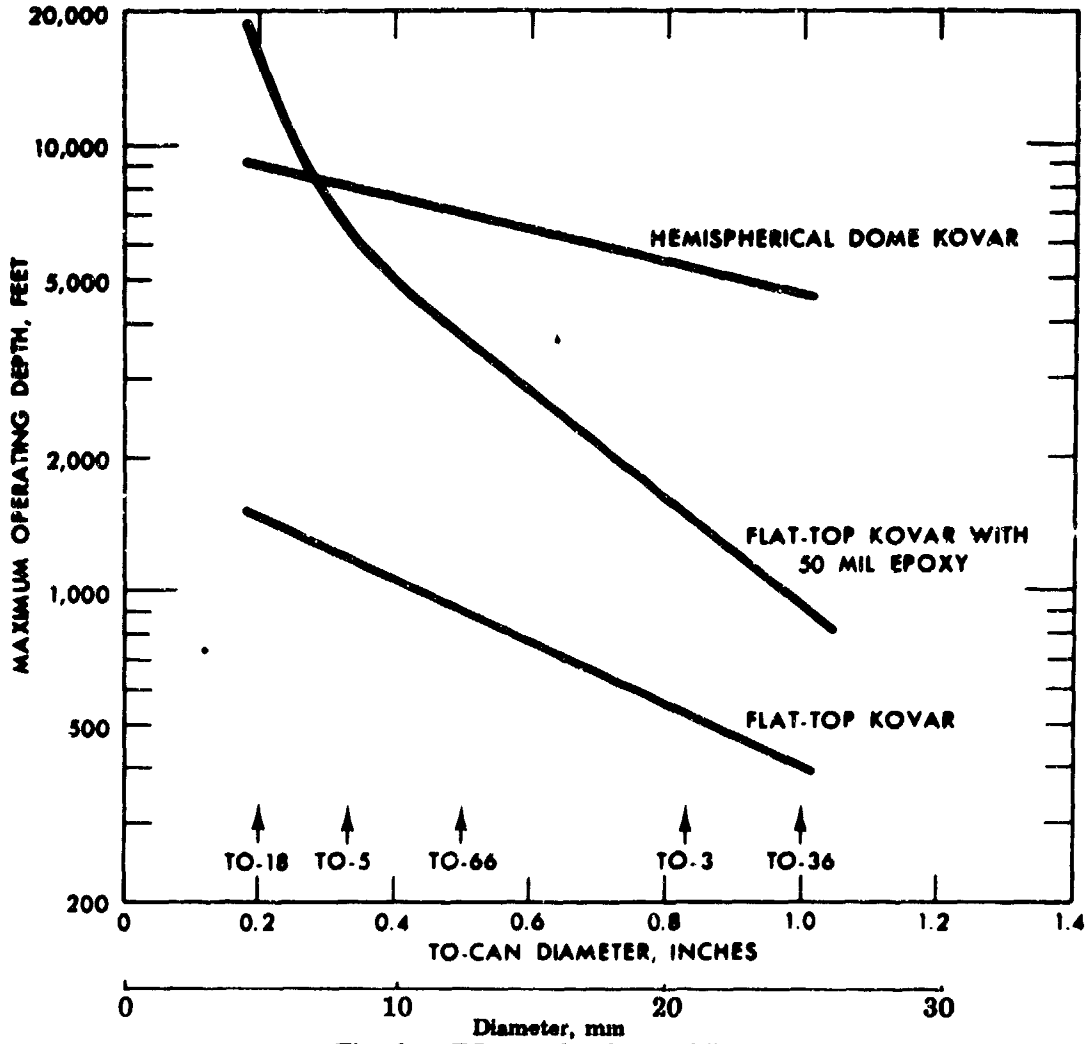

Fig. 6 — TO can depth capability

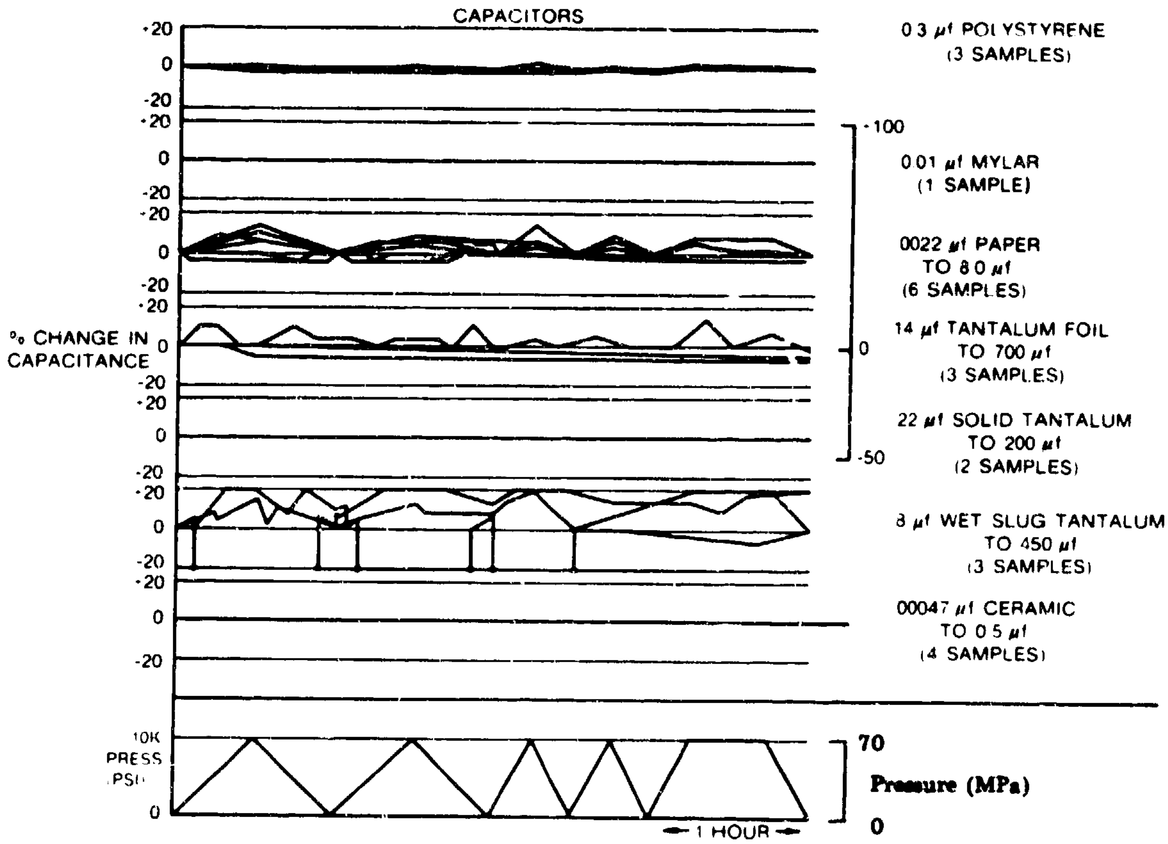

Fig. 7 — Results of capacitor tests

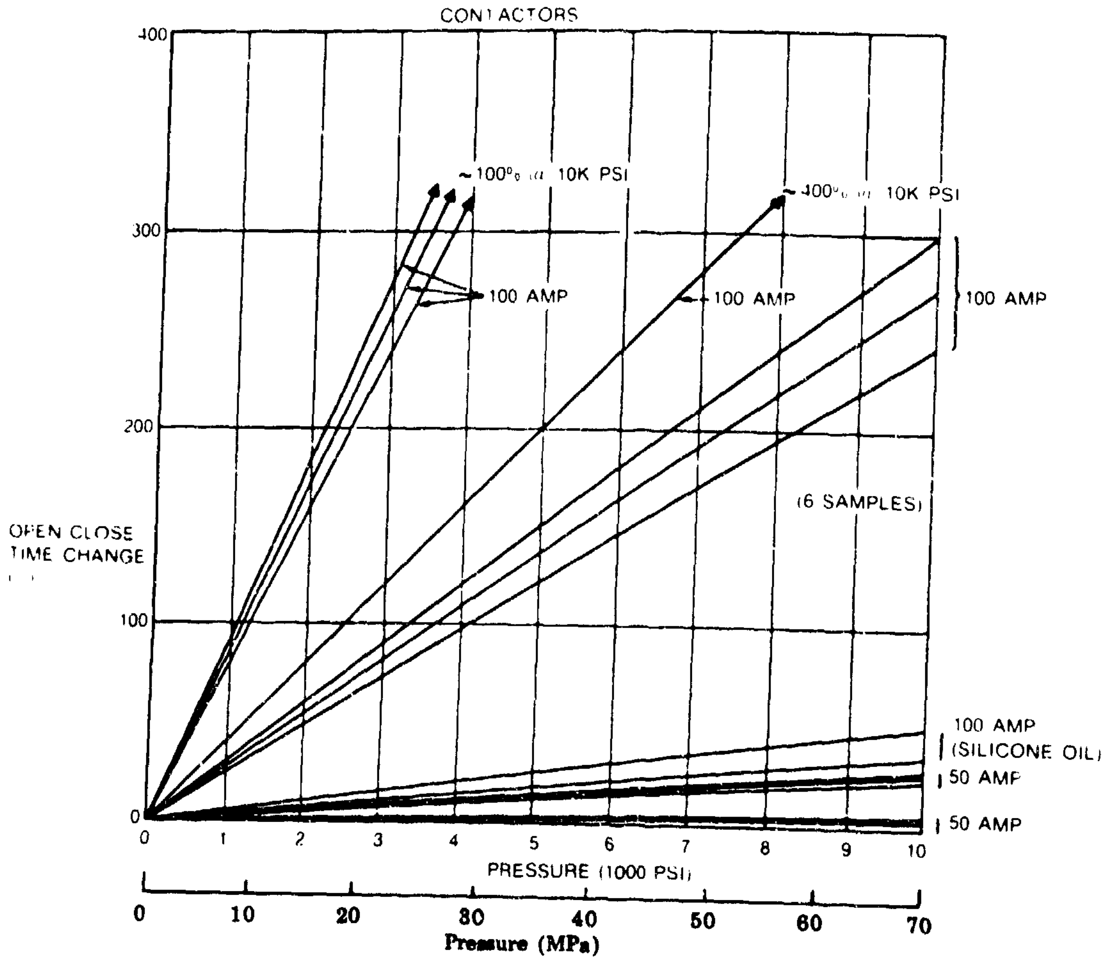

Fig. 8 — Results of contactor tests

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Credit for the figures and table listed below, belongs to the authors of the cited references.

1. Figure 1 - reference 1
2. Figure 2 - reference 3
3. Figure 3 to 7 - reference 4
4. Figure 6 - reference 2
5. Table 3 - reference 5

APPENDIX

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