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PHILCO-FORD DOCUMENT NO.
TR-DA2175

AD 868279

COLD WELDING RESEARCH FINAL REPORT

BY

D. B. SHELDON

PHILCO-FORD CORPORATION
SPACE AND RE-ENTRY SYSTEMS DIVISION

JANUARY 1970

PREPARED FOR:

AIR FORCE ROCKET PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
EDWARDS AIR FORCE BASE, CALIFORNIA

CONTRACT F04611-68-C-0077

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FORWARD

This report (SRS TR-DA2175) describes the activity accomplished on the cold welding research program (Contract F04611-68-C-077) during the period from May 1968 to September 1969. The project was conducted by the Philco-Ford Corporation. The Project Officers were Mr. H. J. Smith and Mr. D. T. Clift. This report was prepared by Philco-Ford, Space and Re-entry Systems Division, Palo Alto, California.

This report has been reviewed and is approved.

D. T. Clift

ABSTRACT

During Phase I of this research, a small experimental contactor was used to obtain electrical contact resistance data in air and and in vacuum. These data show that an electronically-pumped vacuum system can effectively simulate the vacuum of actual space: the contact resistance data obtained in vacuum was in agreement with contact resistance data obtained from two small earth satellites. During Phase II, four solenoid valves were tested in the same electronically-pumped vacuum system used during Phase I; the test results were compared with adhesion data generated by identical valves during space flight tests. The contacting surfaces of the valves and the experimental contactor experienced only normal stresses. In order to determine the margin before failure existing in each of the valves during the space flight tests, incrementally increasing stresses were applied to the valves' sealing surfaces. The results of Phases I and II show that cold welding in space occurs near or above the yield point of one of the surfaces. A space-flight qualification test was written.

ACKNOWLEDGMENTS

Philco-Ford wishes to acknowledge the assistance and contributions of Mr. J. H. Smith and Mr. D. T. Clift, Air Force Rocket Propulsion Laboratory Project Engineers, who provided a number of helpful suggestions on this phase of the Cold Welding Research effort and of Mr. Carl Strombom, Philco-Ford SRS, who performed the laboratory operations.

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SECTION I

SUMMARY

Under certain conditions two metallic surfaces experience adhesion at temperatures substantially below the melting point of either metal; in this case the adhesion is referred to as cold welding. It has been recognized for several years that cold welding is a potential hazard in space. Phase I of this research, discussed in Ref. 9, demonstrated that for the purpose of studying cold welding between engineering surfaces, the ion-pump vacuum system described in Section IV of this report satisfactorily simulated the space environment. The term "engineering surface" is used to designate a surface which has been exposed to ambient atmosphere, but which has not otherwise been contaminated.

During Phase I, a small experimental contactor was used to obtain contact resistance data in air and in vacuum; these data were used to determine the suitability of the ion-pumped vacuum system for simulating the vacuum of actual space. During Phase II, four solenoid valves were tested in the same ion-pumped system used during Phase I; the test results were compared with adhesion data generated by identical valves during space flight tests. The purpose of Phase II was to determine if cold welding between engineering surfaces can result from simultaneous exposure to the space environment and relatively high normal stress. Only normal impact of opposing surfaces was considered in both Phases I and II, slipping was not considered. The experimental results of Phase II show that for four different permutations of stainless steel and tungsten carbide surfaces, cold welding, if it occurs at all, occurs at stresses near or above the yield point of one of the surfaces. Other data obtained during Phase I suggest that this result also applies to copper and aluminum.

SECTION II

INTRODUCTION

This report is part of a continuing cold welding research program which was initiated by the Air Force Rocket Propulsion Laboratory in 1965. A substantial portion of this program is discussed in other reports (Refs. 1-8). Previous work has included instrumentation design and fabrication, space flight tests, and ground tests in simulated space environments.

The purpose of the space flight tests was to determine the vulnerability of metallic surfaces to cold welding in space. Two identical satellites, ERS-15 and ERS-16, were built by TRW to carry and monitor instrumentation designed to study cold welding. ERS-15 was launched on 19 August 1966, and ERS-16 was launched on 9 June 1966; both space experiments were successful. The experimental devices designed to study cold welding consisted of five solenoid actuator units positioned at the five available apexes of each octahedral satellite. An ejection tube connecting the satellite to its launch canister was attached to each satellite's remaining apex. Of the five actuator units, four were derived from solenoid valves in which different materials combinations were incorporated as the poppet-seat contacts; the fifth actuator unit consisted of eight pairs of 1/8" diameter contacting spheres. The eight contacts were closed simultaneously by a solenoid unit derived from the valves' design; the entire device is referred to as a "supplemental contactor". A photograph and schematic diagram of the type of valve tested are shown in Figs. 1, 2 and 3; a schematic diagram of the supplemental contactor is shown in Fig. 4. The materials employed by each valve are shown in Table 1; the materials employed by the supplemental contactor are shown in Table 2.

The supplemental contactor was designed to provide precise data describing any adhesive force which developed between the contacts during space flight and to relate actual space to various types of space simulation techniques. Each contact consisted of a stationary ball and an opposing ball which impacted on the stationary ball. The contacts were normally open. Adhesive force, if any, was observed by using current integration to measure the time each contact remained closed. The contacting balls were 0.125 $\pm$ 0.001" in diameter and made of the following metals: stainless steel, tungsten carbide, aluminum, and copper (see Fig. 4 and Table 2).

The "supplemental contractor experiment" (SCE) was more of a scientific, rather than engineering, experiment since it did not involve specific hardware application. The valves were an actual engineering configuration, testing the interfacial contact characteristics of stainless steels and tungsten carbide while the contractor experiment included aluminum and copper in addition to stainless steel and tungsten carbide. Another comparison should be considered: only four material couples were flown in each space flight through the use of the valves. On the contractor experiment, eight material couples were investigated on each flight. The SCE proved to be an extremely sensitive integrating device for measuring contaminant build-up on a surface due to oxidation, dust, oil-vapor or other sources.

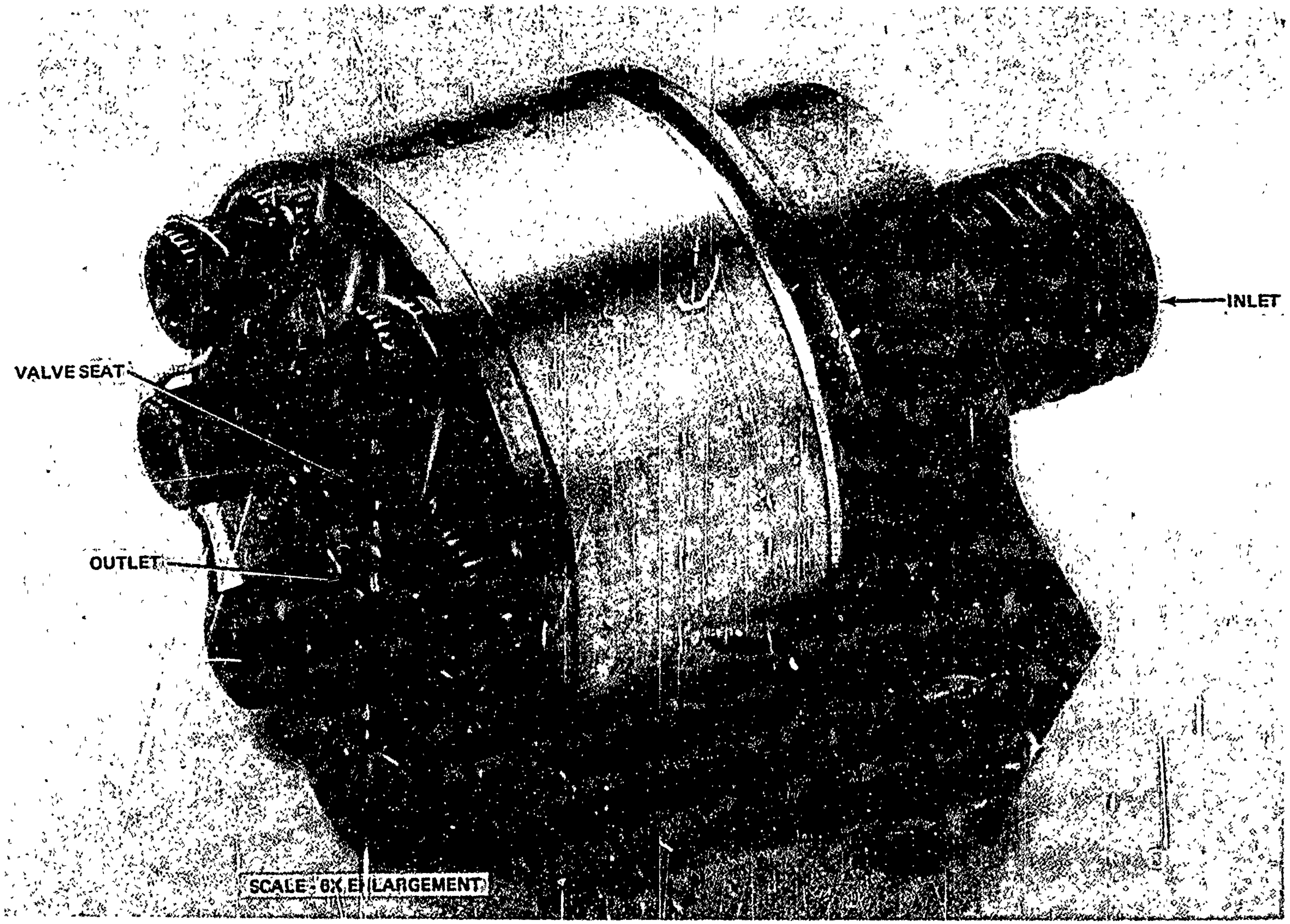

Figure 1

Solenoid Valve

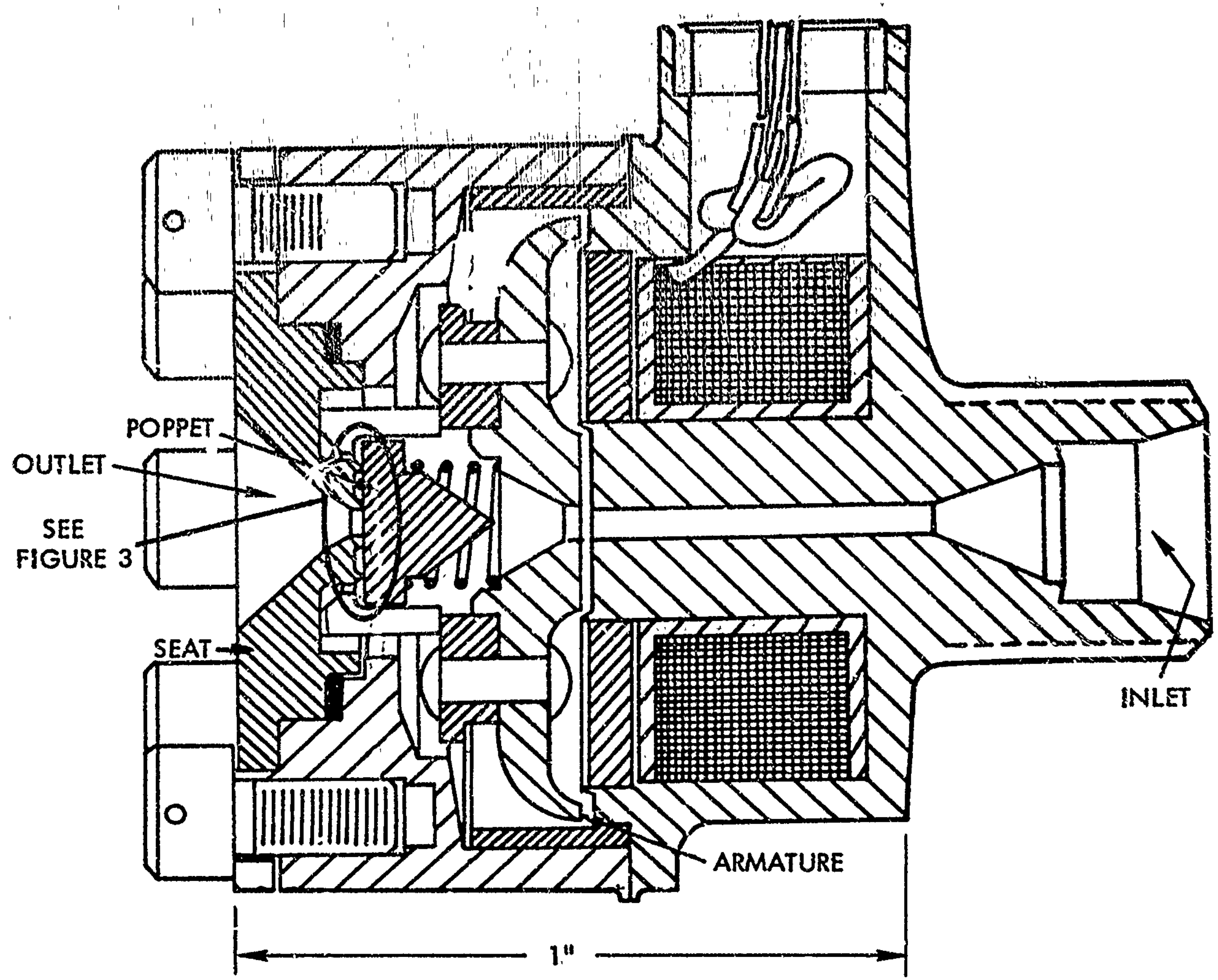

Figure 2
Cross-Section of Solenoid Valve

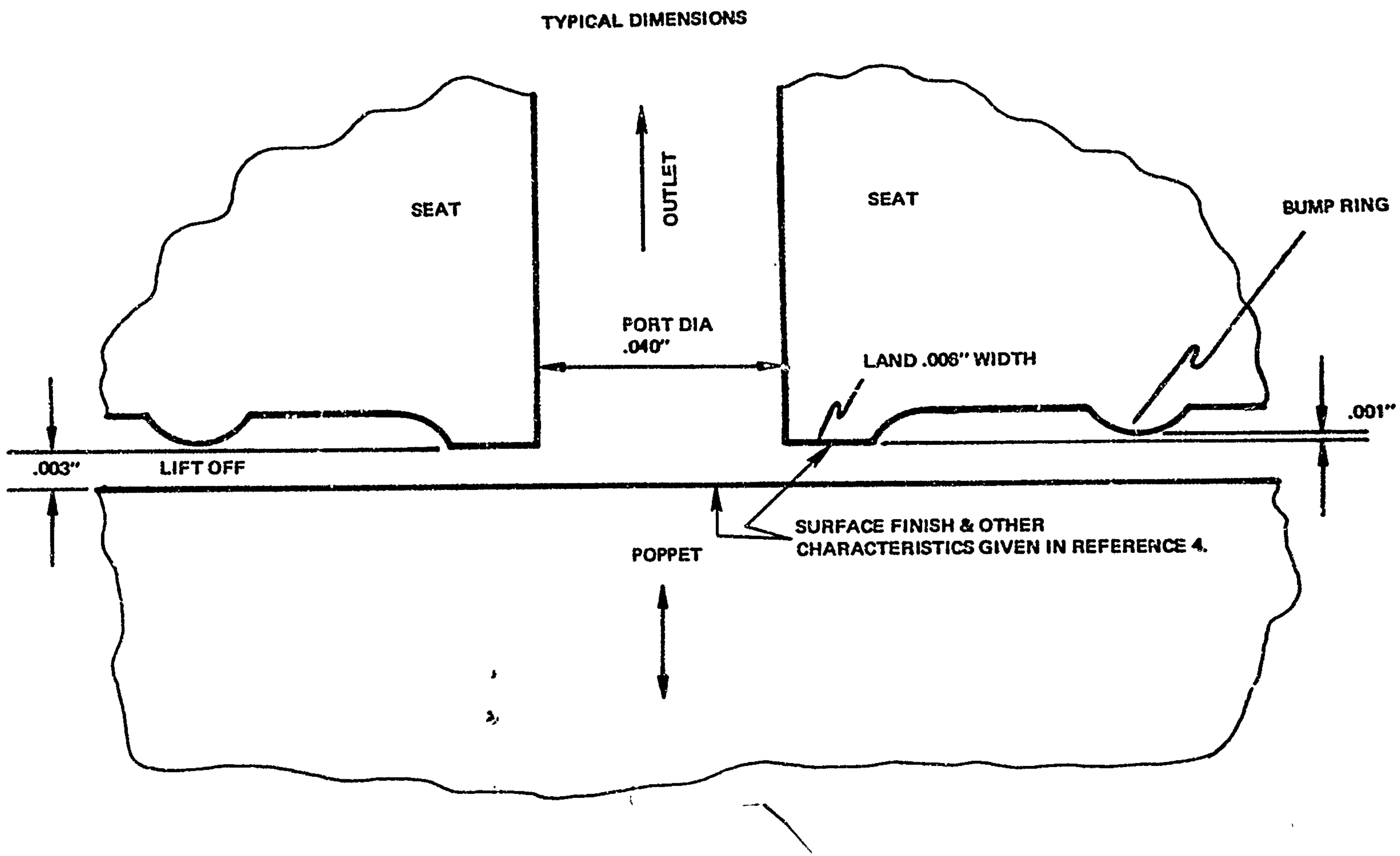

Figure 3
Solenoid Valve Seat Detail

TABLE 1

SOLENOID VALVE MATERIALS

VALVE NO.	MATERIALS	PARKER-HANNIFIN CORP.	SERIAL NO.
V_1	440C x 17-4 PH	5650004	B520003
V_2	17-4 PH x WC	5650005	B520103
V_3	440C x WC	5650006	B52023
V_4	WC x WC	5650007	B520303

MATERIAL IDENTIFICATION

440C - Stainless Steel
17-4 PH - Stainless Steel
WC - Tungsten Carbide

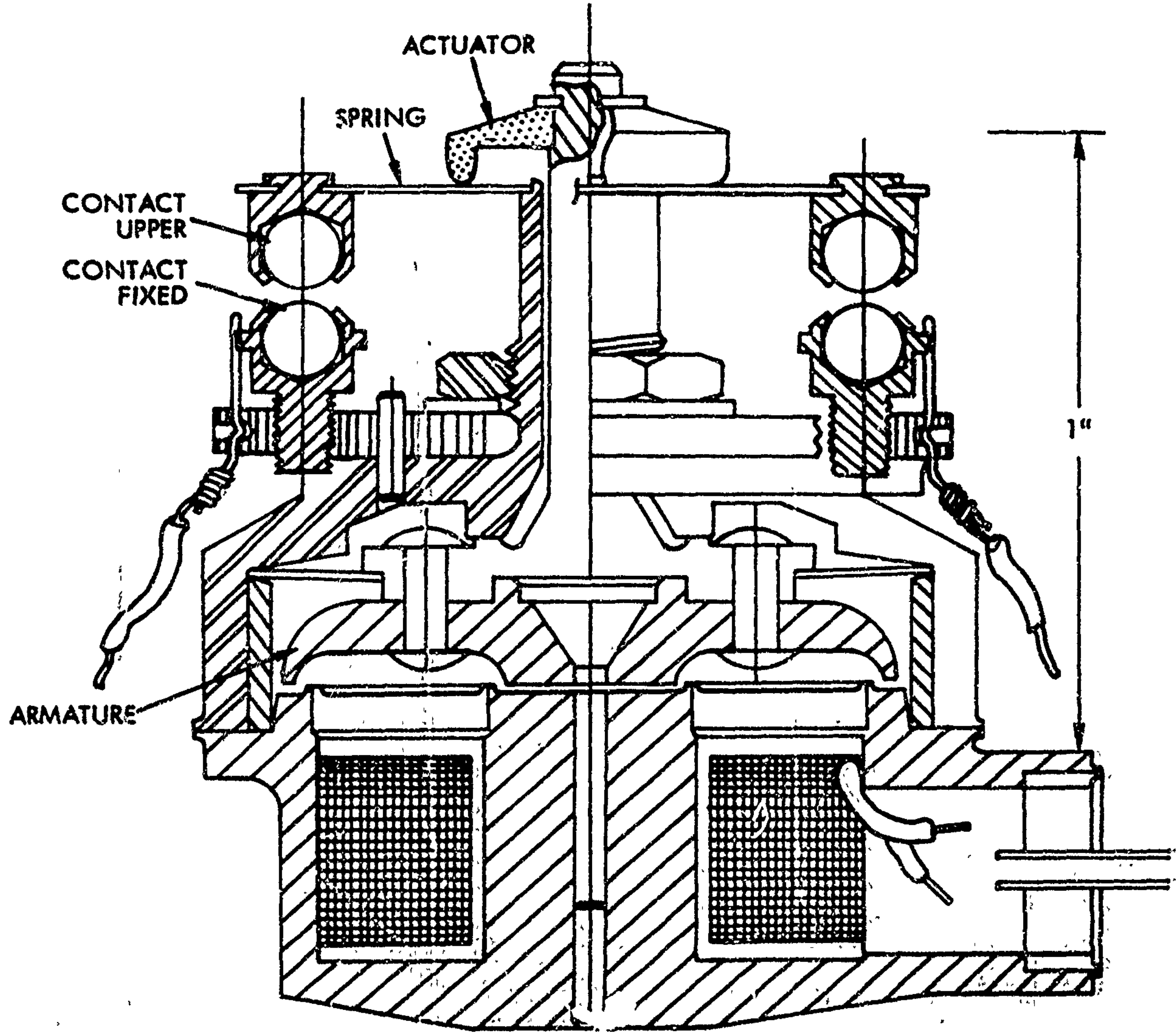

Figure 4

Cross-Section of Supplemental Contactor

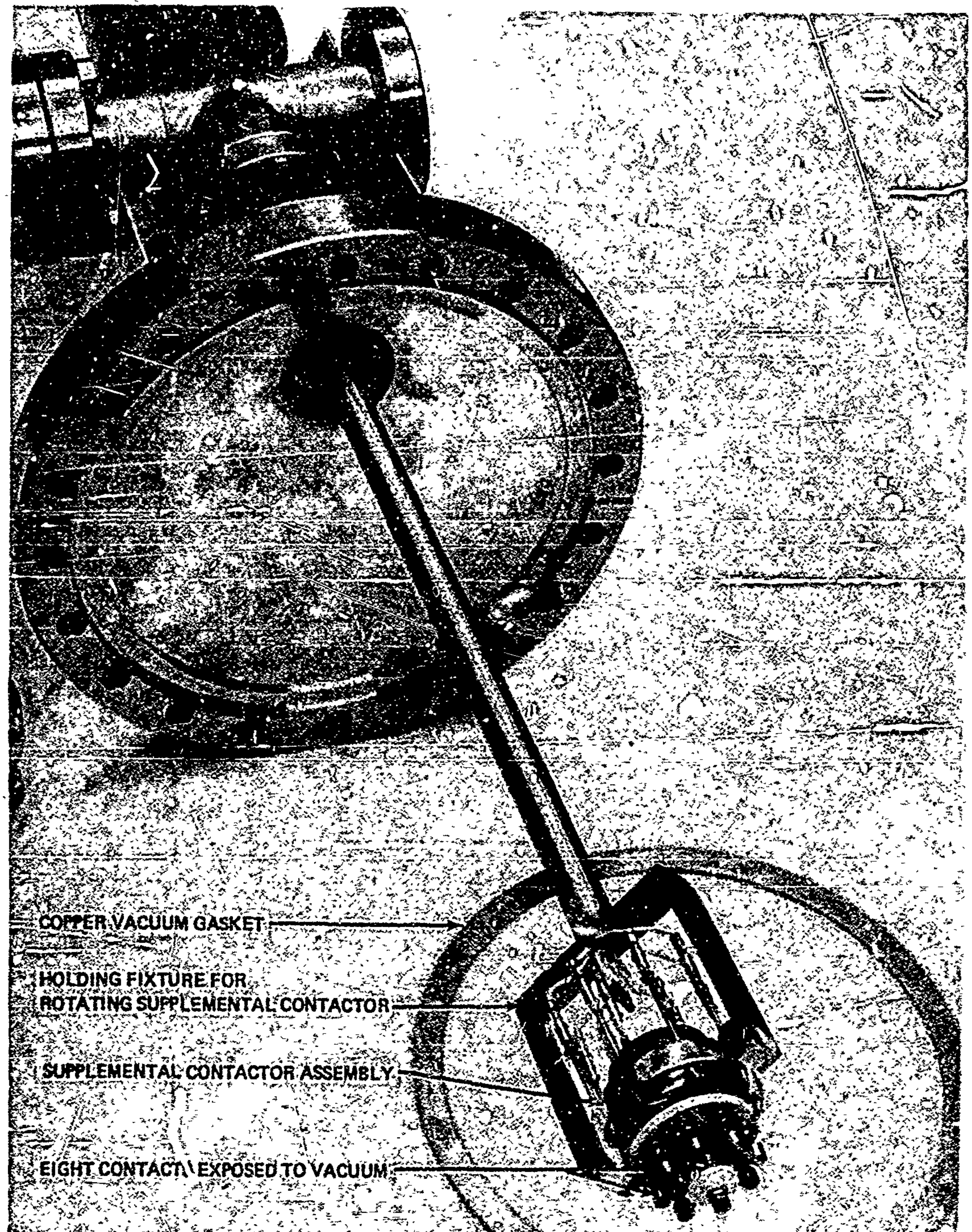

Figure 5
Supplemental Contactor

TABLE 2

TEST SUPPLEMENTAL CONTACTOR BALL ARRANGEMENT
Supplemental Contactor S/N B520406 (normally open)

Contact S_1	-	17-4 PH on 17-4 PH
Contact S_2	-	WC on WC
Contact S_3	-	2014-0 on 2014-0
Contact S_4	-	OFHC on OFHC
Contact S_5	-	440C on 2014-0
Contact S_6	-	440C on OFHC
Contact S_7	-	17-4 PH on 2014-0
Contact S_8	-	17-4 PH on OFHC

MATERIAL IDENTIFICATION

440C	-	Stainless Steel
17-4PH	-	Stainless Steel
WC	-	Tungsten Carbide
2014-0	-	Aluminum
OFHC	-	Oxygen Free High Conductivity Copper

For both of the space experiments, the SCE was cleaned and calibrated during pre-launch preparations. In both cases, the contractor experiment was exposed to sea level atmospheric conditions for more than a week prior to launch; this surface oxidation/contamination was evident during initial data acquisition of both launches. On both flights, the majority of the contracts "cleaned-up" after a brief exposure in space.

The most significant aspect of the current program is that, in the electronically pumped vacuum, the contacts "cleaned up" much the same as they did in space. Therefore, the SCE provided an extremely beneficial measurement of the adequacy of space-simulators.

The four solenoid valves on each satellite were intended to provide data describing the adhesive force which developed between surfaces employed in a typical engineering configuration. Permutations of stainless steel and tungsten carbide were incorporated as the poppet-seat contacts of each of the four solenoid valves (see Figs. 1, 2 and 3 and Table 2). The valves were normally closed. Prior to the flight experiments it was expected that most soft metals would experience some cold welding in space; as a result, two very hard metals were selected to form the poppet-seat interface. Ground tests showed that softer metals are more likely to experience cold welding than hard metals (Ref. 3). Therefore, hard metals were regarded as candidate materials for the suppression of adhesion in space applications requiring metallic contact.

Unexpected results were obtained from both the two satellites and instrumentation located inside environmental chambers employing oil diffusion pumps. No definite adhesion was observed to occur either in space or the simulation chambers, and contact resistance data obtained in space by the supplemental contactor was significantly different from corresponding data obtained using space simulation chambers. The flight data indicated that the contacts' resistances decreased as a result of exposure to the space environment. Pre-flight data obtained from space simulators employing oil diffusion pumps did not indicate a decrease in contact resistance; in fact, contact resistance data obtained using these space simulation chambers showed a greater increase than that observed in ambient air.

In view of the questionable results obtained using oil diffusion pumps, Phase I of the present research was initiated; and it was decided to evaluate an ion pump's capability of simulating surface conditions in space. This evaluation was performed using the same supplemental contactor which was utilized during the oil diffusion pump tests; complete details are given in Cold Welding Research Phase I Report, AFRPL-TR-68-211. The contact resistance of each of the eight contacts of the supplemental contactor was substantially reduced after the pressure in the vacuum system described in Section IV of this report was lowered from atmospheric pressure to approximately 10^{-8} torr.

In addition to high vacuum, ultraviolet radiation was used to simulate the space environment. Ultraviolet radiation at approximately one earth sun intensity did not effect a further reduction of the contacts' resistances. Extended duration tests, up to 70 hours, were performed using the supplemental contactor. The purpose of these tests was to determine if cold welding of any of the eight contacts would occur. An analytical study was also performed to determine the approximate values of the contacts' impact stresses; it was assumed that the response of the contacts was entirely elastic. This information provided a basis for evaluating the extended duration test data. The velocity of impact was determined from high-speed motion pictures.

The copper-copper contact was observed to cold weld in vacuum; momentary adhesion of 17-4 PH stainless steel and copper contact was also observed. The results of the analytical study showed that the impact stresses of all contacts were high enough to deform the substrate which supports the oxide layer. The analysis also showed that the copper-copper contact experienced the highest ratio of impact stress to yield stress, and that the 17-4 PH stainless steel on copper contact experienced the next highest ratio of impact stress to yield stress. This suggests that the ratio of impact stress to yield stress of contacting engineering surfaces in vacuum or space may be an important dinensionless parameter. The above results were obtained during Phase I.

Phase II consisted of testing four solenoid valves whose configuration is typical of the design used in space vehicles. Testing was performed in the same chamber used during Phase I. The poppet-seat interface of each solenoid valve was subjected to increasingly severe applications of increased stress. This was done in vacuum ($p \sim 10^{-8}$ torr). The purpose of applying the increased seating stresses was to determine if the valve's poppet or seat deform prior to the occurrence of cold welding. Deformation of a valve's sealing surfaces was indicated by an increased gas leakage rate. The valves' leakage rates were measured when the valves were outside the vacuum system. Cold welding was indicated by sticking at the poppet-seat interface immediately after the application and removal of increased seating stress. After failure, whetherby cold welding or increased leakage, each valve's poppet and seat were examined with a microscope and an interference profilometer. These inspections served to determine the extent of deformation of the sealing surfaces.

SECTION III

THE RESULTS OF PHASE I

III.1 SUMMARY OF PHASE I

Several tests were performed using the supplemental contactor described in AFRPL Report No. AFRPL-TR-67-1 (AD 380181). These tests included measuring the change in contact resistance of each of the eight pairs of contacts mounted on the supplemental contactor as the supplemental contactor was exposed to a series of different environments. These different environments were air, vacuum ($p = 10^{-8}$ torr), and vacuum in combination with ultraviolet radiation. The test chamber was evacuated by means of ion, sublimation and cryogenic pumps. Slow motion movies of the supplemental contactor's actuation stroke were made; the camera speed was usually faster than 2300 frames per second. The velocities of impact of the contacts were obtained from these movies. Approximate values for the stresses and areas at the contacts' interfaces were obtained by using the theory of elastic deformation.

The experimental results showed that an ion-pumped vacuum system can be successfully employed to remove contaminants which would otherwise lower the probability of successful electrical contact. The results of the analytical study showed that the impact forces of the contacts were high enough to deform the substrate which supports the surface oxide layer.

One case of cold welding was observed in vacuum. The contact involved in the cold welding observation was copper on copper. Adhesion of the stainless steel and copper contact was also observed. The analysis showed that the copper on copper couple experienced the highest ratio of impact stress to yield stress. This suggests that the ratio of impact stress to yield stress of contacting engineering surfaces in vacuum or space may be an important dimensionless parameter. An "engineering surface" is considered to be a surface which has been exposed to the atmosphere, but has not been otherwise contaminated.

The behavior of the contacts in air was somewhat erratic with the general trend being that the majority of the contacts became more contaminated. The data usually followed a stochastic pattern. Successful electrical contact was accomplished with nearly 100 percent reliability when the contactor was in vacuum. Some changes in the contact resistances occurred in vacuum after several hours of testing. Exposing the contactor to ultraviolet radiation did not affect the data. When the contactor was tested in air at temperatures above approximately 100°F, there was an apparent increase in contact resistances. Identical results were obtained in vacuum. This observed increase was probably due, at least to some extent, to the increasing resistance of the contactor's solenoid coil as the temperature of the coil rose along with the ambient temperature.

III.2 THE CONTACT RESISTANCE MEASUREMENTS

Phase I consisted of testing eight metallic contacts which were closed by a common solenoid. The eight contacts are mounted on a platform attached to a magnetic solenoid. The entire unit, consisting of the contacts, the platform, and the solenoid was referred to as the "supplemental contactor" or simply "the contactor". A detailed description of the design and operation of the supplemental contactor is given in Ref. 4. Each of the metallic contacts consisted of a pair of 1/8" diameter metal balls. The data obtained during Phase I was used to compare the performance of ion and oil diffusion pump vacuum systems. A decrease in electrical contact resistance as the ambient pressure was lowered from one atmosphere to below 10^{-6} torr was regarded as a favorable index of performance. Data describing the performance of an ion-pump vacuum system was generated by the present project; data obtained using a diffusion-pump vacuum system is available in Ref. 4. The data obtained using a diffusion-pump vacuum system indicates that this type of system did not effectively reduce contact resistance as the pressure was reduced several decades below 1 atmosphere. The vacuum system which was utilized during the present work was effective in substantially reducing contact resistance. The contact resistances of the supplemental contactor were first studied in air at temperatures near 32°F, 70°F, and 120°F. Later the contactor's contact resistances were studied near room temperature in vacuum ($p = 10^{-8}$ torr) and in a combined vacuum and ultraviolet radiation environment. The manifestation of cold welding (or any metal-to-metal adhesion effect), if it occurred between two contacts, was discovered from visual examination and interpretation of this data.

The stress/strain conditions of the contacts over their area of impact were studied. The stress/strain conditions of each contact pair at its operational impact velocity was examined.

III.2.1 Experimental Apparatus

The experimental apparatus consisted primarily of a supplemental contactor, miscellaneous supporting equipment required to monitor and control the supplemental contactor, an ion-pump vacuum system, an ultraviolet lamp, and photographic equipment. Each of these items will be described individually.

III.2.1.1 Supplemental Contactor

The following three supplemental contactors were available for testing:

No. S/N B520404
No. S/N B520405
No. S/N B520406

Only one supplemental contactor, Serial Number S/N B520406, was tested during Phase I. This contactor previously received 72,000 actuations in a diffusion-pump vacuum system at TRW. A photograph of the supplemental contactor in its holding fixture is shown in Fig. 5. Each contact consisted of a stationary ball and an opposing ball which impacts on the stationary ball. The contacting balls were 0.125 ± 0.001 inches in diameter and are made of the following metals: stainless steel, tungsten carbide, aluminum, and copper. The exact arrangement of the balls is shown in Table 2. The contacts were normally open; each contact was closed simultaneously by a single solenoid. Mechanical motion was transmitted from the solenoid plunger to each of the movable balls by a flat copper-beryllium spring. In Fig. 5 this flat spring can be seen extending from under a white boron nitride disk to the brass sockets holding the movable balls. An electronics package built at TRW was used to regulate the frequency of actuation; three actuation frequencies were available. The electronics package was also used to generate an output voltage signal which was an indication of the amount of charge passing through a contact during each actuation cycle. The voltage output of the electronics package was monitored by a recorder. The recorder readings were normalized with respect to a short circuit condition achieved by manually depressing a contact.

Sample contactor data is shown in Figs. 6 and 7. This data was taken directly from a pin recorder (see Paragraph III.2.1.2. The data comes off the recorder from right to left. In Fig. 6 none of the contacts is making successful electrical contact.

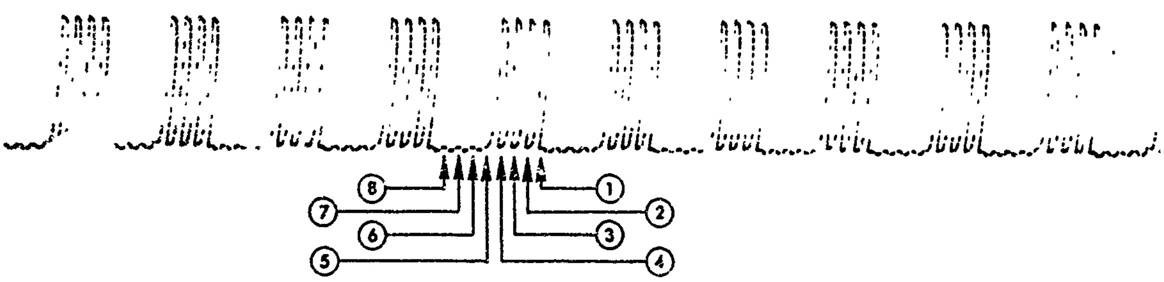

Figure 6

Supplemental Contactor Data: No Contacts Making Successful Electrical Contact

In Fig. 7 all of the contacts are making successful electrical contact; the data were obtained from one of the vacuum tests. The numbers on Figs. 6 and 7 indicate the contact numbers corresponding to the position of the voltage pulses. The groups of four large pulses are not associated with the contactor data; however, they do serve to identify the voltage pulses. For example, the pulse associated with contact No. 1 immediately precedes each group of four large pulses. Fig. 8 shows the result of manually short circuiting contact No. 7. The appearance of such a pulse during an actual test is indicative of cold welding. The appearance of a pulse whose height is only slightly greater than the pulses shown in Fig. 7 is indicative of temporary adhesion.

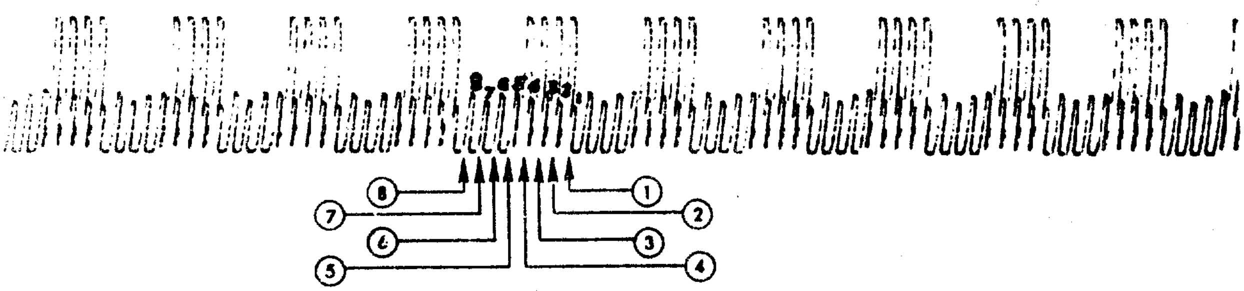

Figure 7

Supplemental Contactor Data: All Contacts Making Successful Electrical Contact

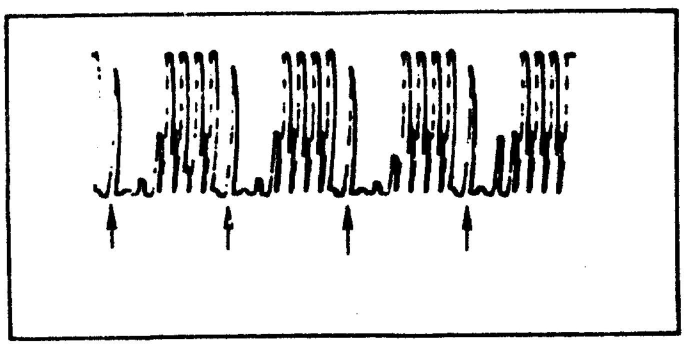

Figure 8

Supplemental Contactor Data: Manual Short-Circuiting

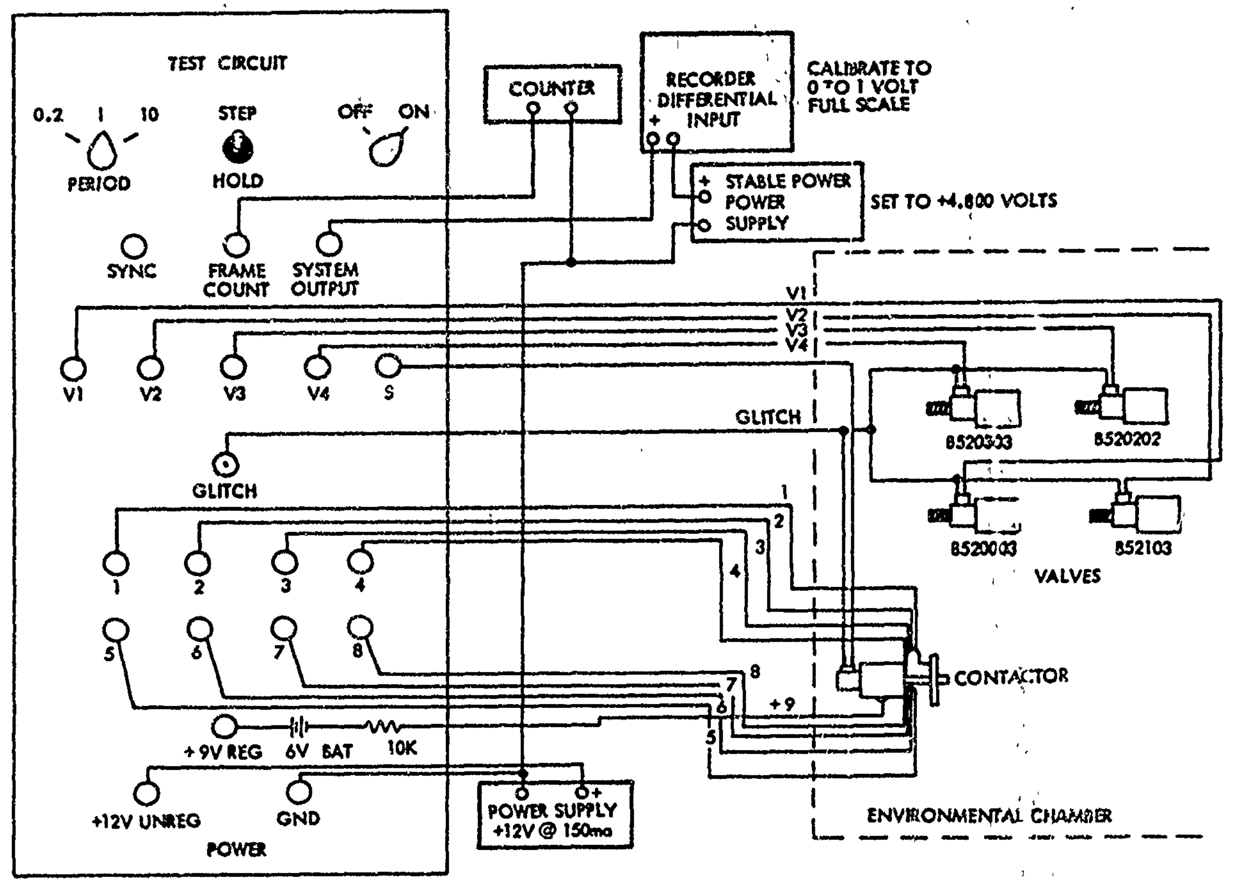

Figure 9

Block Diagram of Cold Welding Experiment

III.2.1.2 Supporting Equipment

The circuit diagram describing how the supplemental contactor was monitored and controlled is shown in Fig. 9. The terminals V1 through V4 were not connected to any valves during Phase I. The test circuit was built by TRW. The counter was a Computer Measurements Company frequency-period counter (Model No. 201B); the recorder was a Beckman RS Dynograph recorder; the stable power supply was a Hewlett Packard power supply (Model No. 721); and the 12-volt power supply was fabricated in the laboratory. A Missimers combination oven and refrigerator (Model FT1.5-120x350) was used to control the temperature of the supplemental contactor during the tests in air at 32°F, 80°F, 120°F, and 150°F.

III.2.1.3 Vacuum System and Related Equipment

The supplemental contactor was tested in a vacuum system at a pressure of approximately 10^{-8} torr. An AH-6 ultraviolet lamp was used to simulate solar U.V. radiation during some of these tests. This section describes the vacuum system, the contactor holding fixture, and the AH-6 lamp.

III.2.1.3.1 Vacuum System

The vacuum system (Fig. 10) consisted primarily of a Varian VI-260 vacuum system. An 18" diameter stainless steel bell jar was sealed to the original VI-260 system by means of a copper gasket. The pumps used in the VI-260 vacuum system are as follows:

1. One 500 l/s VacIon pump and control unit (Varian Model 921-0038)

2. One 8000 l/s titanium sublimation pump (Varian Model 922-0032)

3. Three VacSorb 78°K cyrogenically activated roughing pumps

All pressure measurements were made using a nude ion gauge (Varian No. 971-5008). With the exception of one completely dry rubber O-ring in the ion pump isolation valve, the vacuum system was all metal. The single remaining O-ring could have been removed but this would have introduced additional contamination. Without use of the ion pump isolation valve, it would not have been possible to prevent air at a pressure of one atmosphere from entering the ion pump. The contaminates contained in this air would have been re-emitted into the test chamber during a test. Initial favorable test data obviated removal of the O-ring in the isolation valve.

III.2.1.3.2 Supplemental Contactor Holding Fixture

The supplemental contactor holding fixture is shown in Figs. 5 and 11. The necessary contactor electrical leads and two copper-constantan thermocouples were introduced into the vacuum system through two 2-3/4" O.D. Conflat flanges. The contactor supporting tube was made of 304 stainless steel and

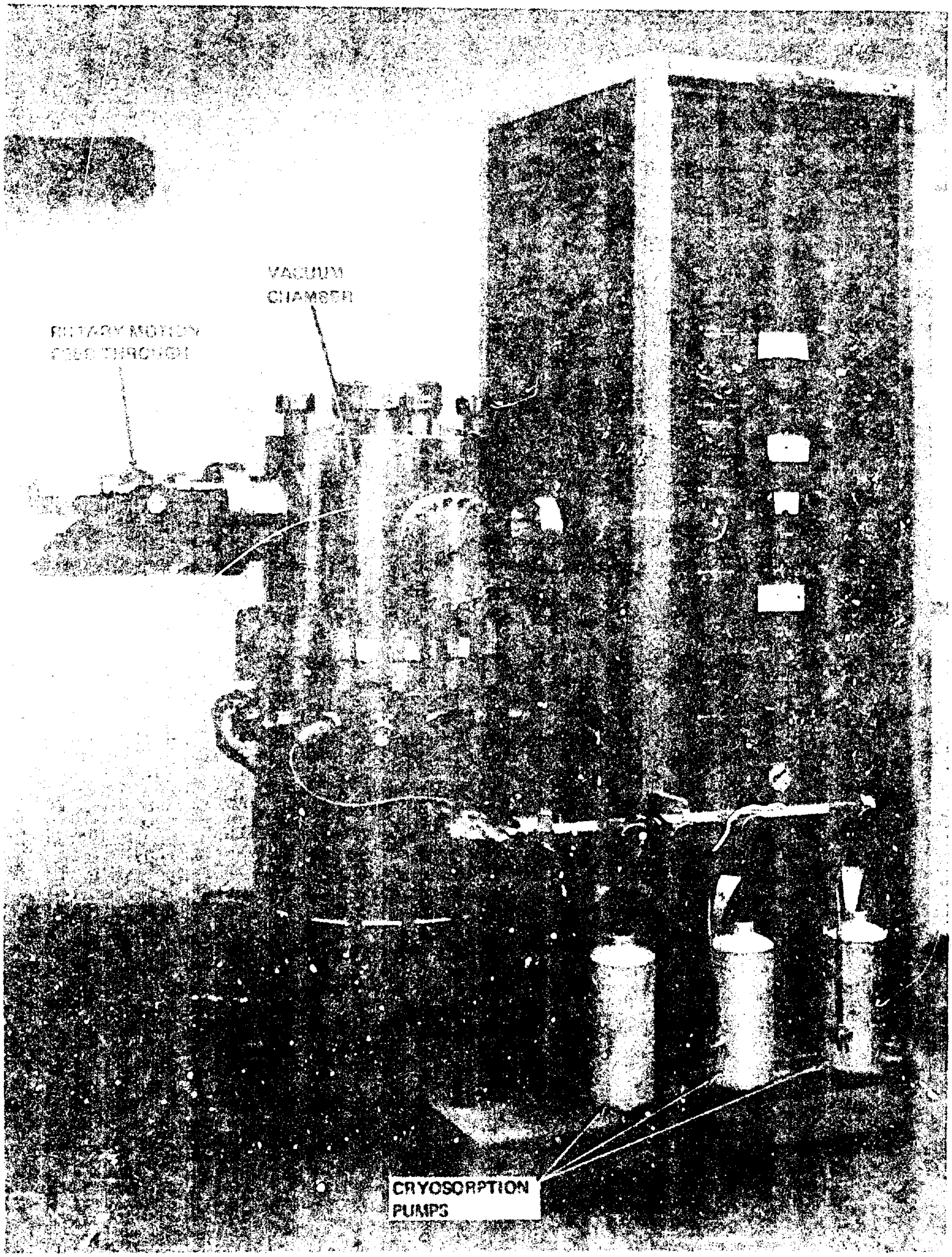

Figure 10

Vacuum System

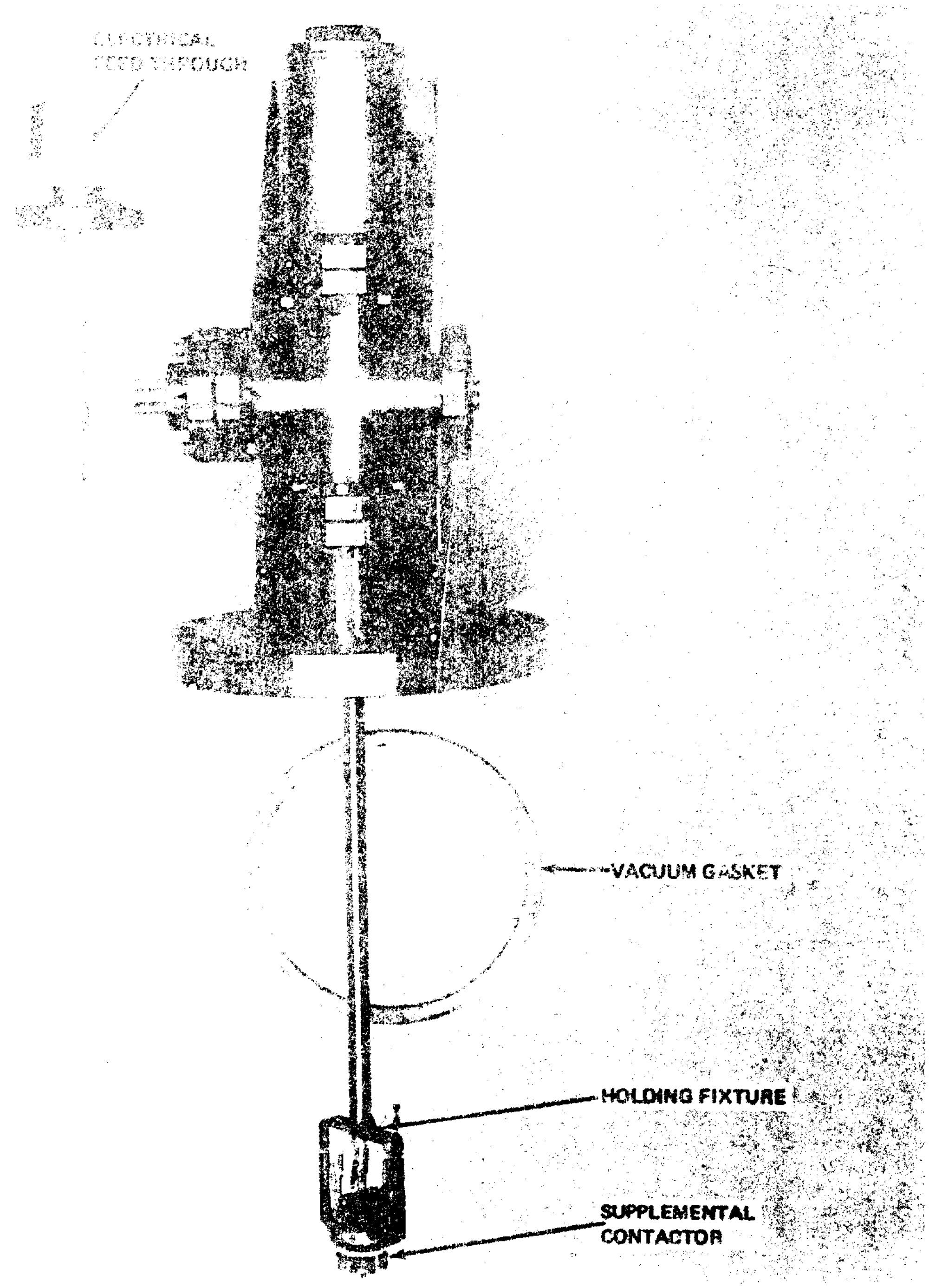

Figure 11

Supplemental Contactor Holding Fixture

the insulation of the contactor lead wires was made of fiberglass. (The insulation shown in Figs. 5 and 11 is Teflon.) The large flange is a 8" O.D. Varian Conflat flange; the flange's copper sealing gasket is also shown in the figures. The rotary motion feedthrough device, Varian Model No. 954-5026, is shown at the top of Fig. 11. This unit does not penetrate the wall of the vacuum system; motion was transmitted into the interior of the system by means of magnets. The rotary motion feedthrough was driven by a 1/12 RPH Haydon timing motor (Model No. F 450). This motor was activated only during the tests involving the use of ultraviolet radiation; in this case only, it was necessary to rotate the main body of the contactor to insure uniform irradiation of the individual contacts.

III.2.1.3.3 Ultraviolet Simulation Equipment

The ultraviolet simulation equipment is shown in Fig. 13. The upright object is a Kovar and Quartz finger that extends sideways into the vacuum system. The AH-6 mercury lamp, which remains external to the vacuum system, is shown in the foreground. This lamp is water cooled. Fig. 12 shows a comparison of Johnson's solar radiation curve and a typical spectrum of the AH-6. As seen from the contactor, the water jacketed AH-6 lamp without filtering provides a source intensity equivalent to about 3 earth suns. During the experimental tests the output of the AH-6 lamp was attenuated by a neutral density filter to an intensity of about three quarters of an earth sun. It was necesary to use this filter in order to avoid overheating the contactor.

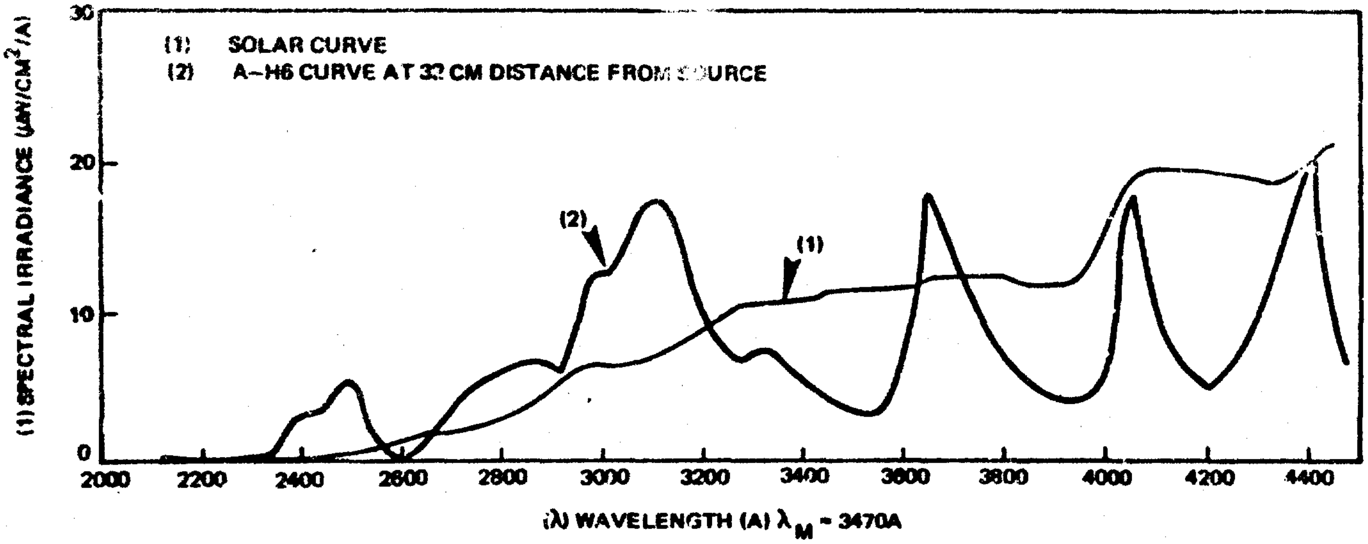

Figure 12

Spectral Energy Districution of A-H6 Lamp and Sunlight

(From GE Bulletin F-N412, 402M4-57)

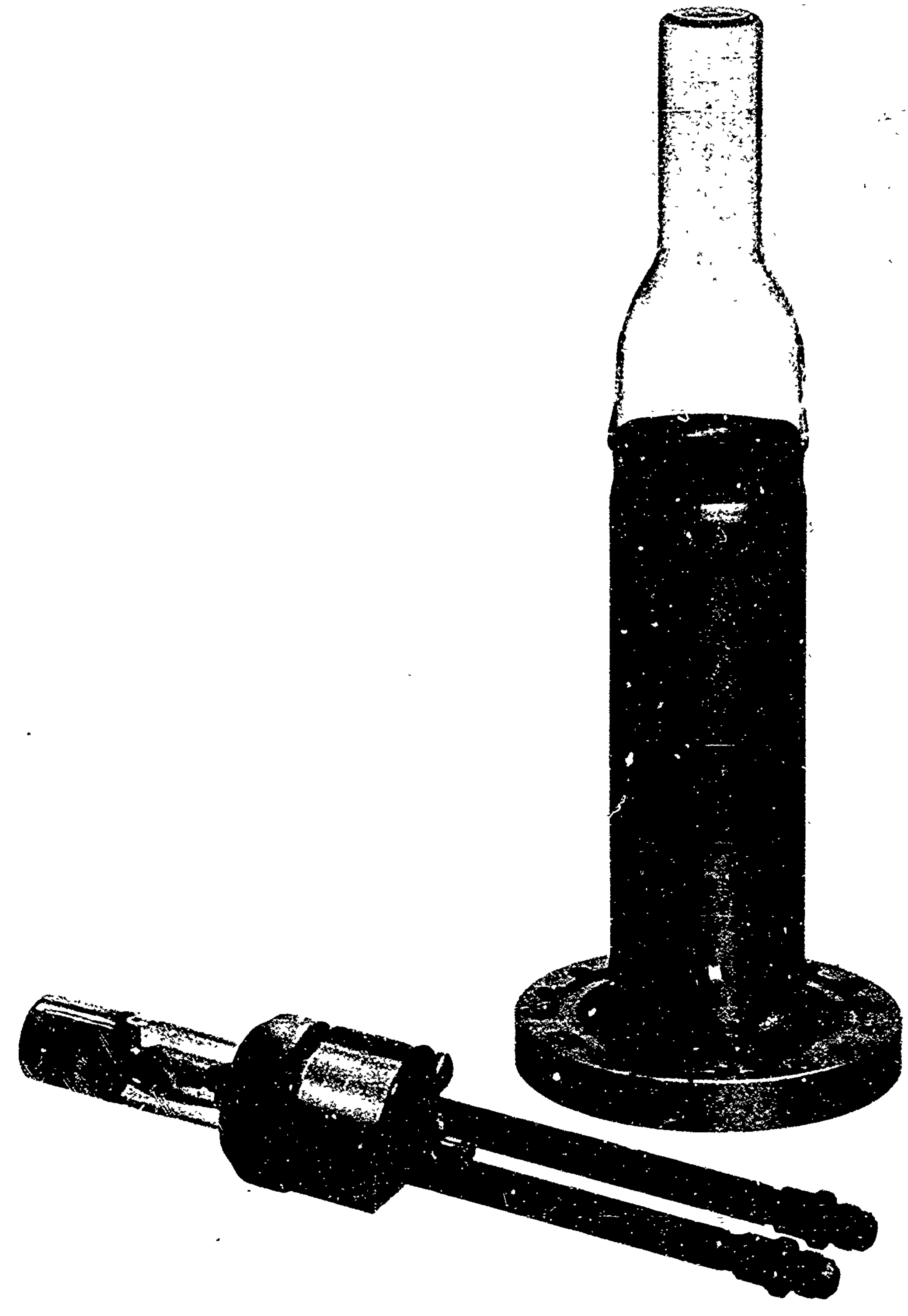

Figure 13
Ultraviolet Radiation Equipment

SECTION IV

EXPERIMENTAL APPARATUS

IV.1 VACUUM SYSTEM

The vacuum system (Fig. 10) has already been described in Section III.2.1.3.1.

IV.2 SOLENOID VALVES

The solenoid valves were of the type P/N 565003 manufactured by the Parker-Hannifin Corporation. The actuation of the valves was controlled bv an test circuit built by TRW. Different material combinations were incorporated as the seat-poppet contacts of each of the four solenoid valves (see Table 1). These four combinations of engineering metals were employed in a typical engineering configuration. The body of the valve unit was modified to permit a maximum vacuum exposure of the test surfaces; the test materials were self-shielded from radiation (see Figs. 1 and 2). In order to apply increased seating stresses, the diameter of the central canal behind the poppet was increased to 0.125". In space, similar valves were cycled periodically from a normally closed position, opening for 70 ms every five minutes, over a minimum of six months except for brief eclipse periods. A change in the monitored dynamic opening response of each valve unit served as the means to detect cold welding. A large line-of-sight included angle was provided to the vicinity of the test materials. In this manner, the vacuum level experienced by the metal contacts was not conductance limited.

Observation of a change in valve response characteristics was accomplished through a circuit designed to monitor the solenoid coil current. This is possible since the solenoid current-time waveform is influenced by the mechanical compliance of the device. For illustrative purposes, a typical solenoid valve current waveform is shown in Fig. 14. Referring to Fig. 14,

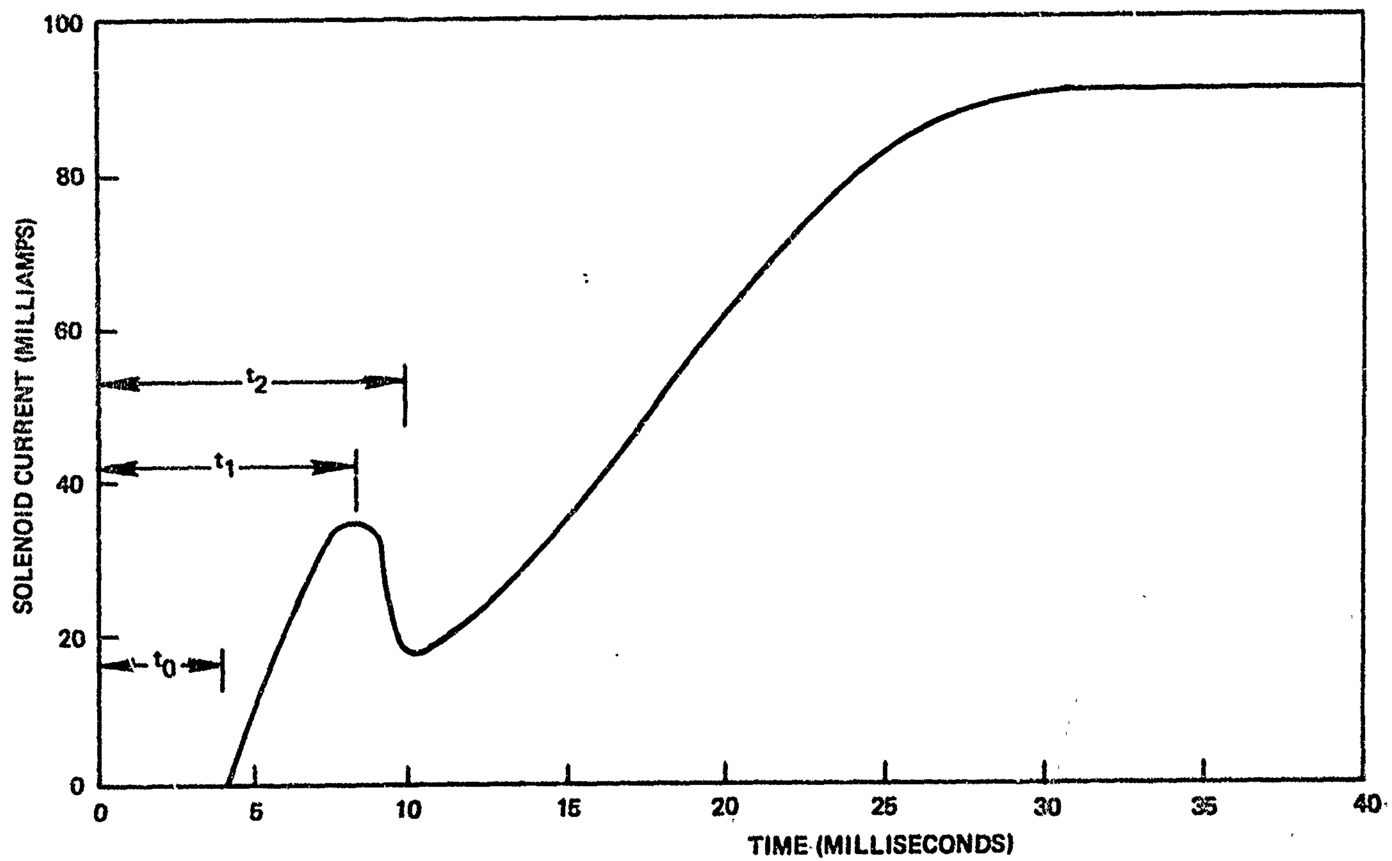

Figure 14

Normal Solenoid Current Waveform (Valve No B520103)

t_0 represents the application of power to the solenoid coil which starts to saturate; at t_1 the poppet starts to move generating a back emf causing the observed inflection point at t_1. The current trace continues to fall until the poppet-armature has stopped, t_2; at which time the second inflection point occurs and the current continues to saturate. The time between t_0 and t_2 represents the valve response time. The shape and characteristics of the curve are proportional to the coil-armature characteristics, spring forces, and cold welding In the absence of cold welding, constant spring forces are the dominant factor. Increased breakway forces at the seat-poppet due to cold welding are reflected in a proportional change in the time interval $t_0 - t_1$; $t_1 - t_2$ might change with sliding or moving friction. Interpretation of the cold welding forces relies upon sustaining constant solenoid coil characteristics and mechanical spring forces; thus, changes noted in the valve response characteristics will be proportional to cold welding and/or friction. Through calibration, (see Section V.2), the change in $(t_2 - t_0)$ can be related directly to forces at the seat-poppet interface of each valve.

IV.3 PNEUMATIC SYSTEM AND INCREASED STRESS APPLICATOR

A pneumatic system was employed to regulate the application of the increased seating stresses. This system permitted the required forces to be applied smoothly without overshoot. As shown in Fig.15, the pneumatic system applied force to a stress applicator rod. This rod was 0.120" in diameter; the applied force was determined from a strain gauge load cell attached to the rod. Motion was transmitted into the vacuum system by a ½" I.D. stainless steel bellows. The rod applied stress directly to the rear of the poppet. An assembled and disassembled view of the testing configuration is shown in Figs. 16 and 17. These photographs show the valve, its holding fixture, the load cell, the stress applicator rod, a vacuum flange, and a tube leading to the pneumatic system. The bellows is contained in the large cylinder attached to the flange. The principal components of the pneumatic system were: an aneroid manostat, a mechanical vacuum pump, two solenoid control valves, a cylinder of compressed nitrogen gas, and a precision pressure gauge. These components were interconnected by ¼" I.D. stainless steel tubing. The operation of the pneumatic system was sequenced by the Test Circuit.

The aneroid manostat (Wallace and Tiernan Model No. FA-149) was a precision pressure regulator designed to be used in the range 0.8 to 60 inches of Hg (absolute); its precision was $\pm$ 0.02 inches of Hg. The nominal I.D. of the two ASCO solenoid control valves was ¼". A Welch mechanical vacuum pump was used in conjunction with the aneroid manostat and also to permit the bellows to return to their neutral position; the capacity of the mechanical pump was 1.40 CFM, and its ultimate pressure was less than 10 microns. When the pneumatic system's internal pressure did not exceed 100 mm of Hg (absolute), a 0-100 mm Hg Wallace and Tiernan diaphram gauge was used to monitor the pressure applied to the bellows.

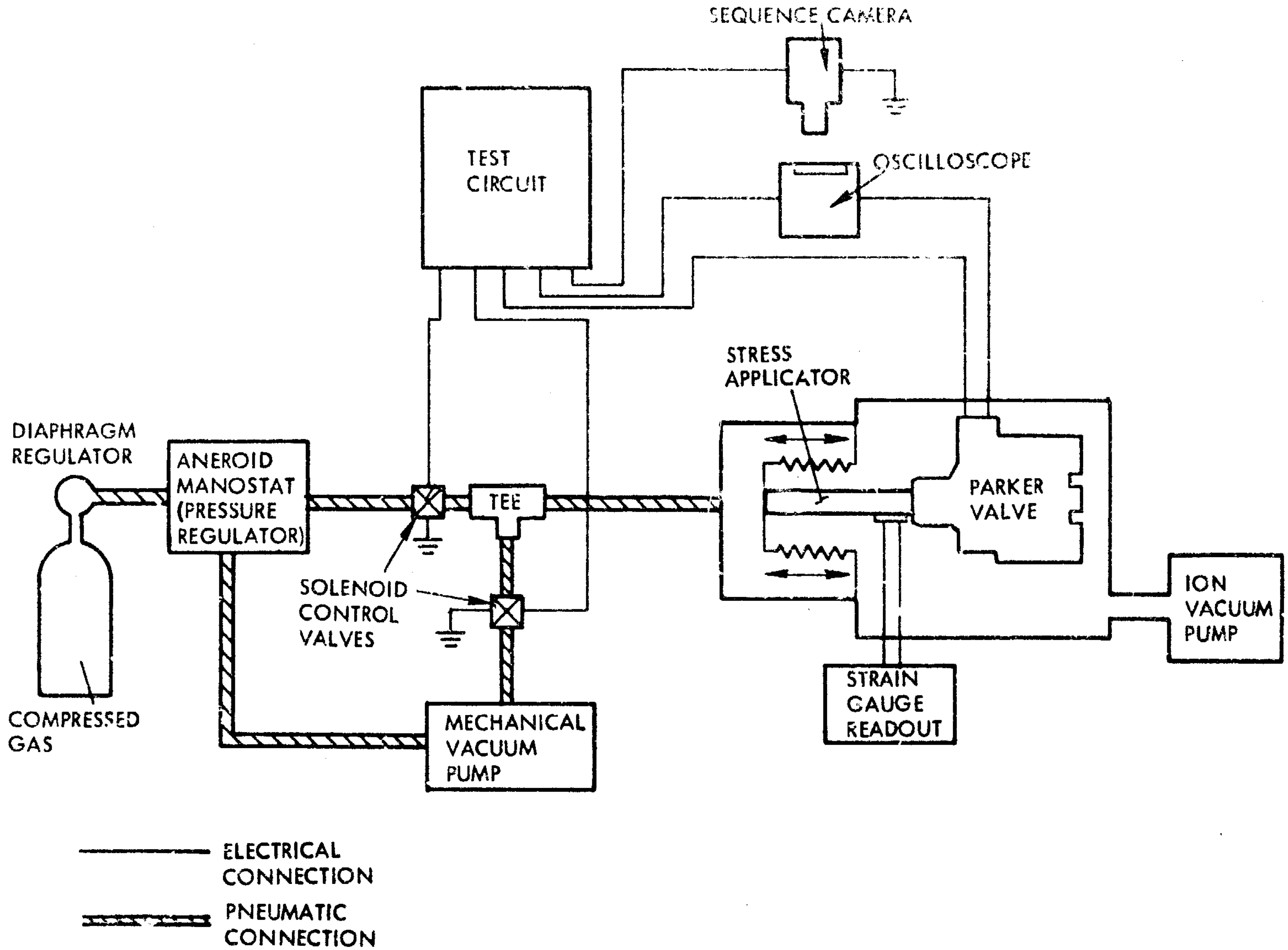

Figure 15

General Schematic Diagram

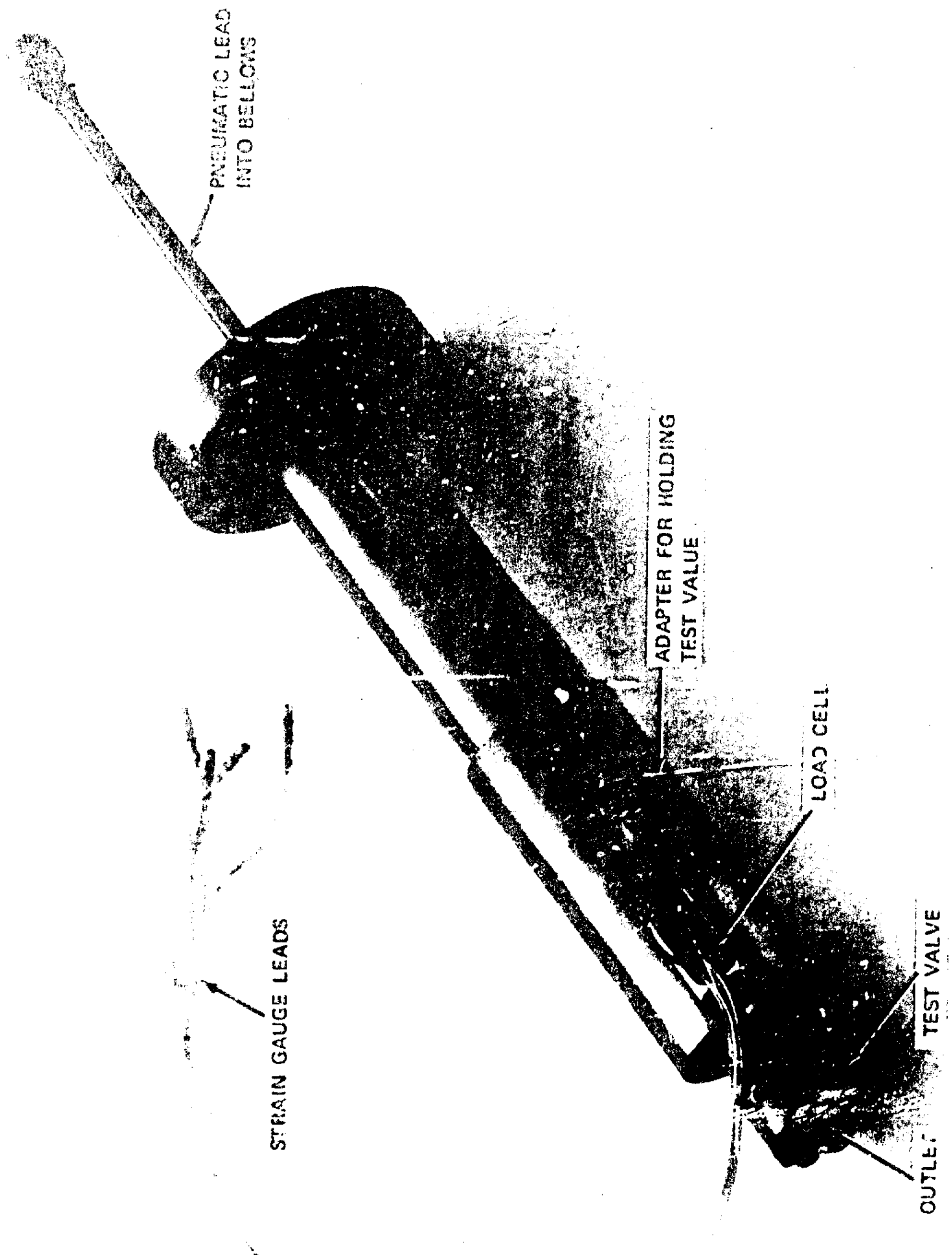

Figure 16

Assembled View of Valves' Holding Fixture

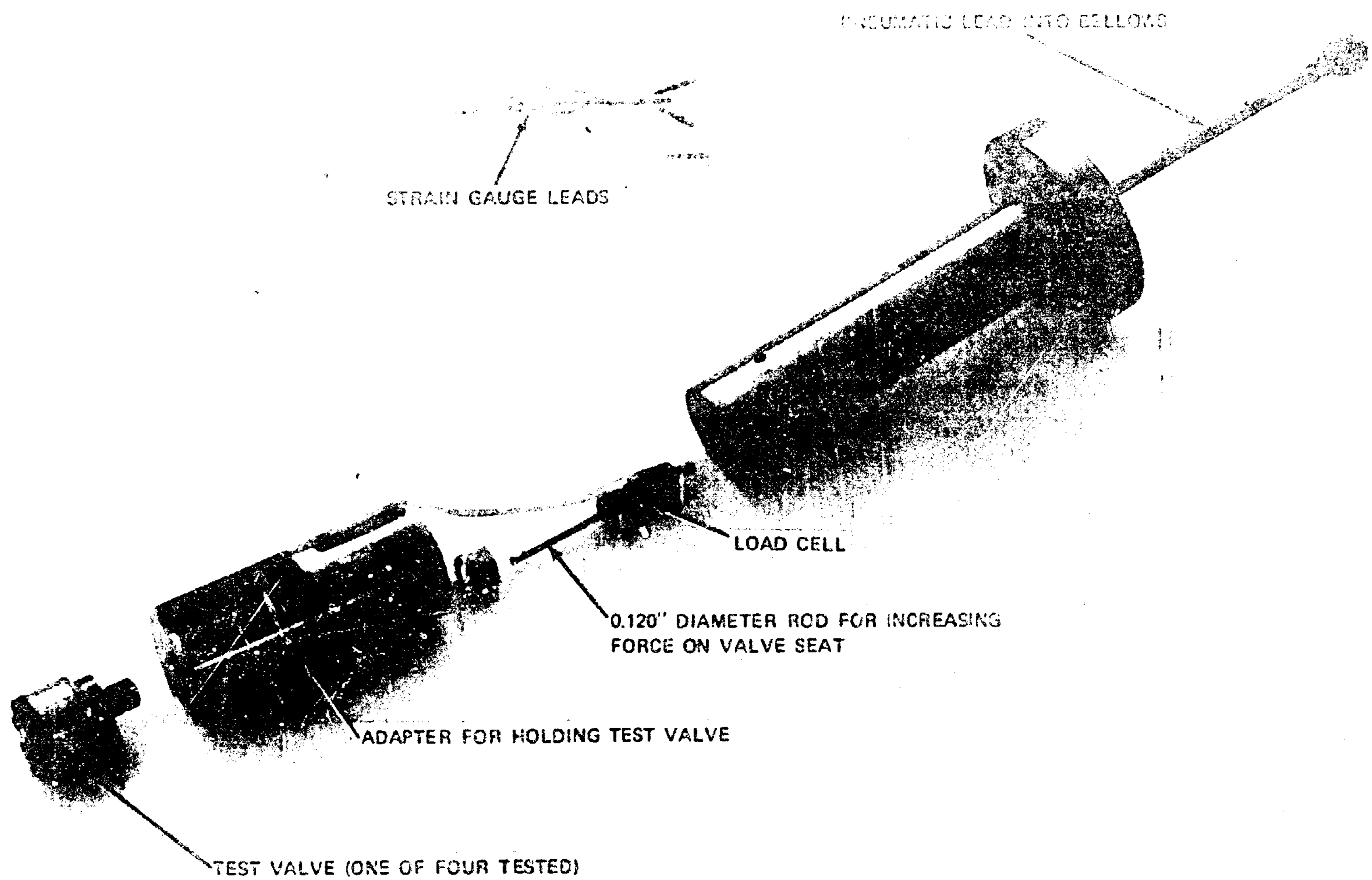

Figure 17

Disassembled View of the Valves' Holding Fixture

IV.4 RECORDING SYSTEM

An automatic recording system was used to monitor the solenoid current waveform of each Parker valve when the valve was actuated. The valves were actuated after the increased seating stress was removed. Any indication of sticking at the poppet-seat interface was indicated by an increase in a valve's opening time. The opening time, $t_0 - t_1$, was obtained from the valve's solenoid current waveform as explained in Subsection IV.2. The principal components of the recording system were a Tektronix 535-A oscilloscope, including a 1A7 differential amplifier; and a 16 mm Bell and Howell movie camera.

The movie camera was operated as a sequence camera; each solenoid current waveform displayed on the oscilloscope was photographed on one frame of movie film. A valve's solenoid current waveform was observed by measuring the voltage across a one ohm resistor in series with the valve's solenoid coil. A 10X probe was attached to each side of the one ohm resistor; the oscilloscope trigger pulse was obtained from a 20X probe attached to the Test Circuit. An electronic counter was also attached to the Test Circuit (Computer Measurements Corporation Counter, Model No. 201B). This counter gave a direct reading of the number of completed increased stress cycles. A Chadwick and Helmuth pulse camera drive was used to advance the 16 mm camera frame by frame. The input pulse for the camera drive was obtained from a 8 volt DC relay connected to the Test Circuit. Kodak Ektachrome type 7256 16mm film was used to obtain high resolution photographs of the oscilloscope trace. Variations as small as 0.5 millisecond in a valve's opening time could be resolved on the Ektachrome film.

IV.5 MICROSCOPE AND INTERFEROMETER

A C&J Multimi No. 3000D Multiple Interference Microscope was used to obtain height contours of the poppet and seat surfaces of each failed valve. As its name implies, an interferometric method was incorporated into the design of this instrument. Half of the wavelength of the light used, conveniently called the interference step, constitutes the scale by which the differences in height of the surface are measured. Thus the scale is not affected by instrument errors. For example, the interference step when using the green line of mercury is 10.75 microinches. The surface contours were photographed with Polaroid film.

After each of the solenoid valves failed due to the application of increased seating stresses, its seat and poppet were carefully examined using a Bausch and Lomb StereoZoom microscope. This microscope magnifies up to 60X, and has a special Polaroid camera attachment.

SECTION V

PROCEDURE

Each of the four solenoid valves was subjected to increasingly severe poppet-seat stresses. The increased seating stresses were effected by applying force to the rear of the poppet. This force was applied to the poppet by means of the 0.120" diameter steel rod. The force applied by the rod was regulated by a pneumatic system outside the vacuum system. Motion was transmitted into the vacuum system through a one-half inch diameter steel bellows.

Immediately prior to the tests described in this report, the four solenoid valves were refurbished by the Parker-Hannifin Corporation. This refurbishment included relapping the poppet-seat interface, adjustment of the sealing stress at the poppet-seat interface, and enlarging the valves' rear inlets. This last procedure was necessary in order to apply the 0.120" diameter steel rod to the rear of the poppet.

V.1 INCREASED STRESS TESTS

The force applied to the rear of the poppet was determined from the pressure in the pneumatic system and from strain gauges attached to the force-applicator rod. Using the pumps described in Section IV.1, the vacuum system was pumped down to a pressure of less than 10^{-6} torr in less than one hour.

The increased stress tests consisted of carrying out the following steps (see Fig. 15):

1. The Parker valve was closed (normal condition) and the solenoid control valves connected the bellows to the mechanical vacuum pump. The bellows was then in its neutral position and the separation distance of the stress-applicator rod and the valve poppet was ~ 0.1".

2. The solenoid control valves connected the aneroid manostat to the bellows. Compressed gas then flowed from the gas cylinder through the aneroid manostat into the small volume around the bellows. The aneroid manostat could be used to regulate the absolute pressure in the volume around the bellows over the range 0.8 to 60 inches of Hg to a precision of $\pm$ 0.02 inches of Hg. A valve in the manostat restricted the flow of gas; as a result, stress was applied slowly and smoothly to the rear of the poppet, and in turn, to the poppet of the Parker valve.

3. During the first few stress application cycles the force applied to the poppet was determined by monitoring strain gauges attached to the stress-applicator rod. At the conclusion of approximately 100 cycles, the force applied to the poppet was again measured by using the strain gauges.

4. After a few seconds of increased stress application, the solenoid control valves again connected the bellows to the mechanical vacuum pump; this removed the increased stress.

5. The Parker valve's solenoid was energized, and the solenoid's current waveform was monitored by an oscilloscope. The oscilloscope's trace was photographed by a sequence camera. If sticking was detected, the force required to separate the poppet from the seat was later determined from the solenoid current's waveform. The force required to open a sticking Parker valve was determined by comparing an abnormal delay in the valve's opening time (obtained from the solenoid current's waveform) with results of previous calibration tests performed in air (see Subsection V.2).

6. The Parker valve's solenoid was de-energized and the Parker valve closed.

7. The cycle started over again.

After being actuated for 1000 times at a given stress level, the valve was removed from the vacuum chamber, its leak rate was measured, and if its leak rate was satisfactory, it was subjected to further increased stress tests (up to 40,000 psi). If the valve's leakage rate was unsatisfactory, i.e., if the valve was judged to have failed, the failed valve's poppet and seat were subjected to microscopic examination.

V.2 VALVE CALIBRATION

In order to relate the deviations of the opening time to any possible sticking force at the poppet-seat interface, it was necessary to calibrate each value prior to the increased stress tests performed in vacuum. This was done by observing the increase in the opening time under ambient laboratory conditions as a function of additional stress applied to the rear of the poppet by the 0.120" tungsten rod (See Fig. 18). For example, an increase in the opening time of valve B520303 from its normal value of six seconds to ten seconds would imply the presence of a sticking force of approximately one-half pound at the poppet-seat interface. For the range of opening time deviations of interest, the increase in the opening times were linear functions of the additional applied stress. The stall condition of valve B520103 occurred at 3000 psi; for the other three valves, the stall condition occurred at less than 1200 psi. The reason for this difference is explained in Section VI.

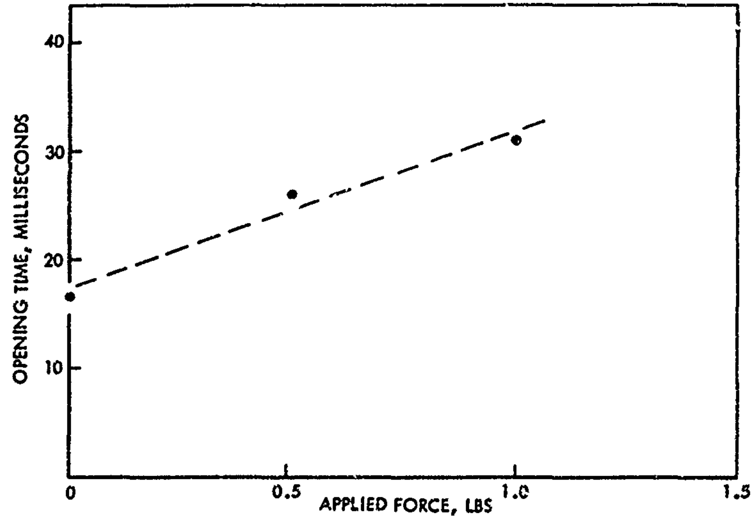

FIGURE 18a VALVE B520003

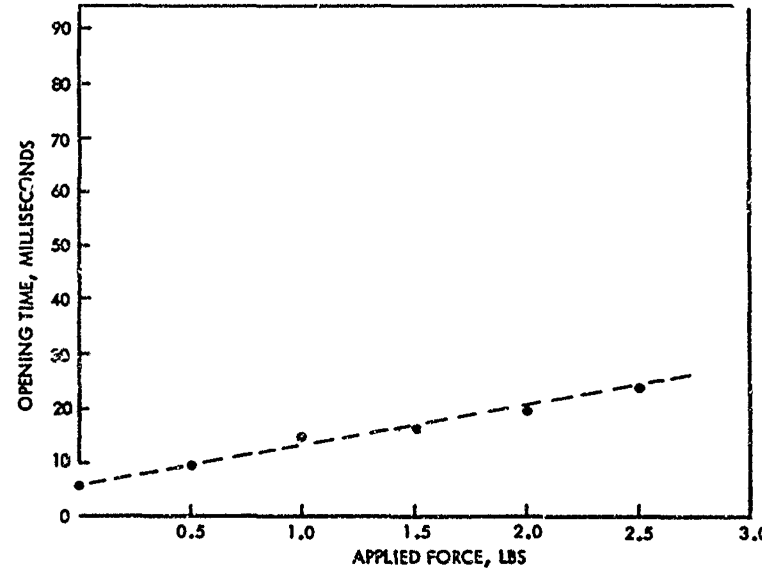

FIGURE 18b VALVE B520103

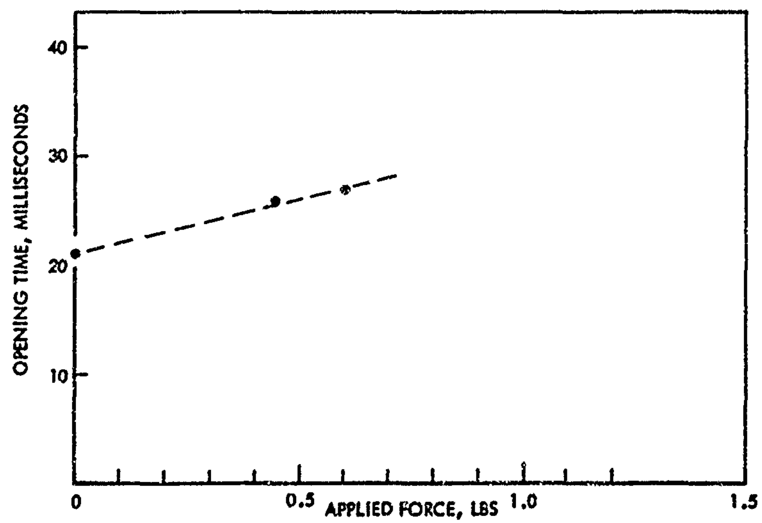

FIGURE 18c VALVE B520203

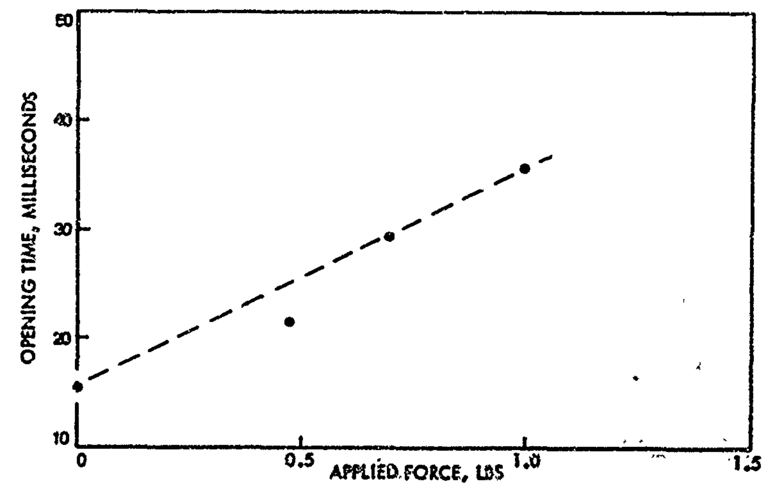

FIGURE 18d VALVE B520303

VALVE OPENING TIME AS A FUNCTION OF FORCED APPLIED TO THE REAR OF THE VALVE'S POPPET.

V.3 LEAKAGE TESTS

The leakage rate of each value was measured prior to each increased poppet-seat stress test. The leakage rates of the valves were measur d by using both nitrogen and helium gas to displace water from an inverted 100 ml graduate. Before the leakage tests were begun, all residual water was discharged from the terminal tip of the gas line, which was located directly under the inverted graduate. A 0.2 micron 1" O.D. Millipore filter was used to prevent contaminant particles from lodging on the seat or poppet surfaces and thus causing an erroneous measurement of leakage. The rate of volume displacement of the water was assumed to be equal to the leak rate of the solenoid valve. Three needle valves immediately upstream of the solenoid valve permitted the solenoid valve to be opened and closed several times between leakage measurements to dislodge any particles that may have been situated between the seat and poppet. The three needle valves also insured that water would not be accidentally drawn into the solenoid valve. The upstream pressure was read by a calibrated 0 to 60 psig Victor diaphram gauge.

V.4 MICROSCOPE AND INTERFEROMETER EXAMINATIONS

Two of the valves, No. 520003 (stainless steel and stainless steel) and B520103 (stainless steel and tungsten carbide), failed prior to completion of the increased seating stresses. These two valves were examined using the conventional microscope and the interference microscope. The remaining two valves which did not fail were not examined with these instruments.

SECTION VI

RESULTS AND DISCUSSION

VI.1 INCREASED SEATING STRESS TESTS

The results of the increased seating stress tests are shown in Tables 3 through 6. The helium and nitrogen leakage rates were measured outside the vacuum system, i.e., under ambient laboratory conditions, before and after each increased seating stress test. As discussed in Section V, each increased seating stress test consisted of executing the following cycle 1000 times:

1. The increased seating stress was applied for about six seconds and then removed.

2. The valve was opened for about 70 milliseconds and then closed (the increased seating stress was not applied during the actuation of the valve).

The average opening time for each valve, $\overline{t_2 - t_0}$, was calculated from the expression

$$\overline{t_2 - t_0} = \sum_{i=1}^{N} \frac{(t_2 - t_0)_i}{N}$$

where i denotes the actuation number and N denotes the total number of actuations of the valve in question.

The value of $\overline{t_2 - t_0}$ for each of the valves was essentially independent of the level of increased stress, and therefore the values given in Tables 3 through 6 represent values obtained by averaging over all the actuations of a specific valve. Only valve B520103 exhibited relatively large deviations in its opening time; the opening time deviations of the other three valves had a normal distribution and were judged to be statistical fluctuations.

The valves that failed, B520003 and B520103, exhibited different behavior prior to failure. Valve B520003 did not stick at any time; valve B520103 experienced adhesion several times and even cold welded. The figures on the following pages show solenoid current waveforms of valve B520103, these photographs are enlargements of individual frames of the 16 mm Ektachrome film and were taken during the 5600 psi test. These figures should be compared with the normal current waveform of the same value shown in Fig. 14. Fig. 19 shows an opening time of 15 ms; Fig. 20 shows an opening time of 24 ms; and cold welding is indicated by Fig. 21. Table 7 gives the opening times of valve B520103 (at an applied stress level of 5600 psi) prior to when this valve cold welded.

TABLE 3

LEAKAGE AND STICKING DATA FOR VALVE B520003
(17-4PH STAINLESS STEEL AND 440C STAINLESS STEEL)

Applied Stress, psi x 10^3	0.35	0.70	1.4*	2.8	5.6	10	20	40
Helium Leakage Before (p_o = 20 psig), cc per hour	2	7	4					
Helium Leakage After (p_o = 20 psig), cc per hour	7	4	38					
Nitrogen Leakage Before (p_o = 20 psig), cc per hour	2	4	6					
Nitrogen Leakage After (p_o = 20 psig), cc per hour	4	6	20					
Mean Opening Time, Milliseconds	21.5 (Average for All Stress Levels)							
RMS Deviation from Mean Opening Time, Milliseconds	4.0 (Average for All Stress Levels)							
Sticking Force Corresponding to RMS deviation of Opening Time, lbs	0.264 (Average for All Stress Levels)							
Maximum Opening Time Deviation from Mean Opening Time, Milliseconds	5.0 (Maximum for All Stress Levels)							
Sticking Force Corresponding To Maximum Opening Time Deviation, lbs.	0.320 (Maximum for All Stress Levels)							

*Testing was terminated after the 1400 psi test.

TABLE 4

LEAKAGE AND STICKING DATA FOR VALVE B520103
(17-4PH STAINLESS STEEL AND TUNGSTEN CARBIDE)

Applied Stress, psi x 10^3	0.35	0.70	1.4	2.8	5.6*	10	20	40
Helium Leakage Before (p_o = 20 psig), cc per hour	13	16	14	10	12			
Helium Leakage After (p = 20 psig), cc per hour	16	14	10	12	588			
Nitrogen Leakage Before (p_o = 20 psig), cc per hour	9	8	12	9	10			
Nitrogen Leakage After (p_o = 20 psig), cc per hour	8	12	9	10	504			
Mean Opening Time, Milliseconds	6.5 (Average for All Stress Levels)							
RMS Deviation from Mean Opening Time, Milliseconds	0.2 (Average for All Stress Levels)							
Sticking Force Corresponding to RMS deviation of Opening Time, lbs.	0.027 (Average for All Stress Levels)							
Maximum Opening Time Deviation from Mean Opening Time, Milliseconds	0.5	1.0	0.1	24.5	25.5			
Sticking Force Corresponding to Maximum Opening Time Deviation, lbs.	0.068	.136	.014	3.33	3.47			

*Testing was terminated after the 5600 psi test.

TABLE 5

LEAKAGE AND STICKING DATA FOR VALVE B520203
(440C STAINLESS STELL AND TUNGSTEN CARBIDE)

Applied Stress, psi x 10^3	0.35	0.70	1.4	2.8	5.6	10	20	40
Helium Leakage Before (p_0 = 20 psig), cc per hour	2	2	0	2	3	1	1	2
Helium Leadage After (p_0 = 20 psig), cc per hour	2	0	2	3	1	1	2	1
Nitrogen Leakage Before (p_0 = 20 psig), cc per hour	<1	2	<1	5	2	2	<1	4
Nitrogen Leakage After (p_0 = 20 psig), cc per hour	2	<1	5	2	2	<1	4	1
Mean Opening Times Milliseconds	21.5 (Average for All Stress Levels)							
RMS Deviation from Mean Opening Time, Milliseconds	0.5 (Average for All Stress Levels)							
Sticking Force Corresponding to RMS deviation of Opening Time, lbs.	0.05 (Average for All Stress Levels)							
Maximum Opening Time Deviation from Mean Opening Time, Milliseconds	5.5 (Maximum for All Stress Levels)							
Sticking Force Corresponding To Maximum Opening Time Deviation, lbs.	0.55 (Maximum for All Stress Levels)							

TABLE 6

LEAKAGE AND STICKING DATA FOR VALVE B520303
(TUNGSTEN CARBIDE AND TUNGSTEN CARBIDE)

Applied Stress, psi x 10^3	0.35	0.70	1.4	2.8	5.6	10	20	40
Helium Leakage Before (p_o = 20 psig), cc per hour	6	3	5	3	4	4	4	3½
Helium Leakage After (p_o = 20 psig), cc per hour	3	5	3	4	4	4	3½	4
Nitrogen Leakage Before (p_o = 20 psig), cc per hour	3	4	4	3	3	2	2	1
Nitrogen Leakage After (p_o = 20 psig), cc per hour	4	4	3	3	2	2	1	3
Mean Opening Time, Milliseconds	17.5*							8.5
RMS Deviation from Mean Opening Time, Milliseconds	0.5*							0.02
Sticking Force Corresponding to RMS deviation of Opening Time, lbs.	0.025*							1.0 x10^{-3}
Maximum Opening Time Deviation from Mean Opening Time, Milliseconds	3.5*							0
Sticking Force Corresponding to Macimum Opening Time Deviation, lbs.	0.175*							0

*These values are average values and apply at all levels of applied stress except 40,000 psi.

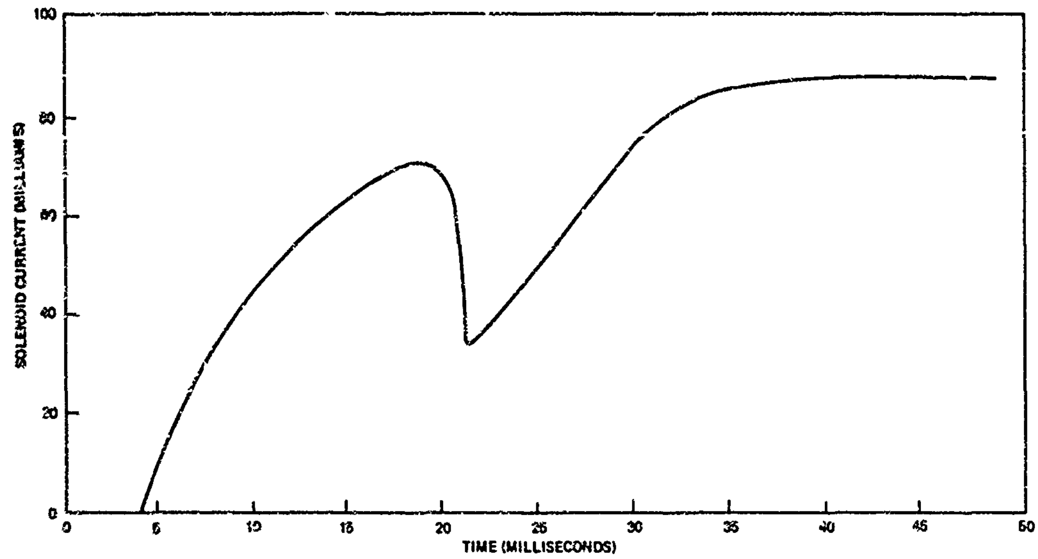

FIGURE 19 STICKING OF VALVE B520103

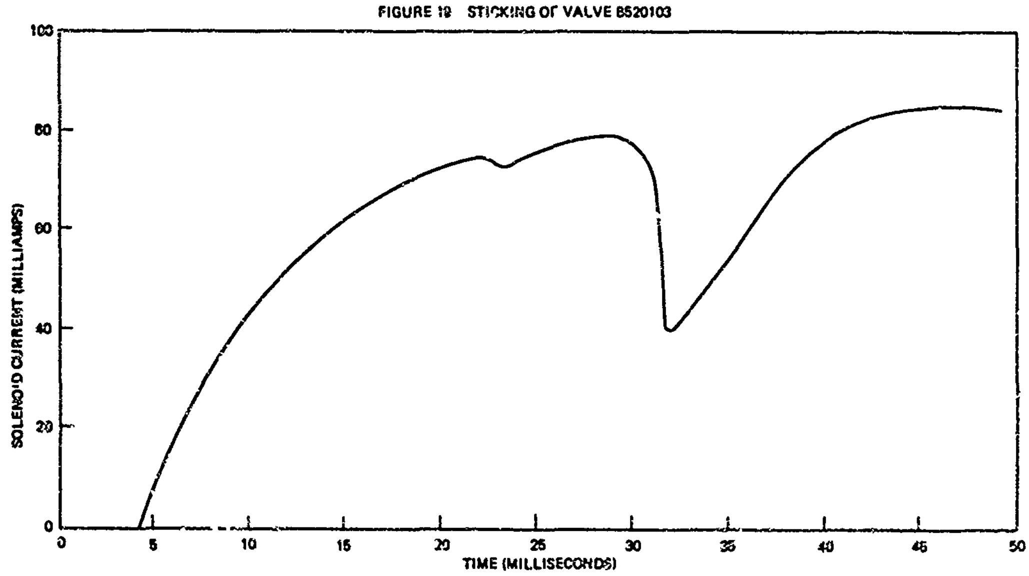

FIGURE 20 STICKING OF VALVE B520103

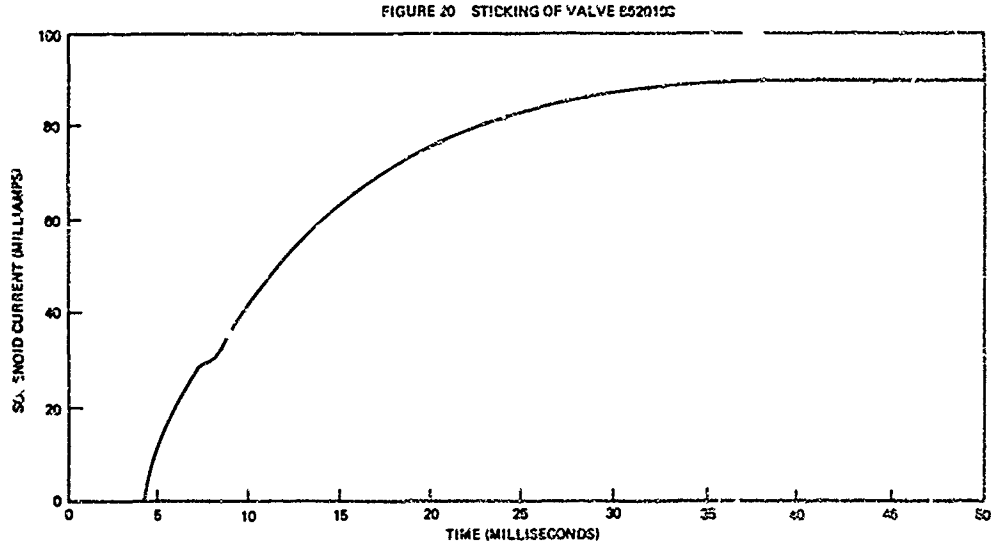

FIGURE 21 COLD WELDING OF VALVE B510103

TABLE 7

OPENING TIME AS A FUNCTION OF
ACTUATION NUMBER
VALVE B520103
APPLIED STRESS = 5600 psi

The opening time of actuations not listed in the Table was 6 milliseconds.

Actuation Number	Opening Time (Milliseconds)
2	5
3	5
4	5
5	15
6	16
7	17
8	18
9	19
10	21
11	23
12	22
13	26
14	26
15	27
16	29
17	32
18	28
19	31
20	30
21	29
22	29
24	35
31	5
32	5
43	Cold Welded

Note that the mean opening time of valve B520103 was substantially shorter than the mean opening times of the other three valves. This resulted from the fact that it was necessary to increase the closing force exerted by the other three valves' belleville springs (see Fig. 2) in order to obtain acceptably low leak rates (less than about 10 cc per hour using 20 psig Helium). Increasing the closing force led to longer opening times for these three valves.*

Increasing the closing forces of the belleville springs put increased loads on the circuitry of the electronics package; as a result some of the transistors became too hot, and the electronics package generated an output voltage which, rather than being square, exhibited substantial decay during the interval of its application across a valve's solenoid coil. An external circuit was attached to the electronics package to obtain a square voltage wave (about 9 volts) across the solenoids of valves B520003 and B520203. The external circuit was also attached to the test circuit during the 40,000 psi test of valve B520303; this explains the reduced opening time of that valve during the 40,000 psi test. It was thought that employing the external circuit during the 40,000 psi test would reduce the RMS deviation from the mean opening time, this conclusion proved to be correct.

VI.2 MICROSCOPE AND INTERFEROMETER EXAMINATIONS

Figs. 22a and 22b show the seat and poppet respectively (both stainless steel) of Valve B520003 at a magnification of about 2X. Note the extreme discoloration of the poppet in the sealing area. Fig. 23 shows the seat of valve B520003 at a magnification of about 50X. This photograph was obtained using the interference microscope. The light source was a hydrogen lamp and a green filter was used. The difference in height between adjacent fringes is one-quarter wavelength (about 12 Angstroms).

Figs. 24a and 24b show the seat (stainless steel) and poppet (tungsten carbide) of valve B520103 at a magnification of about 30X. Note the damaged portion of the seat in Fig. 24a. The large number of scratches visable on the surface of the poppet (Fig. 24b) are due to the lapping process. Again note the extreme discoloration of the poppet in the sealing area.

FIGURE 22a

SEAT OF VALVE B520003
AFTER FAILURE (2X)

FIGURE 22b

POPPET OF VALVE B520003
AFTER FAILURE (2X)

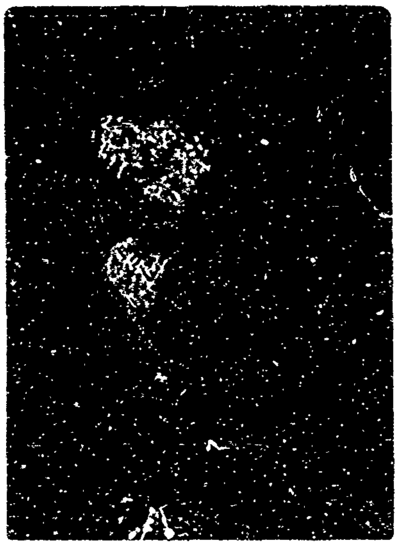

FIGURE 23

SEAT OF VALVE B520003
AFTER FAILURE (50X)

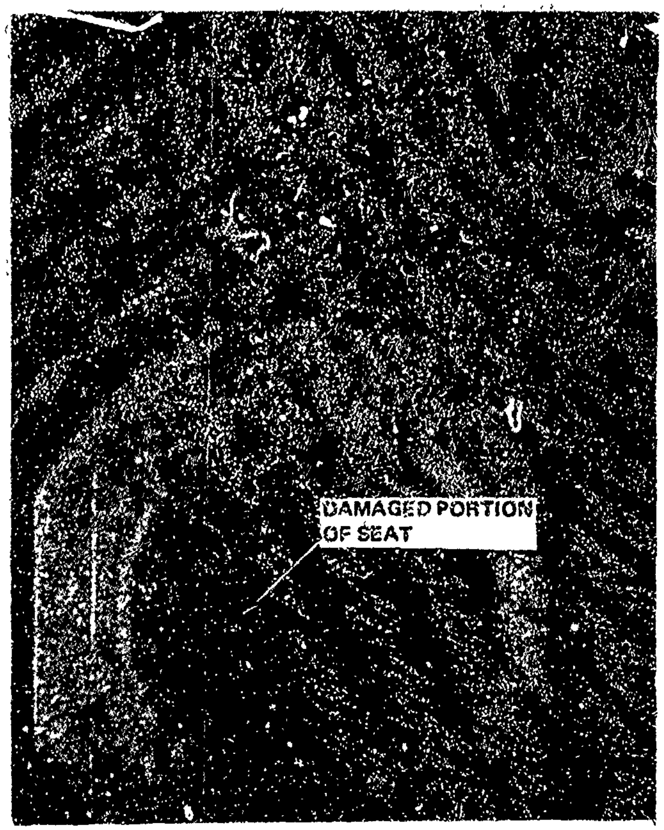

FIGURE 24a SEAT OF VALVE B520103 AFTER FAILURE (30X)

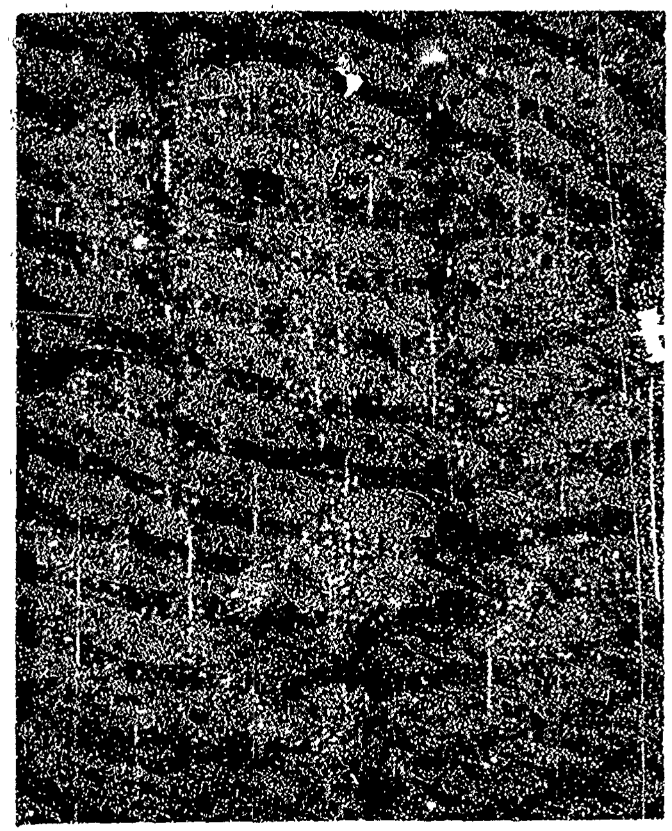

FIGURE 24b POPPET OF VALVE B520103 AFTER FAILURE

VI.3 DISCUSSION

The results of both Phases I and II suggest that for the materials tested the problem of cold welding between engineering surfaces experiencing normal stress does not manifest itself until the stress approaches the yield stress of one of the contacting surfaces. During Phase I, it was observed that adhesion occurred only when the normal stresses were substantially higher than the yield stress of one of the surfaces. Valve B520003 developed a high leakage rate, presumably due to seal deformation, before any adhesion was detected. Valve B520103 experienced some adhesion prior to developing a high leakage rate, but this valve developed a high leakage rate immediately after the next increased stress test which was performed at 5600 psi. However, the contact resistance data obtained during Phase I substantiates th the environment inside the vacuum system was at least as permissive as space. Recall from Section II that the contact resistance data obtained using the supplemental contactor matched the data obtained in space; and further, instances of cold welding and adhesion were observed in the vacuum system and not in space.

In view of the fact that none of the solenoid valves experienced cold welding in space, it is interesting to consider the probable margins before failure existing in the valves during the tests in space. Direct measurement of the static poppet seating force using an Instron Universal Tensile Test Machine yielded the result that this force never exceeded 45 $\pm$ 20 grams for all valves. Note that the poppet seating force is not the force required to move the armature but rather the force required to compress the small spiral spring which presses the poppet against the seat. The impact poppet seating force may be substantially higher than the static poppet seating force. However, the force of 45 $\pm$ 20 grams is substantially smaller than 0.70 lbs., the increased force level at which all of the valves continued to function satisfactorily. Valves B520203 and B520303 can be considered to have had the highest margin of safety since they dod not fail even at an increased stress level of 40,000 psi.

One difficulty related to the design of the four solenoid valves is illustrated by Fig. 20. An irregularity in the valve's solenoid current trace occurred at t = 23 milliseconds; and was probably produced by the poppet's restraining clamp adhering to the valve's poppet. This adhesion increased the opening time to approximately 27 milliseconds. The effect of this adhesion is also evident in Fig. 21 at t = 7 milliseconds. Visual inspection showed extreme wear at the regions of impact of the poppet's restraining clamp and the valve's seat (see Fig. 2). It was observed that no poppet wear occurred at the interface of the restraining clamp and the poppet itself; therefore, no transmission of increased stress to the poppet's restraining clamp occurred during the increased stress tests. The observed wear was very extensive, and may even have led to the failure of valves B520003 and B520103; wear particles which appeared to have come from the impact area of the restraining clamp and the seat were extensively distributed and even reached the valve's sealing surfaces. Future valve designs should avoid this type of secondary contact and wear.

Although the present work was limited to the study of one valve configuration incorporating only stainless steel and tungsten carbide, the results can be generalized to other applications: for example, other types of valves which experience only normal stresses, gimbal stops, and relays.

SECTION VII

SPACE FLIGHT QUALIFICATION TEST

VII.1 SCOPE

This recommended flight qualification test describes a procedure for determining whether or not metallic surfaces will adhere in space as a result of being subjected to exclusively normal stress. Relief valves, main propellant valves, switches, and doors are examples of devices employing metallic surfaces which experience normal stress. It is assumed that the metallic surfaces have not been subjected to special cleaning procedures designed to remove the chemically adsorbed oxide layer; it is also assumed that the more easily removed contaminants such as dust, grease, and other foreign matter have been removed from the surfaces. Trichloroethylene or alcohol is appropriate for this purpose. It is assumed that the contacting surfaces are not deformed during typical operation of the device being tested, and that instrumentation is available which permits the opening time or force of the device to be measured.

VII.2 THE VACUUM SYSTEM

Except as noted below, the vacuum system construction techniques described in ASTM E 332, "Recommended Practice for Combined, Simulated Space-Environment Testing of Thermal Control Materials" shall be followed; however, it is not necessary to cool the vacuum system's walls with liquid nitrogen during a test.

The vacuum system shall contain no mercury or oil diffusion pumps. No vacuum grease shall be used; copper seals are preferred, but the use of Viton seals is permissible provided the seals are kept completely dry. Ion or titanium sublimation pumps shall be used to maintain the total pressure in the vacuum system below 10^{-8} torr as measured by a calibrated ion gauge (see ASTM E 296 and E297, "Recommended Practice for Ionization Gauge Application to Space Simulators" and "Methods for Calibrating Ionization Vacuum Gauge Tubes", respectively). Cryogenic molecular sieve roughing pumps shall be used; the use of a compressed air aspirator is permissible. Mechanical pumps shall not be used as roughing pumps.

Electrical feedthroughs shall contain only metallized ceramic seals (see ASTM F19, "Specifications for Metallized Ceramic Seals"). Electrical leads inside the vacuum system shall either be bare or insulated with specially treated fiberglass. The fiberglass shall be prepared by washing it in alcohol and then heating it to 400°F to drive off the residual alcohol.

The vacuum system components shall be cleaned by ultrasonic techniques, and the components shall be dried in warm air ovens. Technicians working on the vacuum system shall wear vinyl inspectors' gloves when handling interior vacuum system components. Bench work shall be performed on laminar flow benches. Mechanical feedthroughs shall have a minimum number of moving parts, and no unnecessary equipment shall remain in the vacuum system.

VII.3 PROCEDURE

Each space flight qualification test should be designed for the unique conditions peculiar to the situation involved. The detailed test procedure should be prepared after consultation and review with the equipment designer (or manufactuer) and the user. Special situations in the flight test plan should be reflected in a detailed test plan designed for the particular conditions expected. This test plan is designed for assurance that exposure to the vacuum of space will not degrade system operation. The recommended general procedure is as follows:

1. Close off the vacuum system and begin pumpdown.

2. Bake-out the vacuum system if necessary to reach a pressure of 10^{-8} torr. Do not exceed the thermal limitations of the device which will be tested.

3. Identify and correct any leaks or sources of excessive outgassing.

4. Subject the test article to a bench test. During this test the device should execute at least 10% of the cycles correspondong to the mission requirement. Abnormalities in the opening time should be absent.

5. Install the device in the vacuum system and backfill the vacuum system to a pressure of one atmosphere using dry nitrogen gas. Remove any covers or enclosures which would inhibit outgassing of the contacting surfaces. Purge chamber with gaseous nitrogen.

6. Prior to pumpdown retest the device. During this test the device should execute at least 10% of the cycles corresponding to its mission requirement. Abnormalities in the opening time or force should be absent.

7. Pump the vacuum system down to 10^{-6} torr. A mild bake-out is permissable if the thermal limitations of the device are not exceeded.

8. Elevate the temperature of the device to a level ten to twenty percent above the maximum temperature it will experience during the mission.

9. Subject the device to prolonged life cycle testing. During this test the device should execute at least 300% of the cycles corresponsing to the mission requirement. Any particularly severe operational program should be executed at least three times. Abnormalities in the opening time should be absent throughout these tests.

10. Vent the vacuum system to the atmosphere and remove the device from the vacuum system. Re-attach any covers or enclosures which were removed in Step 5.

11. Subject the device to a final bench test. During this test the device should execute at least 10% of the cycles corresponding to the mission requirement. Abnormalities in the opening time should be absent.

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13. ABSTRACT

During Phase I of this research, a small experimental contactor was used to obtain electrical contact resistance data in air and in vacuum. These data show that an electronically-pumped vacuum system can effectively simulate the vacuum of actual space: the contact resistance data obtained in vacuum was in agreement with contact resistance data obtained from two small earth satellites. During Phase II, four solenoid valves were tested in the same electronically-pumped vacuum system used during Phase I; the test results were compared with adhesion data generated by identical valves during space flight tests. The contacting surfaces of the valves and the experimental contactor experienced only normal stresses. In order to determine the margin before failure existing in each of valves during the space flight tests, incrementally increasing stresses were applied to the valves' sealing surfaces. The results of Phases I and II show that cold welding in space occurs near or above the yield point of one of the surfaces. A space-flight qualification test was written.

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