BIPROPELLANT SHUT-OFF VALVE

Final Report

Prepared under Contract NAS 7-733

for

National Aeronautics and Space Administration
4800 Oak Grove Drive
Pasadena, California 91103

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AEROJET LIQUID ROCKET COMPANY
A DIVISION OF AEROJET-GENERAL
SACRAMENTO, CALIFORNIA

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FOREWORD

This final report describes the work accomplished by the Aerojet Liquid Rocket Company, Sacramento, California, under Contract NAS 7-733. The work on this "Bipropellant Shut-off Valve" program was performed during the period from 20 June 1969 to 1 June 1971. The contract was sponsored by the National Aeronautics and Space Administration. The NASA Project Manager was Mr. Frank W. Stephenson, NASA Headquarters, Washington, D.C. and the NASA Technical Manager was Mr. W. F. MacGlashan Jr., Jet Propulsion Laboratory, Pasadena, California.

The author wishes to acknowledge the significant technical support contributed by the following ALRC personnel:

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I. INTRODUCTION

The basic objective of this valve program was to provide an advanced design of an all metal, fast response, bipropellant, shut-off valve for use on long duration space missions. The valve is to provide the flow control capability for a 1,000 lb thrust, bipropellant engine using oxygen difluoride (OF_2) and diborane (B_2H_6) as the propellants. The program consisted of a series of tasks starting with valve concept evaluations. After concept selection, the valve was designed, fabricated, and tested under various conditions. The initial 4 tasks of this program provided a valve design that was fabricated and tested. Subsequent tasks involved redesign to improve specific functional characteristics, fabrication, and testing to confirm the performance of the valve.

Task 1 consisted of analysis of various valve elements and preparation of conceptual designs for a bipropellant valve assembly, Task 2 was the detailed design of the valve and preparation of component drawings. Task 3 included fabrication of hardware and preliminary testing to verify performance and identify problem areas. Task 4 was the documentation of work performed in Tasks 1, 2, and 3. Task 6, valve improvement, was directed toward improving the actuator guide arrangement and testing to confirm performance of the modified designs. Tasks 7 and 8 included propellant flow cycling using liquid fluorine (LF_2) and documentation of the program results. Task 5, development of an all metal, fast response pilot valve, was deleted to allow the addition of the propellant flow testing.

The results of Tasks 1, 2, and 3 have previously been reported in detail in Report 7-733-1I dated 15 December 1970. Section III of this report provides an abbreviated version of the information in that report which is necessary for understanding the subsequent work. The remainder of this report is devoted to the valve improvement and propellant flow test efforts.

II. SUMMARY

The approach to the preliminary valve design concepts was to establish basic design criteria and to evaluate different options for basic elements of the valve assembly. The preferred valve concept resulting from the evaluation was a 250 psig helium actuated, angle mounted, parallel poppet valve as shown on Figure 1.

The shutoff seal selection is a soft-on-hard metal concept. The soft seal is a spherical shell that seats against a hard conical seat. Beryllium copper (BeCu) and beryllium nickel (BeNi) seals were selected to seal against an electrolyzed Inconel 718 seat. Poppet shaft sealing is achieved by use of hydroformed, Inconel 718 bellows. The actuator also uses a hydroformed, Inconel 718 bellows. Other design considerations such as travel limiting, lead-lag capability, poppet guiding, and the actuator drive arrangement were established to be compatible with the selected primary elements and the desired valve assembly envelope.

Two valve assemblies were fabricated and subjected to a series of tests including leak, response time, flow capacity, dry cycles, water cycles, liquid nitrogen (LN_2) cycles, liquid fluorine (LF_2) cycles, and lead-lag operation cycles. These tests demonstrated the ability of the valve to meet design goals as shown below.

Parameter	Design Goal	Demonstrated
Internal Leakage	1.75×10^{-4} scc/sec	4.68×10^{-6} scc/sec; BeNi
	GHe at 200 psig	4.98×10^{-7} scc/sec; BeCu
External Leakage	1×10^{-7} scc/sec GHe	1×10^{-7} scc/sec
Pressure Drop	25 psid, max	10.3 psid
Travel Time	0.005 to 0.015	0.004 to 0.015 sec open
	open and close	0.007 to 0.015 sec close
Operating Temperature	-230 to +100°F	-320 to +75°F

II, Summary (cont.)

Dry cycle tests with lead-lag pintle settings proved that target leak rates and response times could be achieved with either the fuel or oxidizer pintle leading up to 50%.

A water cycle test proved the capability of the valve for 1,000 cycles of fast response operation. The beryllium nickel shutoff seal leakage after 1,000 cycles was 5×10^{-4} scc/sec and the beryllium copper seal leakage was 25×10^{-4} scc/sec.

The LN_2 and LF_2 cycle tests demonstrated the functional capability of the valve at low temperatures and with a highly reactive propellant. The design goals for leakage and response time were achieved at low temperatures.

This program demonstrated the ability of an all-metal valve to meet extremely low leakage and fast travel time requirements. Additional work should be directed toward a compatible pilot valve, confirmation of the ability to meet all anticipated operating environments, and investigation of options to expand capabilities of the basic design to other applications.

III. BACKGROUND

The work performed on valve element evaluation, design studies, detailed design and initial testing has been reported in detail in Report 7-733-1I titled "Bipropellant Shut-off Valve", dated 15 December 1970. This section provides a summary of this work for familiarization with the valve concept and to aid understanding of the subsequent valve improvement work.

The objective of the program was to provide an all metal bipropellant valve design to meet the final design criteria shown on Table I. The approach to this effort was to evaluate valve elements, combine them in different ways, III, Background (cont.)

select a concept, fabricate hardware, and perform tests to verify the capabilities of the design.

A. DESIGN STUDIES

Initial design studies were directed toward evaluation and selection of primary elements of the valve. The general approach to these element evaluations was to define the element function, determine candidates, determine the relative merits of each, and to select a preferred approach. The degree of evaluation varied considerably. In some instances a superficial examination effectively narrowed the choices. In other areas, a parametric and interaction study was used to aid selections.

1. Main Shut-off Concept

Primary consideration was given to mechanical elements. Approaches such as freezing and special electrical effects were not considered compatible with functional and system requirements. Within the general framework of mechanical elements, approaches such as a poppet, ball, butterfly, spool, plug, and gate are candidates. Valve size, allowable leak rate, cyclic life, and the all-metal requirement were governing factors in the selection of a poppet. Concepts such as the ball, butterfly, plug, and gate require a large amount of relative sliding between the seal and the moving element. This condition is not conducive to low leak rates and long life with metal seals. There are ways of eliminating this problem by seal lift-off but the lift-off mechanism complicates the design and results in larger valve envelopes. Also, in the relatively small size valve required, the pressure drop advantages of other elements such as the ball and butterfly are lost. Another factor is actuation. In general, the poppet can be actuated by less complex arrangements than the other elements. Based on these factors, a poppet was selected as the shut-off element.

III, A, Design Studies (cont.)

2. Shut-off Seal

With a poppet shut-off element, the basic decisions for seal selection relate to materials and configuration.

The two basic approaches to metal-to-metal sealing are a soft metal sealing against a hard metal (soft-on-hard) or a hard metal sealing against another hard metal (hard-on-hard). The soft-on-hard approach depends on plastic deformation of the softer metal to establish intimate contact along the sealing interface. The hard-on-hard is more dependent upon fine surface finishes and excellent alignment between the contacting surfaces to achieve sealing with primarily elastic deformation.

The leak rate to be achieved influences the selection. With either approach, seal load must be increased to obtain a lower leak rate but the relative magnitude of the required load is a heavily weighted factor.

The design requirement of zero liquid leakage was established in terms of equivalent helium leakage to aid comparison of the two approaches. Using information present in JPL Technical Report 32-926 entitled "Basic Criteria and Definitions for Zero Fluid Leakage", equivalent gaseous helium leak rates at 200 psi were calculated. The equivalent helium leak rate was 3.4×10^{-4} scc/sec for the fuel and 1.75×10^{-4} scc/sec for the oxidizer. The more severe value of 1.75×10^{-4} was used for evaluation.

Using the equations shown on Figure 2, required seal loads for various materials, hardness conditions, surface finishes, seal contact interface widths, and contact angles were calculated. There are assumptions inherent in the calculations so that the values cannot be treated as precise; however, experience has shown the accuracy on leak rate to be within one order

III, A, Design Studies (cont.)

of magnitude when compared to experimental results. The primary value of these calculated results is to provide a basis for comparison. With equations and assumptions consistently applied, the results reflect a valid comparison between alternatives.

Based upon the seal load analysis, a soft-on-hard material combination was selected. This selection was influenced primarily by consideration of required load to achieve the target leak rate of 1.75×10^{-4} scc/sec GHe and the available valve envelope. The configuration selected was a spherical soft metal seal contacting a conical hard metal seat as shown on Figure 3. This arrangement also involved trade-offs between required valve poppet load and wear life. The conical seat with a seat angle of 20° produces a significant mechanical load advantage, but produces some relative motion between the seal and seat during initial opening and final closing travel. Prior ALRC experience with this seal-seat configuration indicated a life of 1,000 cycles should be attainable; therefore, the load advantage of the angle seat was retained.

3. Poppet Shaft Seal

Metal sealing allows consideration of a sliding seal ring, diaphragm, torque tube, or bellows. The desired external leak rate of 1×10^{-7} scc/sec, maximum stroke length of 0.225-in., and envelope restraints effectively narrowed the candidates to a bellows.

Other options with respect to the bellows relate to bellows location and method of fabrication. The shaft bellows could be located either upstream or downstream from the poppet shut-off seal. The downstream location was selected to minimize any long term (10 years) propellant compatibility effects and to avoid pressure spike effects that may be produced by fluid

III, A, Design Studies (cont.)

hammer during rapid closing of the valve. The candidate methods of fabrication included welded, hydroformed, and machined. The hydroformed bellows was selected as being more reliable, more easily cleaned, and less expensive than the other candidates.

4. Actuation

Selection of the best method for valve actuation is dependent upon many factors, some valve-dependent and some system-dependent. The only response criteria defined for the valve was travel time. The desired pintle travel time was 0.005 sec to 0.015 sec. Criteria for response time from signal to start of travel or for response time repeatability were not defined.

a. Type of Actuation

The many potential types of actuators must be evaluated for use in this valve application. Advanced concepts such as the use of high thermal expansion elastic type materials or phase change metals have shortcomings with regard to load, stroke length, and response time.

Along more conventional lines, candidates include propellant actuation, use of a separate hydraulic system, direct electrical, and pneumatic actuation. A separate hydraulic system would not be a serious candidate unless there are other on-board controls that could use the same system. Even allowing this possibility, the cryogenic propellants would cause problems for conventional hydraulic fluids because of freezing and high reactivity in the event of leakage. This approach is not competitive.

Propellant actuation has advantages in some applications but is not considered a desirable alternate for this valve. There are potential problems with fluid venting, system bleed-in, density changes, varying actuation pressure, and fuel freezing if the fuel were selected for actuation. Use of the oxidizer for actuation would have the same problems as above with the substitution of a materials compatibility problem instead of a freezing problem. Other approaches are more attractive.

Direct electrical actuation is generally considered a prime candidate for small valves on long duration space missions. The primary concerns with electrical actuation were size, weight, and electrical power required to obtain the 0.005 sec travel time with the relatively high valve poppet load. Preliminary calculations showed approaches such as solenoids and torque motors to be uncompetitive. An electromechanical concept using a DC motor, gear train, and clutches may be feasible. Evaluation of sub-component trade-offs and optimization about a specific design point would be required to define this type of actuator.

Pneumatic actuation offers several attractive advantages for an on-off valve such as an available supply of gas, linear actuation to match linear valve travel, relative insensitivity to temperature changes, non-corrosive actuation fluid, low electrical power demands, and great latitude on force and response with a basic actuator size. The major disadvantages of pneumatic actuation are in the areas of delay times and response repeatability. For this application, there are no criteria defined for delay times and overall repeatability; therefore, a pneumatic actuation concept is selected.

b. Pneumatic Actuation Concepts

There are many options within the broad scope of pneumatic actuation. GN_2 or helium at either high or low pressure could be used. An on-board gas supply or a separate reservoir could be used. Also, there are options relating to whether the actuator is single-acting, dual-acting constant area, or dual-acting differential area.

III, A, Design Studies (cont.)

Evaluation of these options is based more upon system and mission considerations than on factors such as size and weight. Comparison of a separate gas supply versus an on-board supply must consider the mission. For a 10-year mission with a separate supply, a reliable gas isolation device is needed. This means a separate isolation valve or a leak free, highly reliable pilot valve is required. If a blowdown mode is used, valve delay and travel times will vary. For constant pressure, a regulator would have to be added. In view of these factors, pneumatic actuation loses much appeal unless there is an on-board supply of gas. The selection is to use an on-board supply.

Selection of an on-board supply makes the gas selection a simple one. Since helium gas will be supplied for propellant tank pressurization, helium will also be used for actuation.

Evaluation of high-pressure vs low-pressure actuation requires both system and valve envelope considerations. High-pressure gas allows use of a smaller actuator and pilot valve. However, this advantage is not really great. Since the valve may have to operate toward the end of the mission, the high-pressure supply at that time will not be much higher than regulated pressure. Actuator sizing will have to be based upon the end of mission requirements; therefore, the actuator size advantage will be quite small. The size advantage is weighed against the need for a high-pressure, leak-free pilot valve. At the start of the mission, the pilot valve may have to handle pressures in the range of 3,000 to 5,000 psi. With helium, this is a definite problem. Considering the relative merits, use of low-pressure helium is preferred. There is an added advantage in this approach in that a constant pressure will be available.

A single-acting piston for opening with spring force closing is the preferred arrangement for this valve. With spring loaded closing,

III, A, Design Studies (cont.)

the valve will seal without having actuation pressure available. This simplifies functional and leak checks. Also, with this arrangement a three-way pilot valve can be used. The use of dual-acting pistons is not considered to offer any definite advantages while having disadvantages of an added leak path during coast periods and the requirement for a four-way valve for the dual-acting equal area approach. If the number of actuations were high, then total gas consumption would be a factor; however, for the present anticipated mission requirements of 5 to 10 cycles, gas consumption is not a significant factor.

B. VALVE DESCRIPTION AND OPERATION

During the conceptual design work, five designs were prepared. The selected concept is as shown on Figure 4. Figure 5 shows an exploded view of the hardware. This design was preferred primarily on the basis of the simple actuator and drive arrangement as compared to other concepts. The materials used for the major valve subcomponents are shown on Table II.

The following is a brief description of the valve and how it operates. A more detailed description of critical elements is contained in Report 7-733-1I.

Propellant shut-off and sealing is achieved by a beryllium copper or beryllium nickel spherical seal which is loaded against an electrolyzed Inconel 718 angled seat. Basic sealing force is provided by helical springs that act directly on each poppet. Additional sealing force is obtained from the upstream pressure acting on the flexible seal. The poppet shafts are sealed by hydroformed Inconel 718 bellows which are welded to the poppet shaft on one end and to a body insert on the other end. The end of each poppet shaft has a threaded cap which retains spacer shims to obtain the desired lead-lag relationship. The actuator uses a bellows.

III, B, Valve Description and Operation (cont.)

assembly which is internally pressurized. One end of the actuator bellows is welded to a piston that has two legs for guiding travel. The other end of the bellows is welded to a plate that is subsequently welded to the actuator cover. Position indication is provided by rotary potentiometers which are driven by racks attached to the poppet spring retainers.

The key subcomponent of the valve is the shut-off seal. The selected configuration is a scaled down version of an ALRC spherical seal which has been successfully fabricated and tested in sizes ranging from 1-1/16 to 2-1/2 in. contact diameters. This seal as shown in Figure 3, consists of a thin, spherical, metal shell seated in a conical seat that is machined as an integral part of the valve body. In operation, the shut-off seal contacts and centers itself upon the valve seat as the valve closes. Then, the poppet travels a slight distance further until the poppet stop bottoms against a shoulder in the body. This additional travel between initial seal-seat contact and bottoming against the stop serves two functions. The seal deflection provides the load necessary to prevent leakage and a slight wiping or lapping action between the seat and seal produces the necessary microscopic conformation of the two sealing surfaces.

Operation of the valve is as follows. With the valve closed, the springs and propellant inlet pressure effect the shut-off sealing. An electrical signal to a normally closed, three-way, pilot valve causes the pilot valve to shuttle thereby admitting gas pressure to the actuator bellows assembly. The pressure force in the actuator overcomes the spring and inlet pressure forces acting on the poppet and the oxidizer poppet lifts off the seat. As the oxidizer poppet moves open, at some point the actuator piston contacts the fuel poppet shaft and unseats the fuel poppet. Travel of both poppets continues until the actuator piston bottoms against a body stop. For closing, the procedure is reversed. The pilot valve is de-energized to vent the actuator. The

III, B, Valve Description and Operation (cont.)

helical springs then close the valve, moving the poppets until the poppet stop contacts a shoulder in the body. By proper selection of the poppet end nuts and shims, simultaneous poppet lift-off or 50% lead with either poppet can be achieved.

C. TESTING

Test work was directed primarily toward evaluation of the seals and the basic functional capability of the valve. The chronological sequence of tests was as follows:

Preliminary seal assembly and leak tests
Dry cycle response time test, 50 cycles
Water flow test for determination of pressure drop
Dry cycle test, 100 cycles, fast travel time
Wet cycle test, 100 cycles, fast travel time
Dry cycle test, 100 cycles, slow travel time
Wet cycle test, 1000 cycles, slow travel time
Cryogenic leak test

These tests were all performed on one bipropellant valve assembly using 2 beryllium copper and 2 beryllium nickel shut-off seals. Test details and discussion of results are contained in Report 7-733-1I.

1. Leak Tests

Initial leak tests were directed toward demonstration of the target leak rate of 1.75×10^{-4} scc/sec GHe. The primary area of concern was the amount of seal deflection under the load required to achieve the desired leak rate with the existing seat surface finish of about 2 to 4.5 arithmetic average (AA).

III, C, Testing (cont.)

Leak checks were conducted using either gaseous nitrogen (GN_2) or gaseous helium (GHe). Leakage was monitored on most tests using a bubble leak meter for a period of 300 to 400 sec. A condition of no bubbles in 300 sec is considered as a leak rate of less than 3.3×10^{-4} scc/sec. To obtain more accurate measurement of low leak rates, a mass spectrometer (helium leak detector) was used. The best leak rates, as determined by a mass spectrometer leak check, were 4.68×10^{-6} scc/sec for a beryllium nickel seal and 4.98×10^{-7} scc/sec for a beryllium copper seal. These values were obtained at the nominal design pressure of 200 psig using GHe as the test fluid.

2. Dry Cycle Testing

Three series of dry cycle tests were run. The primary objectives of these tests were to determine the response time of the valve, and to determine the effects of dry cycles on general seal wear and leakage. With respect to seal wear, there was concern that localized wear resulting from impact during fast closing might cause rapid deterioration or deformation of the seal.

Initial dry cycle tests were performed to demonstrate the response capability of the valve. Over a series of 50 cycles, valve travel time was decreased until the target time of 0.010 sec was achieved. Table III shows that neither the beryllium nickel or beryllium copper seal showed a significant change in leakage as a result of the cycles.

Subsequent series of 50 dry cycles showed that leakage increases more rapidly with fast travel times than with slow travel times as shown on Table IV. The data also indicates that dry cycles have less effect on the beryllium nickel seal than on the beryllium copper seal.

III, C, Testing (cont.)

3. Wet Cycle Tests

Two series of wet cycle tests were conducted; the first to 100 cycles and the second to 1,000 cycles. In both tests, 200 psig water was admitted to the inlet of the valve through a 1/4-in. line to each bore. While open, the valve was flowing 0.65 lb/sec through each bore. Travel times for all the cycles were in the range of 0.008 to 0.011 sec.

Both tests showed wet cycling to have little seal degradation effects. As shown on Table V, both the beryllium copper and beryllium nickel seals had zero bubble leakage (less than 3.3×10^{-4} scc/sec) at the start of the 1,000 cycle test. After 1,000 cycles, helium leakage at 200 psig was 25×10^{-4} scc/sec for the beryllium copper seal and 5×10^{-4} scc/sec for the beryllium nickel seal.

4. Other Tests

Other tests conducted included a water flow test to determine flow vs poppet position characteristics and an LN_2 leak test. The valve pressure drop, at water flow equivalents of 1.63 lb/sec and 0.86 lb/sec for the oxidizer and fuel respectively, was 10.3 psi for the oxidizer and 3.1 psi for the fuel at the 0.150-in. nominal opening stroke position. The test performed with the valve immersed in LN_2 did not provide valid shut-off seal leakage data as a result of flange joint leakage. Ambient leak checks before and after the LN_2 test showed less than 3.3×10^{-4} scc/sec GHe leakage for both shut-off seals.

D. PROBLEM AREAS

The initial evaluation tests were defined primarily to demonstrate the shut-off seal performance. During the testing, two other areas were

III, D, Problem Areas (cont.)

identified as significant problems with respect to future test activity and final application of the valve.

1. Actuator Guide

For the first series of dry cycles, the valve was assembled without any lead or lag between the two pintles. With this condition, load on the actuator piston is balanced. As the dry cycle test was run, a small glitch on the valve closing traces was noted.

The actuator was removed from the valve and examined. One of the guide legs was scratched and a localized build-up of material in the guide bore indicated galling. Both external guide legs and the guide bores in the body were reworked to improve the surface finish. Also, the edges of the guide bore holes were chamfered to avoid heavy contact on a sharp edge.

The condition noted would be aggravated when the valve was operated with a lead-lag setting on the pushrods. With a lead-lag setting, the lead pintle imposes a high cocking load on the actuator during initial travel until the lagging pintle is contacted.

The valve was reassembled with a 0.071-in. lead on one pintle. With this setting, the valve would not close adequately to achieve sealing of the lagging poppet seal.

Subsequent tests were conducted with a lubricant on the guide pins and with the valve set for simultaneous poppet lift-off.

III, D, Problem Areas (cont.)

2. Pintle Bellows

The majority of the valve cycles were run with the nominal 0.150-in. stroke. To evaluate the actuator and pintle bellows, the stroke on both pintles was set for the maximum of 0.225-in. for the 1,000 wet cycle test. The actuator bellows and both pintle bellows were checked for leakage before and after the cycle test using a 15 min pressure decay test. There were no bellows leaks at the start of the test; however, after the test the pintle bellows in the right hand bore was leaking. A special test setup was made and leakage was measured in the closed, relaxed, and open positions. Leakage was from 10.2 to 13.2 scc/sec GHe at 200 psig in all three tests.

The leaking pintle assembly was machined out of the body after conducting the low temperature test. There were circumferential cracks in the outer diameter of two convolutions as shown in Figure 6. The cracked convolutions were located approximately 1/3 of the bellows length from each end. The cracks appeared to be much more severe than would be expected from the leak rate of 10 to 13 scc/sec. The initial failure was probably aggravated by the low temperature testing and the fact that the bellows was extended to provide access for removal of the pintle assembly. Normal valve operation has the bellows in compression over the full stroke.

The most significant visual observations were an apparent oxide coating on the bellows and an etched or pitted appearance of the polished section of bellows adjacent to the weld.

IV. DESIGN IMPROVEMENT

The purpose of the design improvement effort was to improve the functional capability of the valve assembly. This work was guided by the results of the prior testing and was directed toward areas that would provide higher confidence of meeting design goals with the basic concept.

A. PINTLE BELLOWS

Evaluation of the pintle bellows cracking involved cyclic life analysis, dynamic effects, and fabrication factors. The dynamic effect of the 0.010 sec travel time was calculated to be equivalent to an additional bellows deflection of 0.031-in. Thus, the effective stroke during the cycle test was 0.256-in.

A computer program developed as part of a cryogenic bellows IR&D program was used to evaluate the effects of stroke length, material thinning, and temperature on the cyclic life of the bellows. Predicted cycle life was based on the combined stress level resulting from bellows compression and 200 psig external pressure. This is a more severe condition than that existing in service since maximum bellows compression occurs with the valve closed. When the valve is closed, there is no external pressure acting on the bellows.

The results of this analysis are shown on Figures 7 and 8. Figure 7 shows the effect of stroke while Figure 8 shows the effect of material thinning. Normal material thinning for these hydroformed bellows is about 10%. Based on the curves, with 10% material thinning the predicted ambient temperature cycle life is reduced from about 8,800 down to about 3,300 as the effective stroke is increased from 0.225-in. to 0.256-in. If the material thinning were 15% instead of 10%, cyclic life would be reduced to about 1/2 of the above. Thus, the added dynamic effect of rapid valve travel and 15% thinning reduce predicted cycle life to about 1,650.

IV, A, Pintle Bellows (cont.)

Cycle life was evaluated with respect to operation at the nominal stroke of 0.150-in. Under anticipated test conditions of -320°F, 0.150-in. stroke, plus 0.031-in. dynamic effect, the predicted life is 25,843 with 10% material thinning. Assuming 20% thinning as a basis to allow for the observed bellows surface finish, predicted life is 8,937 cycles.

Subsequent to the bellows stress and cycle life analysis, evaluation was directed toward hardware fabrication and material processing aspects. The failed bellows was checked by X-ray diffraction. The coating was a nickel-manganese oxide. Fabrication and material processing records were reviewed to determine whether some variation from specified procedures may have influenced the failure and oxide formation. No variations were found to explain the oxide formation or any possibility of changed material characteristics.

Based on the analysis, the original bellows were used; however, the stroke was limited to the 0.150-in. nominal value for the planned 1,000 cycle propellant flow test in order to assure an ample margin on bellows life.

B. ACTUATOR GUIDE

The actuator guide redesign was directed toward elimination of binding and reduction of friction when the valve is operated with a pintle lead-lag setting. A change in the required valve envelope allowed consideration of concepts having a longer actuator. This change resulted in reduced loads at the contact areas of the guide. Although no problems were experienced with the actuator bellows, with the longer envelope the bellows was also changed to provide a greater margin of safety for cycle life.

Several conceptual designs were drawn including features such as a linear ball bushing, guides with monoball contact alignment, and shaped contact

IV, B, Actuator Guide (cont.)

lands. The selected concept, as shown on Figure 9, incorporated the guide inside the actuator bellows. An electrolyzed 304L CRES post with contact lands at each end operates in a gold plated Inconel 718 sleeve which is pressed into the actuator cover. The ends of the contact lands were contoured to avoid digging or shaving and to increase the contact areas. The materials were selected based on a zero wear life analysis and review of friction wear data which indicated a 1,000 cycle life could be achieved. A sealed joint between the actuator body and cover was included to allow separation of the parts for examination of the guide after testing. The bellows change resulted in an increase in predicted cycle life from 10,000 to 55,000 cycles at the maximum stroke condition.

C. OTHER AREAS

Two other areas of concern during the valve improvement effort were locking the shut-off seal to assure no rotation and offsetting the actuator bellows load.

The original arrangement to prevent the shut-off seal from rotating after installation involved use of a tab washer. Two tabs were bent one direction and were placed in blind holes in the seal. Locking the seal to the pintle was to be accomplished by bending a tab the other direction against a flat on the side of the pintle. This final locking could not be accomplished on the hardware without potential damage to the shut-off seal. The corrective change made was to add a flat on the underside of the pintle so that the flat and bend tab would be accessible through the valve outlet port.

The actuator bellows load was a concern primarily with a pintle lead-lag setting. The actuator bellows is desired to be in compression over the full stroke. With the existing valve design, the greatest compression

IV, C, Other Areas (cont.)

exists when the valve is closed. Thus, when the pintles are set for lead-lag operation, the lead pintle shut-off seal load is reduced by the actuator bellows *load acting in opposition to the pintle spring closing force. The* combined effect of actuator guide friction and actuator bellows load may reduce shut-off seal load to a level where leakage would occur. This effect could reduce shut-off seal load to about 70% of the design load.

This potential problem was solved by the addition of two helical compression springs operating between the actuator piston and the valve body. The spring load was designed to just offset the actuator bellows load. Subsequent testing of the valve proved the springs to be unnecessary since the target leak rate was achieved without installation of these springs.

V. FABRICATION AND ASSEMBLY

Fabrication for the valve improvement effort included modifications to parts made previously and procurement of one redesigned actuator assembly. Locking tab flats were machined on two pintle assemblies fabricated during the initial program procurement. The pintle assemblies were electron beam welded into a valve body that had not been used previously. The four shut-off seals (2 beryllium nickel and 2 beryllium copper) used in earlier test work were reworked by grinding the seal edge and then polishing the sealing area using diamond dust. The new actuator was fabricated by outside suppliers.

The basic valve assembly and seal installation procedures had been established during work on the first valve assembly. Details of assembly techniques are contained in Report 7-733-1I.

The improved actuator was assembled using conventional tools and techniques. Figure 10 shows the valve assembly with the new actuator installed.

V, Fabrication and Assembly (cont.)

During initial assembly, several areas for modification to simplify assembly and assure proper stroke control were identified. The piston travel stop pads should be made longer to assure that the pintle stroke is limited to 0.225-in. The stroke on the lead pintles of the test valve was 0.250-in. To avoid excessive stress on the pintle bellows, 0.050-in. thick spacers were installed on the piston travel stops to limit pintle travel to 0.200-in.

Another desirable change is the addition of a shoulder in the actuator cover bore to allow easier shrink fit installation of the gold plated sleeve. With the present hardware there are two potential installation problems. If the sleeve is not positioned properly, it can bottom in the bore and restrict the actuation gas flow. Another possibility is that the sleeve can "freeze" in the bore before it is flush with the surface. This condition could result in reduced stroke capability. The addition of a shoulder in the cover should eliminate the potential assembly difficulties mentioned.

A third change is the addition of a shoulder in the 0.1875-in. diameter actuator bleed plug hole. This shoulder would provide a stop for easier installation of the check valve.

VI. TESTING

The tests performed during the valve improvement effort were directed toward confirming satisfactory lead-lag operation, demonstration of low temperature functional capability, and determination of propellant flow effects. The tests conducted included ambient storage functional tests, LN_2 cycling, and liquid fluorine (LF_2) flow cycling. LF_2 was chosen for cycle tests as a significantly lower cost option that would effectively demonstrate compatibility with the design oxidizer, OF_2. Test costs flowing both diborane and oxygen defluoride were prohibitive. LF_2 tests could be performed more cheaply than OF_2 tests because a fluorine valve flow test setup was available from test work performed under Contract NAS 3-12035, Space Storable Oxidizer Valve.

A. AMBIENT STORAGE

A short term, ambient, dry storage test was prompted by results observed on another metal seal valve program being performed under Contract NAS 3-12035. One of the seals being used on the NAS 3-12035 Space Storable Oxidizer Valve (SSOV) program is made from beryllium nickel. The beryllium nickel seal contacts an electrolyzed Inconel 718 seat. This is the same material combination being used in one bore of the bipropellant valve on this program. During work on the SSOV program, on two occasions increased leakage was noted after the assembled valve had set for periods of 2 to 3 weeks and was then operated. Although the seal and seat materials are the same, there are physical differences between the two valves. A brief test on the all-metal bipropellant valve was considered desirable to determine whether a similar leakage increase might result from ambient storage.

A beryllium nickel seal was installed in one bore of the valve used for prior testing. The assembly was leak checked at 200 psig with GHe after 5 manual open-close cycles, stored for 18 days, and leak checked again after 5 manual cycles. At the start of the storage test the leak rate was

VI, A, Ambient Storage (cont.)

2.09×10^{-4} scc/sec. After storage and 5 cycles the leak rate was 4.75×10^{-4} scc/sec. After one more cycle, a leak check showed no bubbles in 5 minutes which is a leak rate of less than 3.3×10^{-4} scc/sec with the leak meter used for these tests. Examination of the valve seat after disassembly did not reveal any evidence of metal transfer.

B. LEAD-LAG OPERATION

A series of dry cycle tests were conducted with a lead-lag pintle arrangement to evaluate the effects of the unbalanced load on the actuator guide and on valve sealing capability. The test consisted of a series of dry cycles with the left pintle as the lead pintle and then a series with the right pintle as the lead pintle. During these tests, periodic actuator pressure readings were taken to determine whether the friction load increased. Also, shutoff seal leakage was checked to determine any adverse effects of lead-lag operation.

The valve was assembled with beryllium nickel seal S/N 2 in the left bore and beryllium copper seal S/N 2 in the right bore. The initial assembly had the left pintle as the leading, or longer stroke pintle. Both seals had less than 3.3×10^{-4} scc/sec leakage at 200 psi helium pressure as installed. During setup and checkout of the test setup, the valve was cycled 105 times. One hundred cycles were with slow travel times approximately 0.130 sec open and 0.080 sec closing. Five cycles were with travel times of about 0.015 sec. A leak check at this point showed the lag pintle with zero bubble leakage. The lead pintle was zero at 50 and 100 psig but leaked 28×10^{-4} scc/sec at 200 psig (Table VI shows leak rates and conditions for this test series).

VI, B, Lead-Lag Operation (cont.)

Fifty dry cycles were run with travel times of about 0.016 to 0.020 sec. The seals were again leak checked. Both seals had zero bubble leakage at all pressures.

The actuator was removed and the lead-lag arrangement reversed so that the right pintle would be the leading pintle. After reassembly of the actuator to the valve, the lead pintle leaked 47×10^{-4} scc/sec at 200 psig while the lag pintle had zero bubble leakage. The valve was dry cycled 50 times with travel times in the range of 0.014 to 0.020 sec and leakage checked again. Both seals leaked less than 3.3×10^{-4} scc/sec at 200 psig.

The slow pressurization tests performed in an attempt to determine actuator friction load did not provide meaningful data. The end of stroke readings were adversely affected by the friction between the shutoff seal and the seat. Full open readings were fairly consistent; however, at this position the actuator load is balanced and seat-seal friction is not a factor. Although actual friction loads could not be determined from the data, the pre and post test data indicate that cycling did not significantly increase the friction load. Cracking pressure readings before and after the test were consistent although not identical. The variations recorded, from 1 to 7 psi, include the friction effects of the actuator guide, pintle guide, potentiometer rack, and shutoff seal.

A better indication of the actuator guide performance was the condition of the guide after testing. The actuator guide and sleeve were examined after the first 50 fast cycles and again after the change in lead-lag and 50 additional cycles. The guide showed no signs of wear. The gold plated sleeve had slight wear marks in a localized area but there was no evidence of the gold being shaved or removed.

VI, Testing (cont.)

C. LN_2 CYCLING

A 100 cycle functional test with the valve immersed in LN_2 and flowing LN_2 was conducted. The objectives of this test were to determine the shutoff seal leakage at low temperature and to demonstrate valve operation at low temperature.

During final leak checks after the dry cycle, lead-lag tests, both the beryllium nickel and beryllium copper seals had zero bubble leakage in five minutes (less than 3.3×10^{-4} scc/sec). Therefore, the valve was not disassembled prior to running the LN_2 tests. The pintle nuts were set up to provide the nominal 0.150-in. stroke on both pintles and the actuator assembly was installed. Special flat lapped test flanges with spacers to accept gold plated Inconel "V" seals, manufactured by the Parker Seal Co., were installed on the valve inlet and outlet. The poppet seals were again leak checked and had zero bubble leakage. The pintle bellows, actuator bellows, and flange seals were satisfactorily leak checked. The valve was then installed in the LN_2 test setup shown schematically on Figure 11.

The poppet shutoff seals were leak checked at ambient temperature using a mass spectrometer. The beryllium nickel seal leaked 5.51×10^{-5} scc/sec at 80 psig. The beryllium copper seal leakage stayed within the range of the leak detector up to 200 psig. At 200 psig the leakage was 2.37×10^{-5} scc/sec. The valve was immersed in LN_2 up to the level of the potentiometers. After the temperature had stabilized, a bubble leak check showed no bubbles in 5 minutes at 200 psig on both bores (less than 3.3×10^{-4} scc/sec).

Fifty cycles were performed while flowing LN_2 through the valve. Valve travel times were 0.013 to 0.015 sec open and 0.011 to 0.014 sec closing. A leak check performed at LN_2 temperature after 50 cycles showed 67×10^{-4} scc/sec leakage on the beryllium copper seal. The bore containing the

VI, C, LN_2 Cycling (cont.)

beryllium nickel seal showed a varying leak rate ranging from about 0.001 to 0.011 scc/sec with no pressure applied to the inlet. This indicated that some leakage past one of the joints in the submerged plumbing was occurring. Leak rates with pressure applied were also variable. Recorded leakage ranged from 0.038 scc/sec at 50 psig to 0.19 scc/sec at 200 psig. Even allowing for a variable tare leakage, the shutoff seal leakage was significant.

Fifty additional LN_2 cycles were run and another leak check performed. The beryllium nickel seal now indicated a leak rate of about 1 scc/sec at 100 psig. Beryllium copper seal leakage had increased to 0.0118 scc/sec at 200 psig. The valve was removed from the test setup and allowed to warm to ambient temperature. An ambient leak check showed both seals having low leak rates. The beryllium nickel seal leakage was 7.5×10^{-4} scc/sec and the beryllium copper seal leakage was 4.05×10^{-4} scc/sec, both at 200 psig. The actuator and pintle bellows were leak checked and no leaks were found.

The valve was disassembled and hardware examined. The valve seats looked good with no evidence of scratching or wear. The beryllium copper seal had an even wear pattern about 0.003 to 0.004-in. wide but had no significant scratches or surface deformation. The beryllium nickel seal did not have a uniform wear pattern and 3 scratches across the contact area were noted. Figure 12 is a photograph of the damaged area. These scratches are believed to be the major cause of the high leakage at LN_2 temperature. The cause of the scratches is not known. The length and proximity of the scratches are such that a contaminant particle that subsequently got flushed through could have been the cause.

VI, Testing (cont.)

D. LF_2 CYCLING

The LF_2 test was to consist of 1,000 functional cycles while flowing 1.99 lb/sec LF_2 through each bore of the valve. Leak checks were to include an ambient leak check after system passivation, a cryogenic leak check after 10 cycles, an ambient check after 100 cycles and both ambient and crygenic leak checks after 1,000 cycles. The test was performed in the J 4A test facility.

1. Valve Assembly and Checkout

Following the LN_2 test, the valve was completely disassembled, all hardware cleaned in a sonic cleaner, and the valve reassembled on a laminar flow bench in a controlled clean room. The valve was assembled with beryllium nickel seal S/N 1 in the left bore and beryllium copper seal S/N 1 in the right bore. Initial leak checks were satisfactory but after 10 dry cycles, the beryllium nickel seal leaked 7.5×10^{-4} scc/sec which was above the desired leak rate.

During disassembly and rework, the beryllium nickel seal was damaged. Beryllium nickel seal S/N 2, which had been used previously, was repolished, cleaned and installed. Deflection settings were 0.0055-in. on the beryllium nickel seal and 0.0048-in. on the beryllium copper. The pintles were set for simultaneous lift-off with a stroke of 0.137-in. and the cracking and full lift pressures were checked. The shut-off seals were leak checked before and after 10 dry cycles. Both seals had zero bubbles in 5 minutes on both tests. The inlet and outlet flanges were installed with gold plated Inconel "V" seals and the flange joints leak tested. A final cleanliness verification was performed and the assembly was sent to the test facility.

VI, D, LF_2 Cycling (cont.)

2. Test Setup

A mockup bipropellant valve was used for plumbing the test setup. The test stand flow loop was essentially the same as that used on the SSOV flow test. Modifications were made to accommodate the bipropellant valve. A large metal box was constructed to allow immersion of the test valve, downstream shutoff valves, and connecting plumbing in LN_2 for cryogenic leak tests. The required flow plumbing, helium actuation supply plumbing, and instrumentation were installed. Photographs of the test setup are shown on Figures 13, 14, and 15. The workhorse actuation pilot valve was wrapped with an electrical strip heater to avoid problems caused by repetitive operation with cold gas. Burn wires were wrapped around various joints in the system to provide a shutdown signal in the event of a fluorine leak.

The leak test arrangement used the water displacement method. The volume between the test valve and the downstream shutoff valves was plumbed to have this volume immersed in LN_2 for temperature control. Both stainless steel and tygon tubing were used to direct leakage to water filled, inverted, 10 cc graduates. The relatively large downstream test volume and the compliance of the tygon tubing raise some doubts as to the accuracy of leak indications in the 1×10^{-4} scc/sec range. Leak rates of 1×10^{-2} scc/sec are considered quite readily detected by this test arrangement. Other options were considered; however, cost and schedule restraints effectively eliminated these more complex alternates.

3. Test Results

The test bipropellant valve was installed in the setup. The valve timing was adjusted to provide opening and closing travel times of 0.010 to 0.012 seconds. An ambient leak test of the shutoff seals was

VI, D, LF_2 Cycling (cont.)

conducted after system passivation using the water displacement method. Leakage results are shown on Table VII. This initial leak check showed no bubble leakage on both seals.

Liquid fluorine was admitted to the system for flow cycling. The first flow cycle was 35 seconds to assure full system bleed-in and to check flow rates. The measured flow was about 5% higher than the nominal 1.99 lb/sec for each flow bore and the pressure drop across the valve was about 8 psi. Valve travel times for the first ten cycles were in the range of 0.004 to 0.010 sec opening and 0.007 to 0.010 sec closing. A cryogenic leak check conducted after 10 cycles again showed no bubble leakage; however, the leak data is subject to some doubt because of the setup as is discussed in Section VI,D,2 above.

Cycles 11 through 100 were completed without any problems except that one potentiometer trace shifted indicating potentiometer wiper slippage. Travel times during this series of cycles were 0.004 to 0.010 sec opening and 0.008 to 0.010 closing. An ambient leak check after 100 cycles showed zero bubbles on the beryllium nickel seal; however, the beryllium copper seal leaked 856 x 10^{-4} scc/sec at 200 psig.

During the next series of cycles, several anomalies occurred. Both potentiometer traces indicated wiper slippage. At about 125 cycles, the pilot valve failed to operate. No cause for this failure was found and energization was tried again. The valve functioned so cycling was continued. Starting at about cycle 132, the potentiometer trace for the pintle with the beryllium copper seal showed about 1/2 normal travel and by cycle 148 was only showing about 1/3 normal travel. Also, opening travel times were down to 0.002 to 0.003 seconds. At cycle 160, the pilot valve again failed to operate. A review of conditions, resulted in suspension of testing. A cryogenic leak

VI, D, LF_2 Cycling (cont.)

check after 160 cycles showed leak rates of 0.182 scc/sec for the beryllium nickel seal and 0.833 scc/sec for the beryllium copper seal. A subsequent ambient leak check with the valve still in the test facility produced leak rates of 0.0685 scc/sec for the beryllium nickel seal and 0.370 scc/sec for the beryllium copper seal. The valve was removed from the test facility and returned to the Controls Laboratory for disassembly.

4. Posttest Checkout and Disassembly

The valve was leak checked as received from the J4a test facility. The valve had not been operated since completion of flow testing two weeks previously. The beryllium nickel seal showed no bubble leakage while the beryllium copper seal leaked 0.054 scc/sec at 200 psig. The pintle bellows and actuator bellows were leak checked and no leaks were detected. Inlet and outlet flange seals were checked and displayed no bubble leakage. Cracking and full lift pressure tests were performed. Cracking pressure was about 15 psi lower than before the cycle tests. Full lift pressure was about 47 psi higher than before the LF_2 tests. Also the hysteresis was much greater than before the test. The significance of these readings relative to shutoff seal performance is discussed in Section VII.A.5.

After initial tests, the actuator assembly was removed. The spring retainer on the pintle having the beryllium copper seal was cocked indicating that the potentiometer drive rack was binding in the guide bore. The potentiometer rack retaining nuts were removed. This allowed the spring retainer to return to the normal position. A 200 psig helium leak check showed zero bubble leakage on the beryllium nickel seal and 0.0351 scc/sec on the beryllium copper seal. The pintle with the beryllium copper seal was tapped lightly on both ends and the leak check repeated. There was no bubble leakage for 300 sec with 200 psig GHe.

VI, D, LF_2 Cycling (cont.)

The valve was completely disassembled and parts examined. The following conditions were noted:

Actuator - the actuator guide showed no significant evidence of wear. The gold plated guide sleeve had several areas of local rubbing that looked about the same as prior to LF_2 testing. The surface was bright and shiny over the stroke contact length. A light haze was noted between the contact lands. This haze was removed by light wiping. Figures 16 and 17 are photographs of the actuator guide components after testing.

Valve body - no body damage or attack was noted except the potentiometer rack guide bores. The seal seat had rings in the seal contact area. This contact area appeared to have fine particles of material some of which were from the seal as indicated by the copper color tinge in the one bore.

Pintle guides - both guides had scratches across the surface in the direction of pintle travel as shown on Figure 18. The body did not have comparable marks. These same guides had been used on prior tests with the first valve body and scratches were found on the first body. The majority of the guide scratching probably occurred during the earlier tests which included a 1000 cycle test.

Seals - both seals had a haze or etched appearance over the polished surface with this effect more noticeable on the beryllium copper seal. The seal contact surfaces were fairly even around the circumference. The contact line was on the edge of the beryllium copper seal. On the beryllium nickel seal, the contact line was about 0.006 to 0.008-in. below the edge of the seal. There were no significant scratches or deformities. Both seal contact lines had a somewhat darkened appearance. This was

VI, D, LF_2 Cycling (cont.)

particularly noticeable on the beryllium copper seal where the contact area was a much darker color than the rest of the seal. The seal contact areas are shown on Figure 19.

Potentiometer racks - the potentiometer rack on the beryllium copper side was galled and tightly bound in the bore. Figure 20 shows the rack after removal from the bore. The other rack also had heavy rub marks along the sides of the rack; however, it was not bound in the bore.

VII. DISCUSSION OF RESULTS

The test results showed that an all-metal valve could achieve zero liquid leakage after 1000 cycles of operation with travel times as fast as 0.005 sec. Further refinement may expand the performance and life of the valve. This section relates information obtained during testing to potential refinements and discusses the effect of various factors on valve performance.

A. SHUT-OFF SEALING

1. Seal Seat Surface Finish

To achieve a leak free metal to metal seal with reasonable loads, good surface finishes are required. With a soft-on-hard approach, the most critical surface finish is the hard material. In the bipropellant valve, the hard material is the electrolyzed Inconel 718 seat. The conical seat provided some difficulties in attaining the desired surface finish.

With the conical shape, final lapping or polishing was somewhat restricted. Plugs used as carriers for the lapping compound could be rotated but not moved axially in the seat cone. With this condition, circumferential scratching of the seat could occur. Thus as the surface finish

VII, A, Shut-Off Sealing (cont.)

was worked, there was always the potential of degrading rather than improving the surface finish.

This problem could be eliminated by design of special lapping tools that would change diameter while maintaining the correct seat angle. This would permit both rotational and axial motion. Another approach is to make the seat spherical and the seal conical. With this configuration, essentially the same seal-seat contact interface could be established. The advantage would be the use of spherical laps for polishing which should attain surface finishes better than the 3 to 4 AA achieved with the conical seat.

The major advantage of a better seat surface finish is lower load required to attain a given leak rate. Reduced loads on the seal interface could result in less seal wear, a smaller valve, and less weight.

2. Storage Effects

Data from the SSOV program and data from the storage test conducted during this program are contradictory. One shows an adverse effect of storage on leakage, the other shows no effect. This divergence indicates that further evaluation is needed.

For the planned application of the OF_2/B_2H_6 valve, several factors must be considered. The reactivity of the propellants will require a high cleanliness level for the valve. Sterilization cycles at 300°F may be required. Coast time in space may be several years duration. The combined effects of very clean hardware, high temperature, and long durations under the high seal load may result in some seal material transfer that could effect leakage during subsequent functional cycles. In addition to potential metal transfer, the possibility of material creep in the stressed seal should be considered. Relaxation or creep would result in a lower seal-seat interface stress that may change the leak rate. Thus, the storage aspect requires further consideration to assure success in the proposed application for the valve.

3. Seal Wear

A small amount of rubbing between the seat and seal occurs during normal functioning. The rubbing length depends upon the deflection setting but is normally in the range of about 0.004 to 0.006 in. This rubbing produces some seal wear. An added wear effect results from the fast closing times. The design of the seal and the pintle guide is such that a small arc of the seal edge is subjected to impact during rapid closing. The guide was designed to have enough clearance in the guide bore so that the seal could center in the conical seat. When the valve is closed, the seal establishes the pintle position. When the valve is open, the guide establishes the pintle position. The transition from the guide controlling to the seal controlling produces an impact wear effect on the seal during closing.

The 1000 wet cycle test showed seal wear to be very minor; however, dry cycle tests indicate that seal wear could be a problem. Seal wear is indicated by increased leakage as shown on Table IV, increased width of the contact line on the seal, and the color of the contact line on the seat which indicates some removal of seal material. The data shows that travel times of about 0.008 sec result in more wear than the 0.150 travel times. Also, the softer beryllium copper material is subject to more wear than the beryllium nickel.

VII, A, Shut-Off Sealing (cont.)

The primary concern with regard to seal wear is dry, functional cycles that may be required during valve processing, installation, and checkout of a vehicle. To minimize any seal wear, a method to slow travel times during dry cycles would be desirable. This could be done quite easily by adding a flow restriction in the actuation cavity vent line.

4. Pintle Guide Wear

The scratching noted on the pintle guides is a concern with regard to potential seal damage. Since the guide is located upstream of the shut-off seal, any particles that might result from continued guide rubbing might damage the seal. The low leak rates obtained after the 1000 cycle water flow test indicate that no significant damage occurred; however, the possibility exists.

This potential problem could be eliminated by analysis of the loads involved, wear analysis of the parts, and selection of materials to obtain zero wear.

5. Friction Effects on Leakage

There are several areas in the valve where friction may have an effect on the seal-seat interface load. The pintle guides, the seal rubbing on the seat, and the potentiometer racks in the guide bores may singularly or in combination reduce the load transmitted to the seal interface. A reduced seal interface load would result in higher leakage.

Evidence of the friction effects were noted during several tests. During the LF_2 cycle test, one potentiometer rack was stuck in the bore and the other rack had rub marks. The added friction from the rubbing

VII, A, Shut-Off Sealing (cont.)

racks is believed to be the cause of the high leak rates during the LF_2 tests as indicated by both seals displaying no bubble leakage after the racks were disengaged during posttest work. The same may be true of the LN_2 test where high leakage was experienced at low temperature while the posttest leakage was very low even though one seal was scratched. Friction effects were also evident during lead-lag tests involving cracking and full lift pressure checks. After a slow opening and closing, as experienced on a cracking pressure test, the shut-off seal leaked. After one cycle at the normal travel time, the seal did not leak.

Based on the LF_2 and LN_2 tests, the primary problem was the potentiometer drive rack. Before LF_2 cycle tests, the cracking and full open pressures were recorded as 109 and 150 psig respectively. After cycling, cracking was 95 psig and full open was 207 psig. These data indicate that the load on the seal-seat interface was reduced. A 14 psi change in cracking pressure converted into load per pintle is 22 lb. This represents about a 10% reduction in seal load at ambient conditions. This condition may be more severe at cryogenic temperatures as a result of slight thermal distortion affecting the alignment of the drive rack in the guide bore. Provision of greater alignment capability between the spring retainer and the rack should correct the rack rubbing condition. Use of a harder material for the rack would also be beneficial.

B. VALVE RESPONSE TIME

The total valve response time includes the time from electrical signal until the pilot valve shuttles, delay time until start of main valve travel, plus the travel time for the main valve. Only the valve travel time was defined as a goal for this program; however, all parts of the response time would have to be considered in a final application.

VII, B, Valve Response Time (cont.)

1. Travel Time

The desired travel time of 0.005 to 0.015 sec was quite readily obtained. Actual times varied dependent upon test conditions such as lead-lag setting, total stroke, inlet pressure, outlet pressure, and actuation pressure supply plumbing. Opening travel times of 0.002 to 0.003 sec were obtained during LF_2 cycling. These very fast times resulted from increased valve friction. Under normal flow conditions, the actuation pressure required to crack the poppet off the seat is lower than the pressure required to reach the full open position. With increased friction at cracking, the full open pressure can be lower than cracking pressure. Thus, when the actuation pressure is high enough to start opening, it is high enough to reach full open. Under this condition, the valve is opened by gas expansion rather than being controlled by a flow restriction such as the pilot valve or a timing orifice.

Two areas affected by rapid travel times, the shutoff seal and pintle bellows, were discussed previously. Another affected component is the potentiometer. The fast travel time causes the potentiometer wiper to slip on the shaft as was noted after about 700 cycles of water flow cycling. Low temperature accelerates the start of wiper slip. During the LF_2 test, wiper slip occurred between 54 and 98 cycles. A modification to the wiper retainer would be required to eliminate slip during extended low temperature cycling.

2. Signal Time

The pilot valve used for the test program was a workhorse unit having the desired flow capacity to obtain the 0.005 to 0.015 sec travel times. This valve was P/N BF35C-11 manufactured by the Eckel Valve Co. The

VII, B, Valve Response Time (cont.)

valve signal times were 0.012 sec open and 0.005 sec closing at ambient conditions with 250 psig supply pressure and 28 VDC. During testing, these times varied widely. Supply pressures above 250 psig and low temperatures were major factors producing longer signal times. Consistency of opening and closing signal times was not a requirement for this program; however, in a vehicle application repeatable times under all anticipated operating conditions would be desirable.

VIII. CONCLUSIONS

The results of work performed during this program demonstrate the feasibility of an all-metal valve to meet the desired functional criteria. Major conclusions are as follows:

1. Zero liquid leakage can be achieved with metal shutoff seals. The equivalent gaseous helium leak rates of 1.75×10^{-4} and 3.4×10^{-4} scc/sec were demonstrated consistently with both the beryllium nickel and beryllium copper seals.

2. The valve can operate with up to 50% lead on either pintle and achieve the target leak rate without use of special compensating springs.

3. Travel times in the range of 0.005 to 0.015 sec are easily attained with this valve.

4. Contact at the edge of the shutoff seal is not critical to effective seal performance. Used seals were repolished by conventional techniques resulting in seat contact below the edge. The leak rate or cyclic life did not appear to be degraded.

5. A cycle life of 1000 cycles is attainable. The test seals after 1000 wet cycles had leak rates of 5×10^{-4} scc/sec for a beryllium nickel seal and 25×10^{-4} scc/sec for a beryllium copper seal.

6. The basic valve and shutoff seals can operate successfully at fast travel times while flowing a highly reactive, cryogenic propellant. The LF_2 cycles demonstrated short term materials compatibility. Based on this test and comparison of propellant properties, the valve should perform satisfactorily with oxygen difluoride and diborane.

VIII, Conclusions (cont.)

7. Both the potentiometer and potentiometer drive arrangement would require improvement to reliably meet the desired performance. The potentiometers were added to aid analysis of valve performance during the test program. If position indication were needed for an application, other options such as end position proximeters could be used in lieu of a continuous indication device such as a potentiometer.

IX. RECOMMENDATIONS

The valve tested has demonstrated the ability to meet the basic functional criteria; however, additional information may permit an expanded capability for this valve as well as provide guidance for design of all metal valves for other applications. Within this context, the following recommendations are presented.

1. Analyze and evaluate the seat-seal arrangement to reduce the effects of fast closing and dry cycling. Configuration changes such as a spherical seat and conical seal may allow better surface finishes, and improved guiding which would reduce seal load and seal interface rub.

2. Correlate the relationships between surface finish, load, contact width, rubbing distance, and leakage with the analytical model predictions. An analytical model was used during the preliminary design effort to evaluate the various factors affecting leakage and wear. Evaluation of test results with controlled parameters would allow improved predictability of the analytical techniques.

3. Perform concurrent OF_2/B_2H_6 flow tests to provide confirmation of material compatibility and evaluate thermal gradient effects resulting from the propellants being at different temperatures.

IX, Recommendations (cont.)

4. Redesign the position indication arrangement to provide more reliable, longer life position indication for test work.

5. Perform detailed analysis on the dynamic effects of fast travel on bellows. Variable convolution diameters and thicknesses may be advantageous to long life.

6. Perform extended duration storage tests under conditions simulating production processes and the flight environment. Conditions not encountered during this program may have an adverse effect on the metal seal interface.

7. Investigate and evaluate pilot valves for compatibility with the bipropellant valve and the operational criteria for response time and firing duration.

BIBLIOGRAPHY

1. Advanced Valve Technology, Contract NAS 7-436, by TRW Systems Group; November 1966.

2. Advanced Valve Technology, Contract NAS 7-436, by TRW Systems Group; January 1969.

3. An Electro/Mechanical Bipropellant Valve for Use With Cryogenic and Storable Propellants, Contract AF 04(695)-197, by Aerojet-General Corporation, December 1967.

4. Basic Criteria and Definitions for Zero Fluid Leakage, JPL Technical Report 32-926; December 1966.

5. Bipropellant Shutoff Valve, Contract NAS 7-733, by Aerojet Liquid Rocket Company, December 1970.

6. Cryogenic Bellows Program, Technical Report No. 32-F, by Aerojet Liquid Rocket Company, November 1970.

7. Final Report on the Development of Analytical Techniques for Bellows and Diaphragm Design, Technical Report AFRPL-TR-68-22, by Battelle Memorial Institute, March 1968.

8. Friction Evaluation of Materials for Valve Applications, Report RN-TM-0393, by Aerojet-General Corporation, October 1966.

9. Investigation of Leakage and Sealing Parameters, Technical Report AFRPL-TR-65-153, by IIT Research Institute, August 1965.

10. Leakage Testing Handbook, Contract NAS 7-396, by General Electric Company.

11. Rocket Engine Valve Poppet and Seat Design Data, Technical Report RPL-TDR-64-68, by Rocketdyne; May 1964.

12. Stress and Elevated Temperature Fatigue Characteristics of Large Bellows, Contract AT(11-1)-GEN-8, by Atomics International, September 1964.

13. Study of Bipropellant Shutoff Valves, Contract NAS 7-733, by Aerojet-General Corporation, September 1969.

14. Study of Dynamic and Static Seals for Liquid Rocket Engines, Contract NAS 7-102, by General Electric Company, August 1964.

BIBLIOGRAPHY (cont.)

15. Study of Dynamic and Static Seals for Liquid Rocket Engines, Contract NAS 7-102, by General Electric Company, November 1965.

16. Study of Dynamic and Static Seals for Liquid Rocket Engines, Contract NAS 7-436, by General Electric Company, May 1968.

TABLE I

DESIGN REQUIREMENTS

<table>
<tr><td colspan="4">APPLICABLE FLUIDS</td></tr>
<tr><td colspan="2">FLOW PASSAGES</td><td colspan="2">ACTUATION</td></tr>
<tr><td>Diborane (B_2H_6)</td><td>Oxygen Difluoride (OF_2)</td><td>Gaseous Helium</td><td>Gaseous Nitrogen</td></tr>
<tr><td colspan="4">FLUID PRESSURES, psig</td></tr>
<tr><td></td><td>Operating</td><td>Proof</td><td>Burst</td></tr>
<tr><td>PROPELLANT CAVITIES</td><td>200</td><td>400</td><td>600</td></tr>
<tr><td>ACTUATION CAVITIES</td><td>250</td><td>500</td><td>750</td></tr>
<tr><td colspan="4">FLOW RATE, lb/sec</td></tr>
<tr><td>Fuel</td><td>0.57</td><td>Oxidizer</td><td>1.99</td></tr>
<tr><td colspan="4">PRESSURE DIFFERENTIAL AT RATED FLOW: 25 psig</td></tr>
<tr><td colspan="4">LEAKAGE RATE, scc/sec helium</td></tr>
<tr><td>External</td><td>1×10^{-7}</td><td>Internal</td><td>1.75×10^{-4}</td></tr>
<tr><td colspan="4">VALVE TRAVEL TIME, sec</td></tr>
<tr><td>Open</td><td>0.005 to 0.15</td><td>Close</td><td>0.005 to 0.015</td></tr>
<tr><td colspan="4">ENDURANCE LIFE: 1000 cycles, minimum</td></tr>
<tr><td colspan="4">STORAGE LIFE: 10 years</td></tr>
<tr><td colspan="4">TEMPERATURE, °F</td></tr>
<tr><td>Operating</td><td>-320 to +100</td><td>Nonoperating</td><td>-320 to +300</td></tr>
<tr><td colspan="4">OTHER ENVIRONMENTS</td></tr>
<tr><td colspan="4">Zero g; Radiation; Shock; Vibration; Thermal Shock; Sterilization; Thermal Cycling, and Hard Vacuum</td></tr>
<tr><td colspan="4">OTHER DESIGN FACTORS</td></tr>
<tr><td colspan="4">The design shall be an all-metal valve
The valve shall have the capability to provide either a 50% fuel or oxidizer lead.
Valve position indicators shall be provided.
Inlet and outlet valve assembly interfaces shall be parallel.</td></tr>
</table>

TABLE II

VALVE COMPONENT MATERIALS

Component	Preferred Material	Alternates
Body, valve	Inconel 718	
Guide-poppet	Electrolyzed CRES 304	Electrolyzed CRES 347
Seal	Beryllium Nickel, Beryllium Copper	
Spring	CRES 17-7 PH	
Shaft, poppet	Inconel 718	
Bellows, shaft	Inconel 718	CRES 321, 347
Body, actuator	CRES 304L	CRES 347
Piston, actuator	CRES 304L	CRES 321, 347
Bellows, actuator	Inconel 718	CRES 321, 347
Tube and flange weldment	CRES 304L	CRES 347

TABLE III

DRY CYCLE RESPONSE TEST DATA

Cumulative Cycles	Travel Time, sec		*Leak Rate, scc/sec $GN_2 \times 10^{-4}$					
			Beryllium Copper			Beryllium Nickel		
	Open	Close	50 psi	100 psi	200 psi	50 psi	100 psi	200 psi
0	-	-	0*	10	20	160	330	1010
10	1.2 to 0.025	1.0 to 0.050	-	-	17	-	-	910
30	0.025 to 0.011	0.050 to 0.014	0	5.5	14	110	307	970
40	0.011	0.014	-	-	14	-	-	1010
50	0.010	0.011	0	5.5	16	100	330	1050

*Zero leakage denotes no bubble in 300 sec.

TABLE IV

DRY CYCLE TEST DATA

Test Conditions	Number of Cycles	*Leak Rate, scc/sec GHe, x 10^{-4} Beryllium Copper 50 psi	Beryllium Copper 100 psi	Beryllium Copper 200 psi	Beryllium Nickel 50 psi	Beryllium Nickel 100 psi	Beryllium Nickel 200 psi
100 dry cycles, travel time 0.006 to 0.008 sec	0	0		0	60	150	360
	20	0	0	0	53	167	470
	100	27	77	233	197	500	1,460
100 dry cycles, travel time 0.150 sec	0	12	21	47	0	0	0
	25	-	-	350	-	-	0
	50	-	-	500	-	-	0
	75	-	-	890	-	-	0
	100	93	247	710	0	0	0

*Zero leakage denotes no bubbles in 300 sec.

TABLE V

WET CYCLE TEST DATA

Test Conditions	Number of Cycles	Leak Rate, scc/sec GHe x 10^{-4}* Beryllium Copper 50 psig	Beryllium Copper 100 psig	Beryllium Copper 200 psig	Beryllium Nickel 50 psig	Beryllium Nickel 100 psig	Beryllium Nickel 200 psig
100 wet cycles, travel time 0.008 to 0.011 sec	0	20	70	100	0	0	0
	100	7	17	31	0	0	0
1000 wet cycles, travel time 0.008 to 0.011 sec	0	0	0	0	0	0	0
	500	2	15	57	0	0	0
	1000(before dehydration)	19	36	6	0	0	0
	1000(after dehydration)	11	19	25	3	5	5

*Zero leakage denotes no bubbles in 300 sec.

TABLE VI

LEAD-LAG DRY CYCLE TEST DATA

Test Condition	Travel Time	*Leak Rate, scc/sec GHe X 10^{-4} Beryllium-Copper, psig 50	100	200	Beryllium-Nickel, psig 50	100	200
at build-up w/o actuator	-	0	0	0	0	0	0
at build-up w/actuator	-	0	0	0	0	0	0
after 105 slow cycles	open .080 sec close .130 sec	0	0	0	0	0	28^{+}
after 50 fast cycles	open .016 sec close .020 sec	0	0	0	0	0	0
after reversing pintle lead	-	0	17^{+}	47^{+}	0	0	0
after 100 fast cycles	open .014 sec close .020 sec	0	0	0	0	0	0

* Zero leakage denotes no bubbles in 300 seconds ($< 3.3 \times 10^{-4}$ scc/sec)

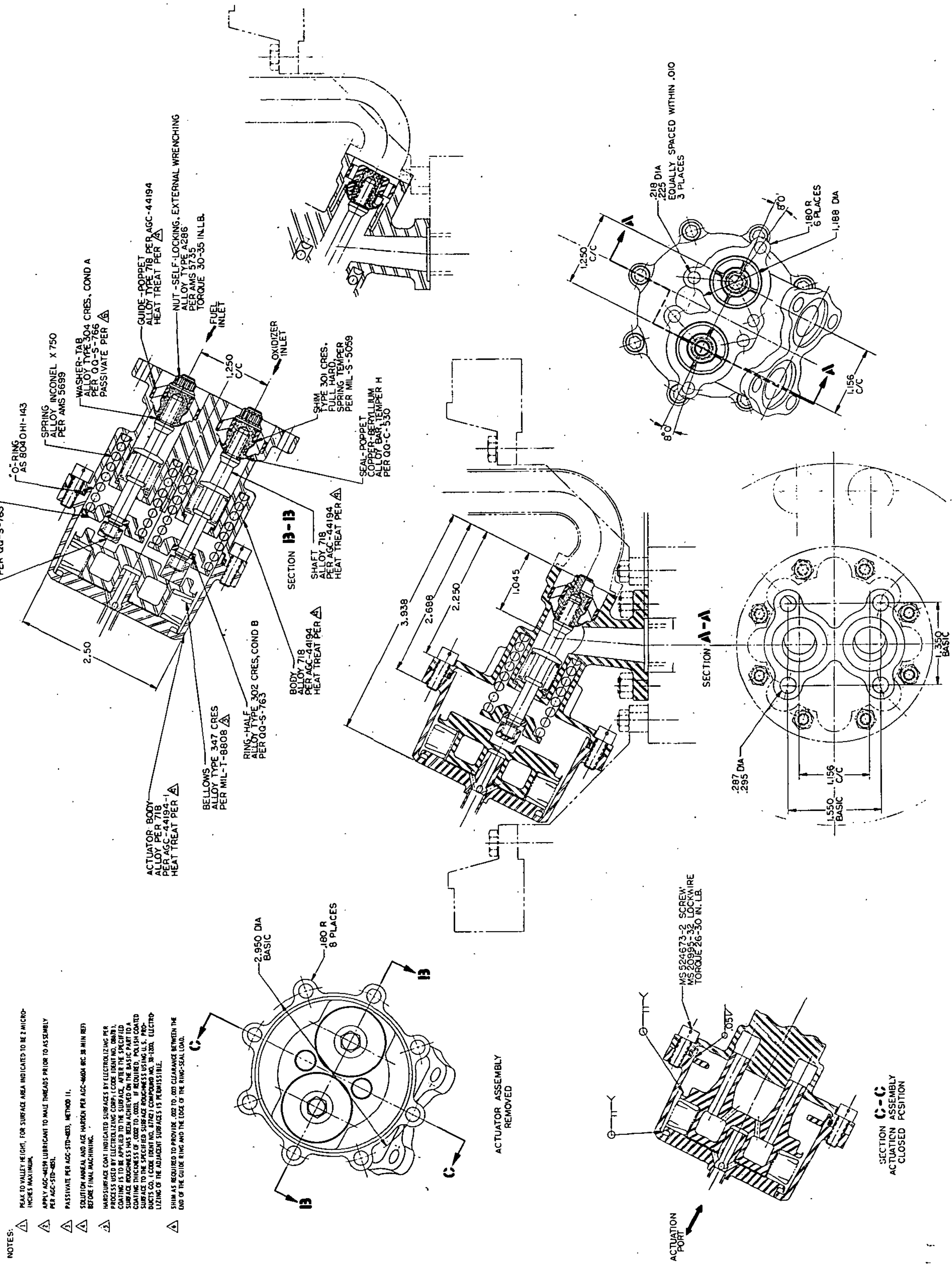
+ On lead pintle.

TABLE VII

LF_2 CYCLE TEST LEAKAGE

Test Condition	Test Facility	Cumulative Cycles	GH_e Leak Rate, scc/sec x 10^{-4*} Beryllium Nickel 50 psig	200 psig	Beryllium Copper 50 psig	200 psig
ambient (pre-test)	J4a	0	0	0	0	0
cryogenic	J4a	10	0	0	0	0
ambient	J4a	100	0	0	0	856
cryogenic	J4a	160	449	1820	1720	8330
ambient	J4a	160	213	685	953	3700
ambient (as received)	Controls Lab	160	0	0	40	540
ambient (after rack bind release)	Controls Lab	162	0	0	57	351
ambient (after tapping pintle)	Controls Lab	162	-	-	0	0

*Zero denotes no bubbles in 5 minutes.



Valve, Poppet Bipropellant-Direct Actuation

Figure 1

Equations and parameters are based on information contained in Investigation of Leakage and Sealing Parameters, Technical Report AFRPL-TR-65-153, by IIT Research Institute, August 1965

(1) $$Q_L = \frac{(P_1^2 - P_2^2)\, wh^3}{24\, \mu\, L\, P_o}\left(1 + 6.39\, \varepsilon\, \frac{\bar{\lambda}}{h}\right)$$

Q_L = leak flow, atm. in.^{3}/sec

P_1 = upstream pressure, psia

P_2 = downstream pressure, psia

w = length of sealing edge normal to flow, in.

L = sealing edge width in direction of flow, in.

h = equivalent leak path height, in.

μ = fluid viscosity, lb-sec/in.^{2}

P_o = pressure used for selection of μ and λ psia

ε = gas constant

$\bar{\lambda}$ = mean free path of gas, in.

(2) h^3 = f(R) empirical relationship

R = modified stress ratio

(3) $$R = \frac{W^{2/n'}}{A_a\, \sigma_m}$$

W = applied normal load, lb

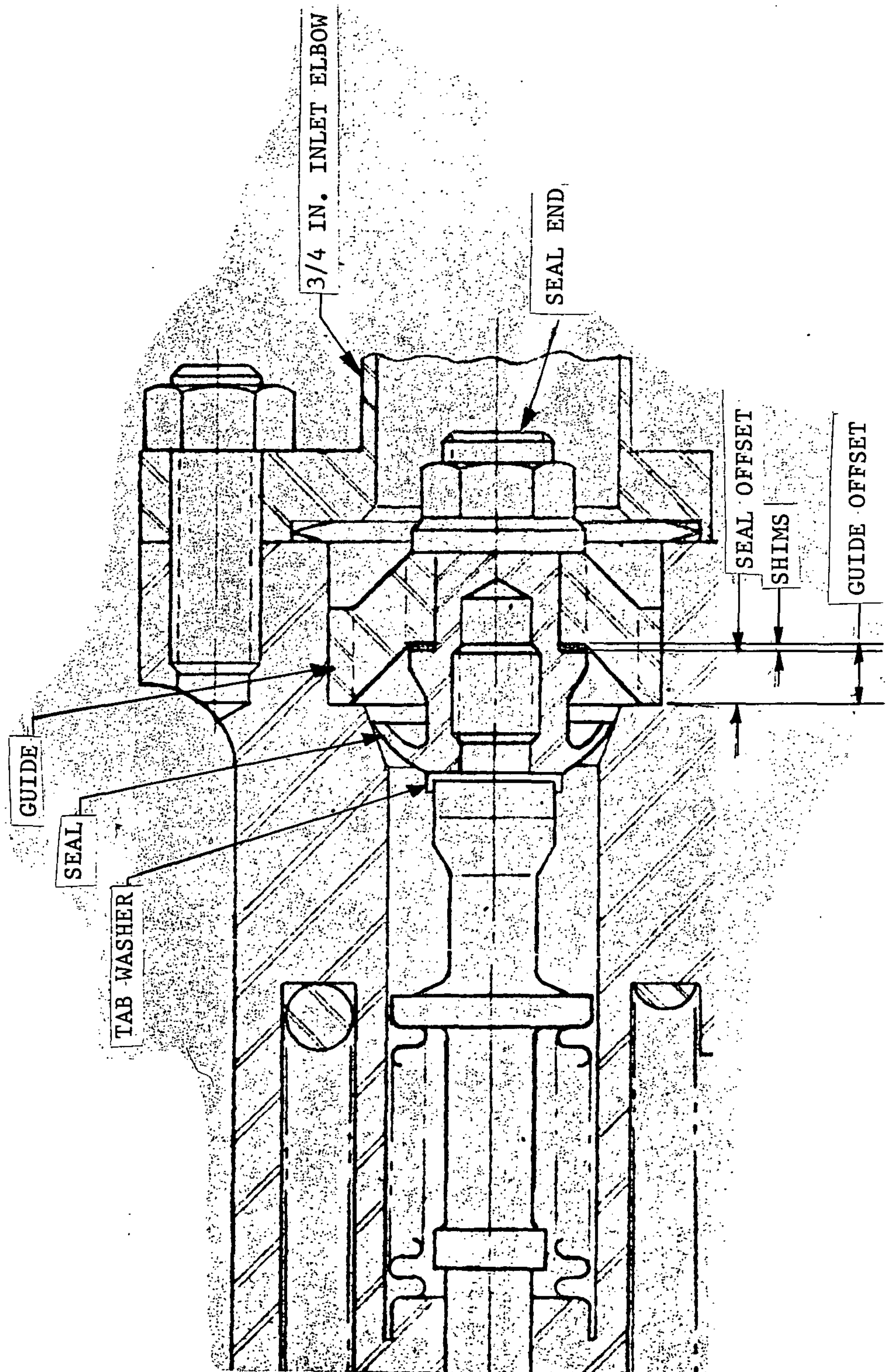
n' = Meyer index

A_a = apparent contact area, in.^{2}

σ_m = Meyer hardness, lb/in.^{2}

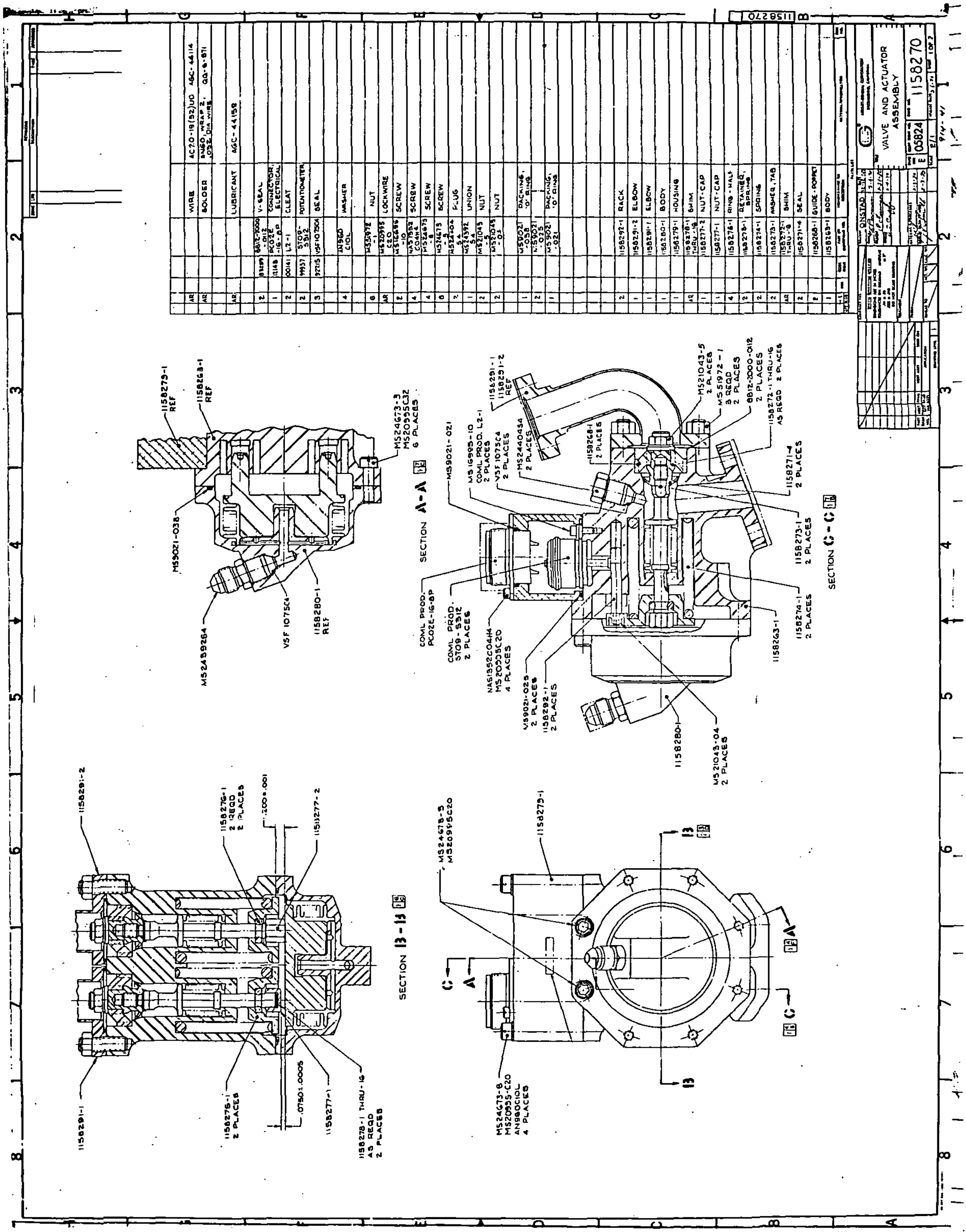
Equations for Calculation of Sealing Loads

Figure 2



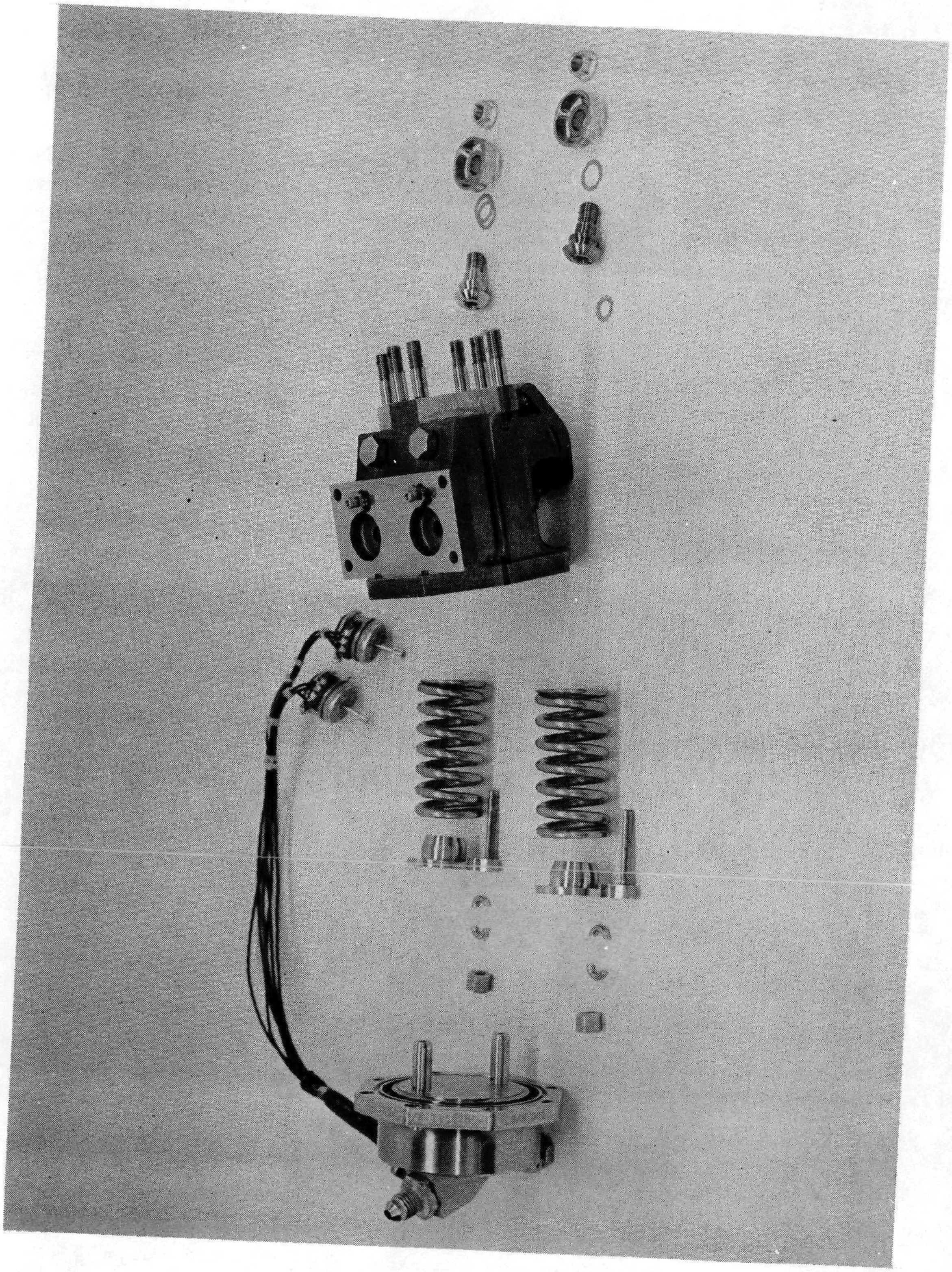
Shutoff Seal-Seat Configuration

Figure 3



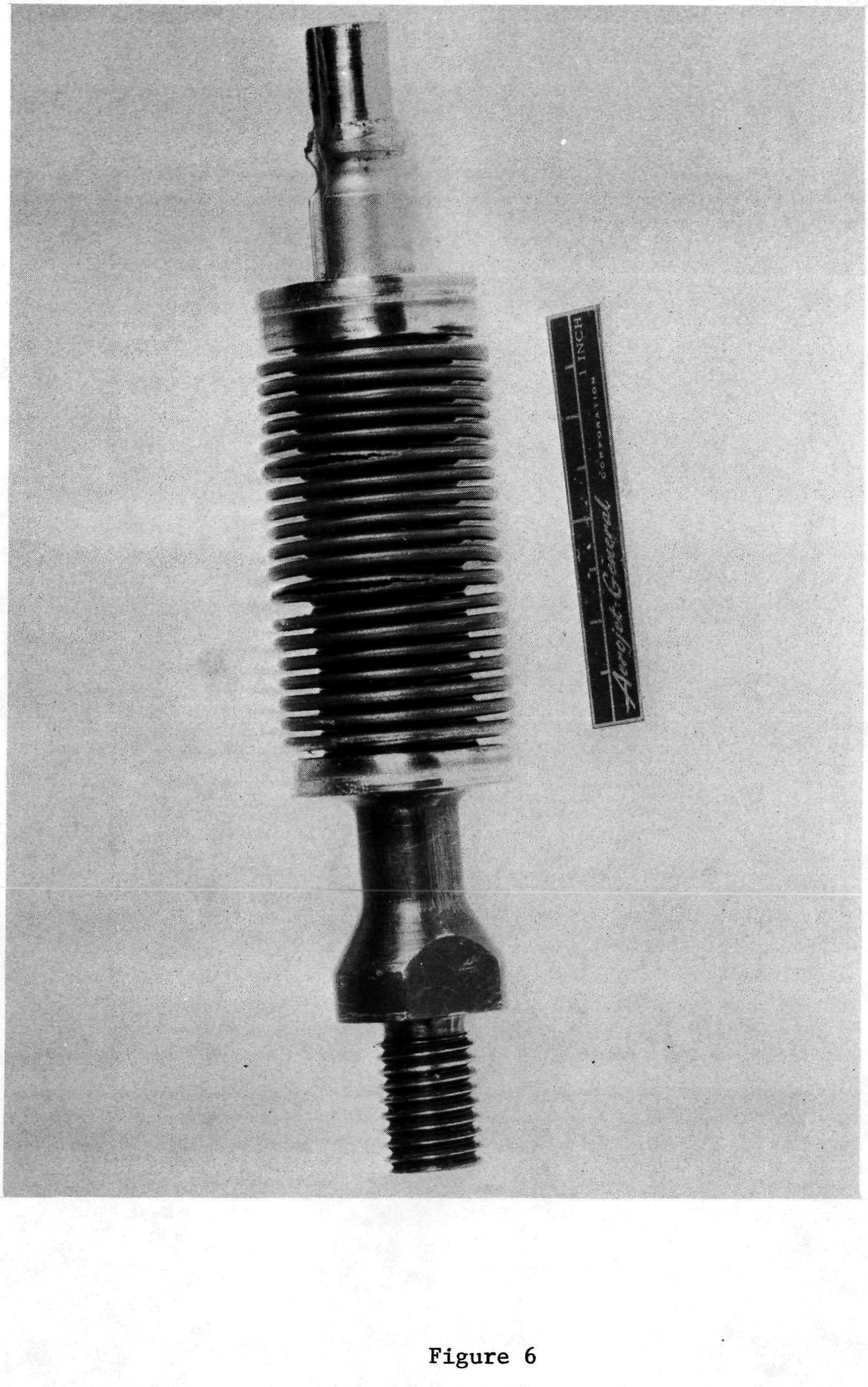
Valve Actuator Assembly

Figure 4



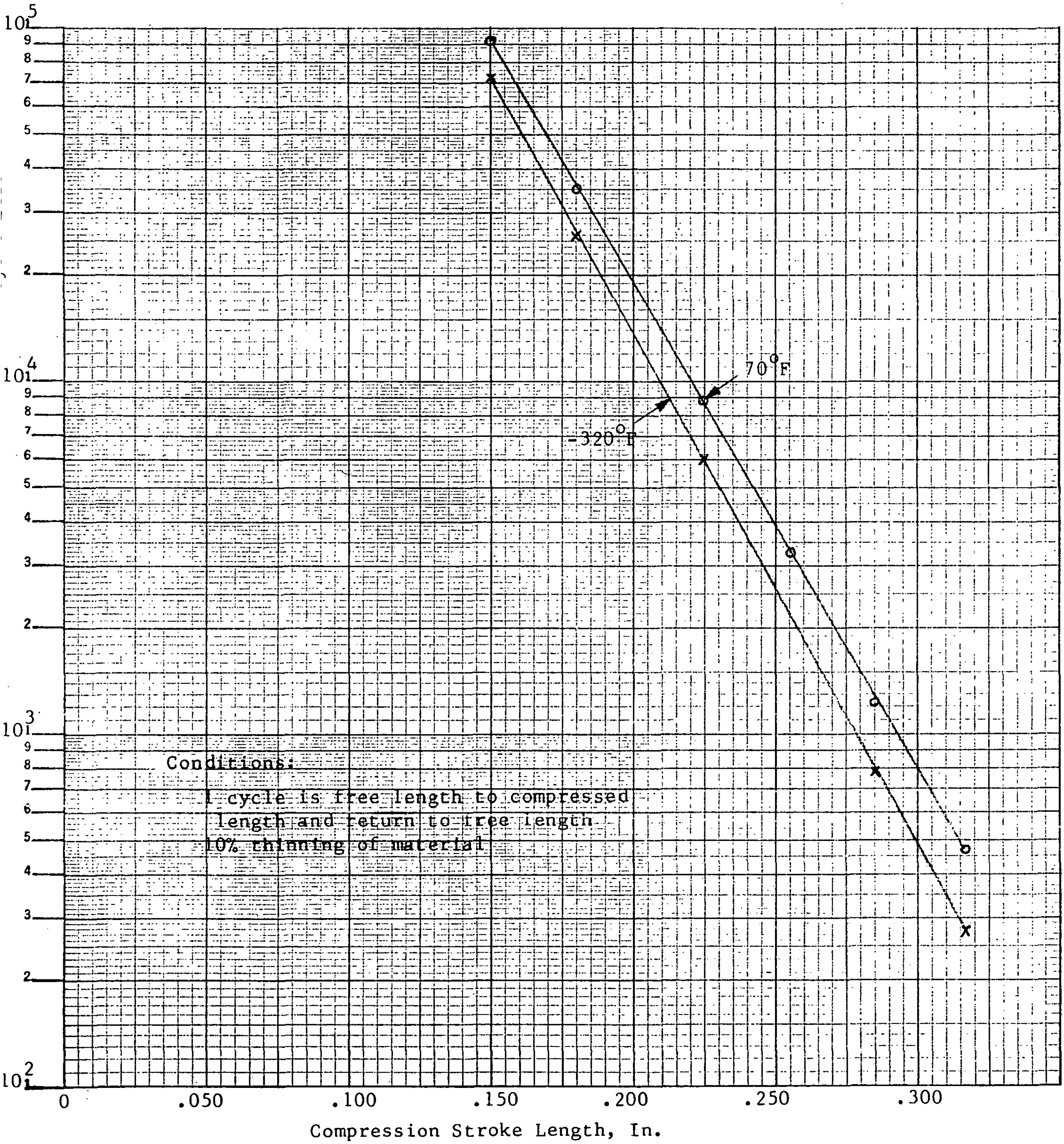
Bipropellant Valve Components

Figure 5



Failed Pintle Bellows

Figure 6



Shaft Bellows Cycle Life vs Compression Stroke Length

Figure 7

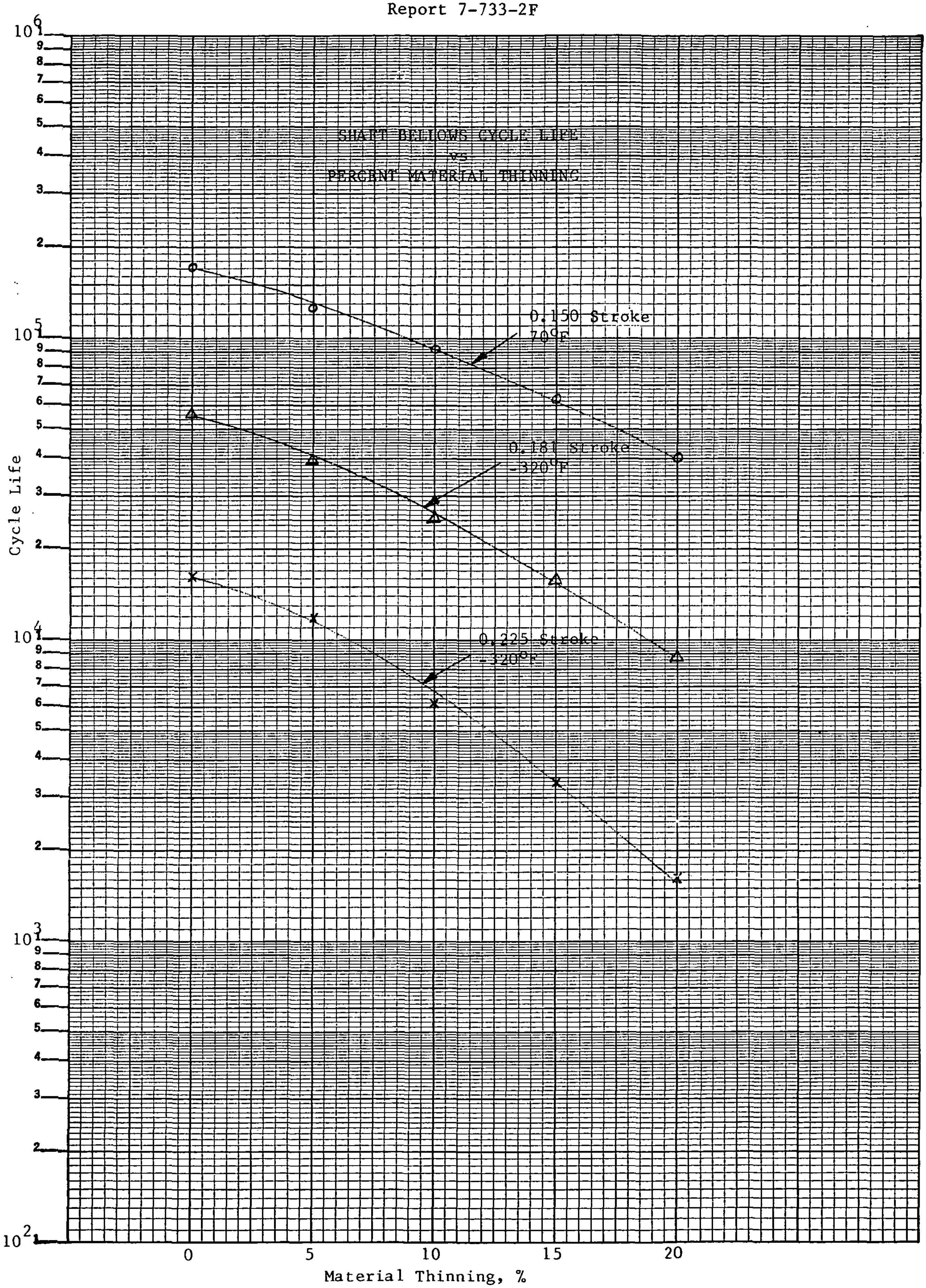
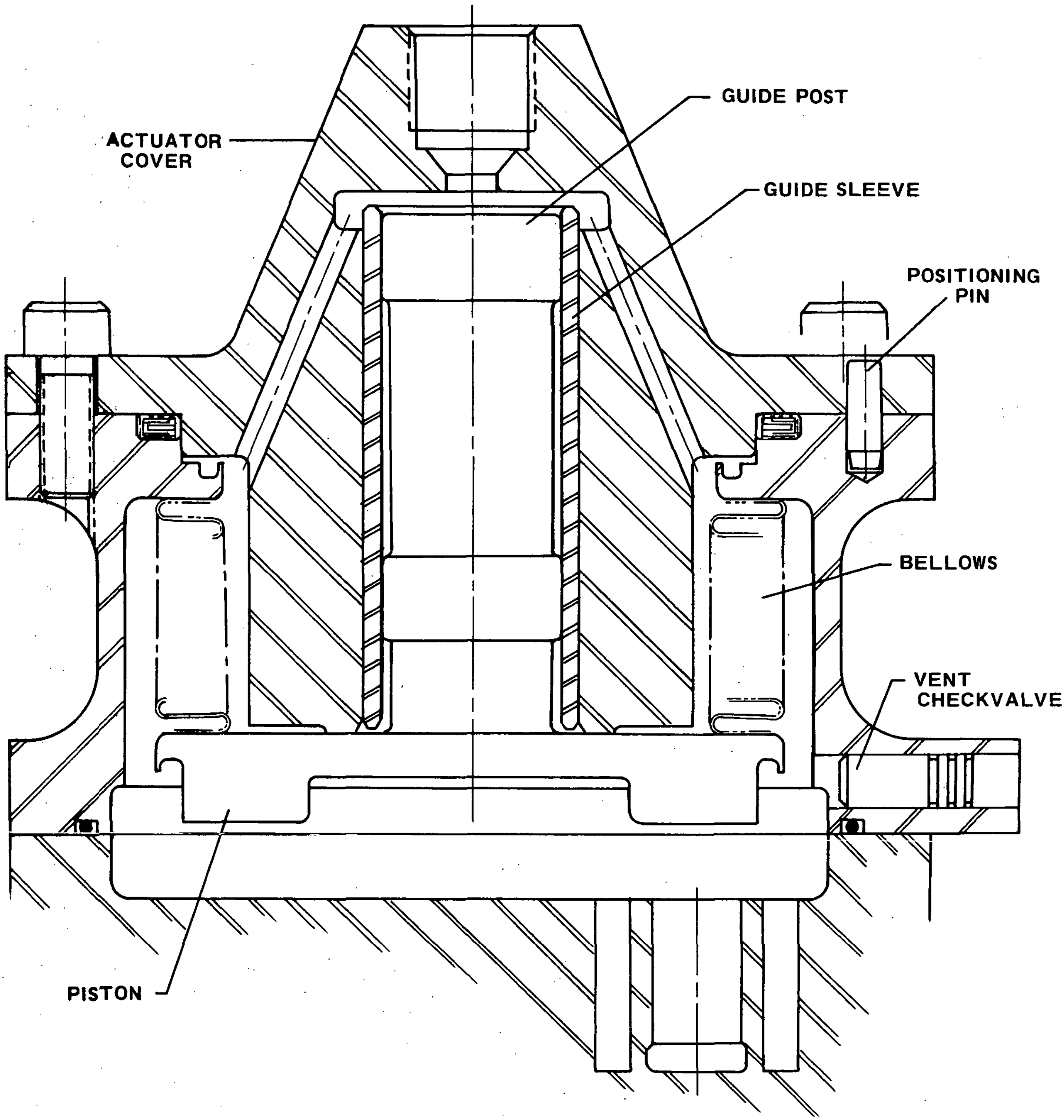
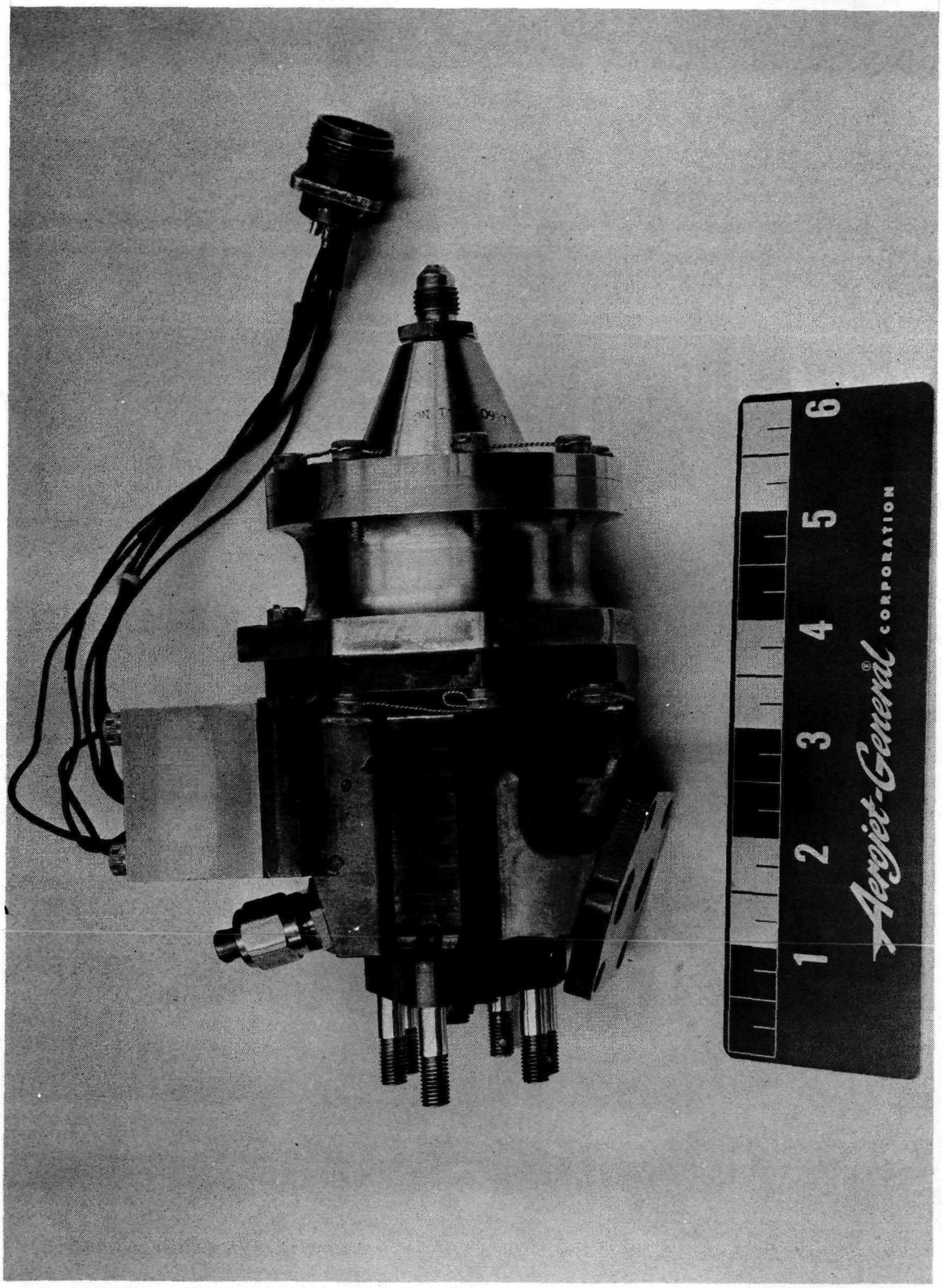

SHAFT BELLOWS CYCLE LIFE
vs
PERCENT MATERIAL THINNING
0.150 Stroke
70°F
0.181 Stroke
-320°F
0.225 Stroke
-320°F
Cycle Life
Material Thinning, %
0
5
10
15
20

Figure 8



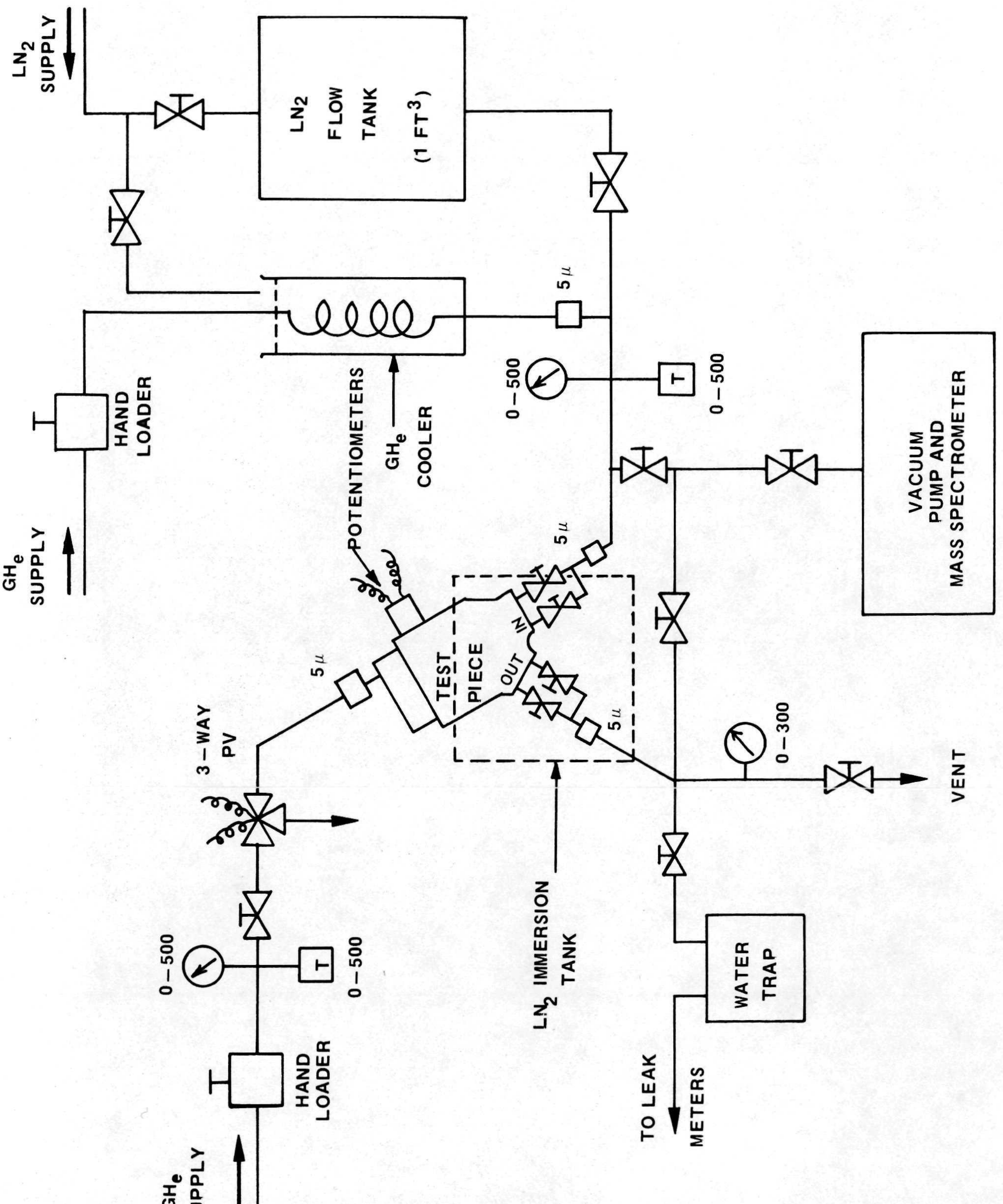
Actuator Guide Concept

Figure 9



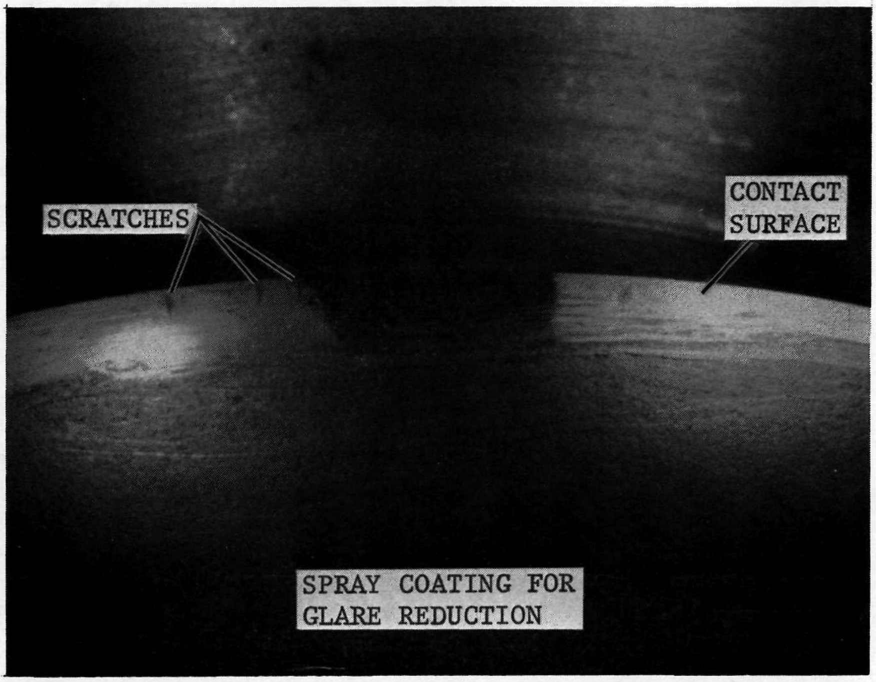
Bipropellant Valve with Improved Actuator

Figure 10



LN_2 Flow Test Schematic

Figure 11



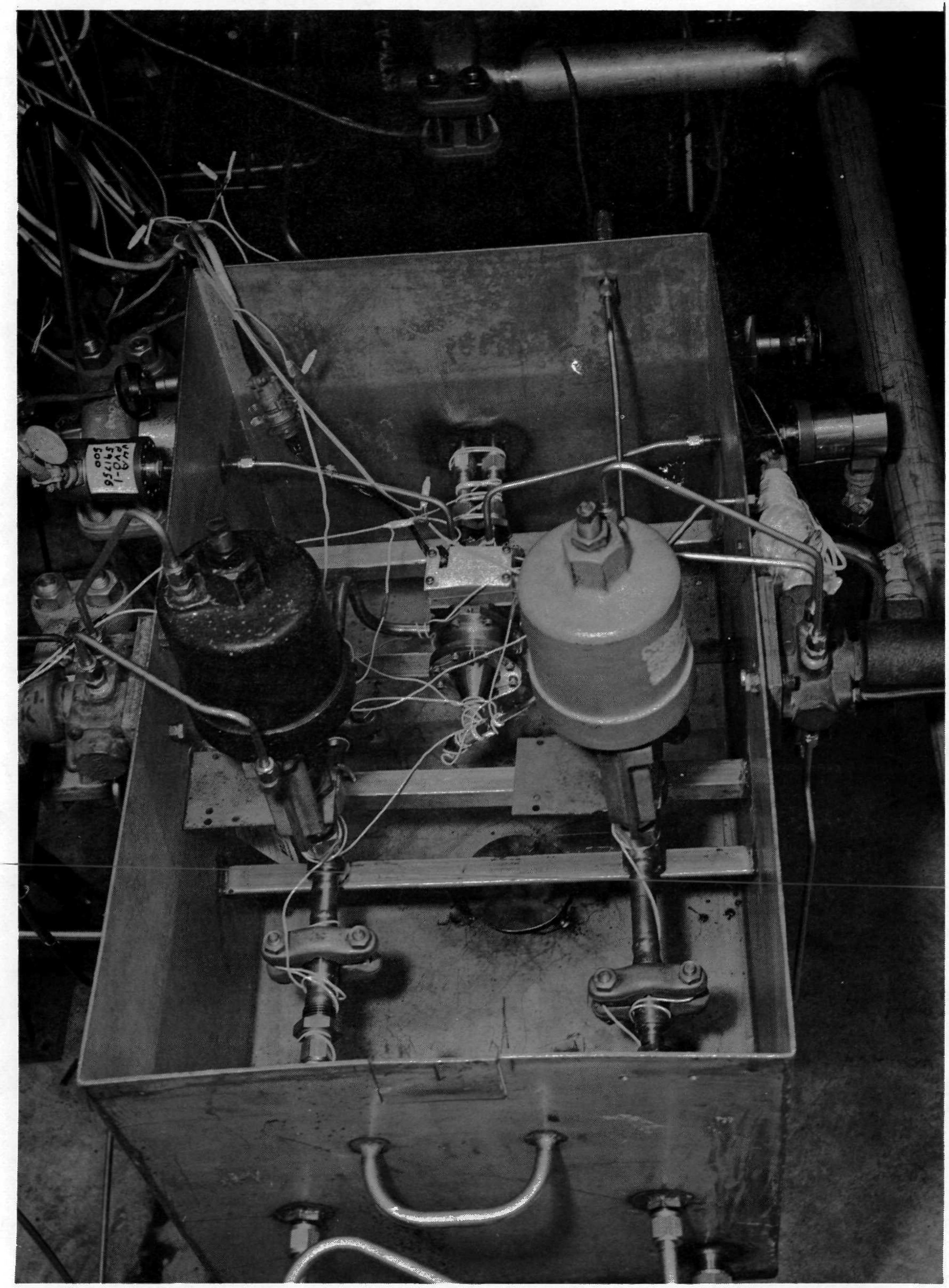
16X MAGNIFICATION

Beryllium Nickel Seal, Post LN_2 Test

Figure 12

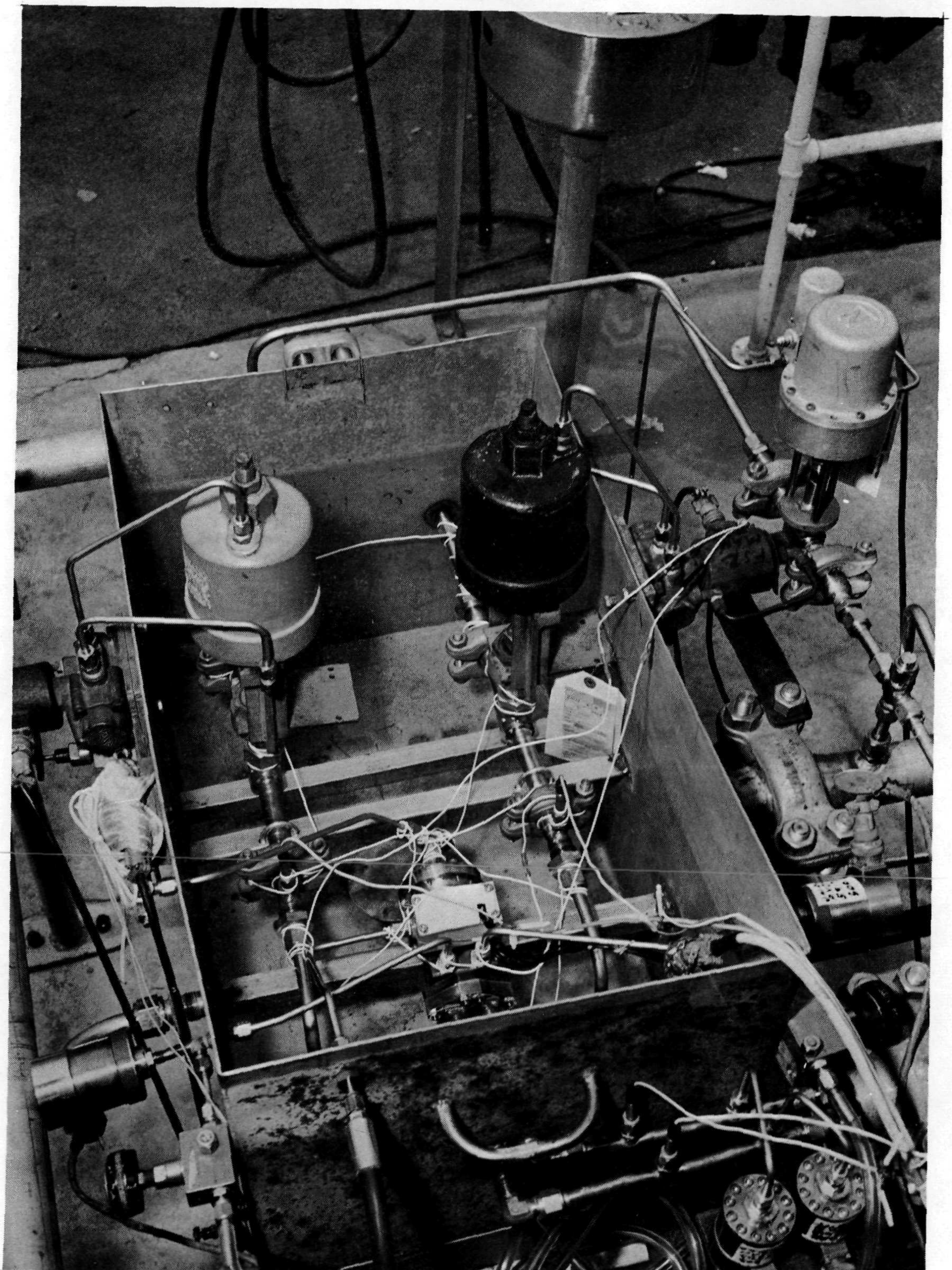
LF_2 Flow Test Facility Installation

Figure 13



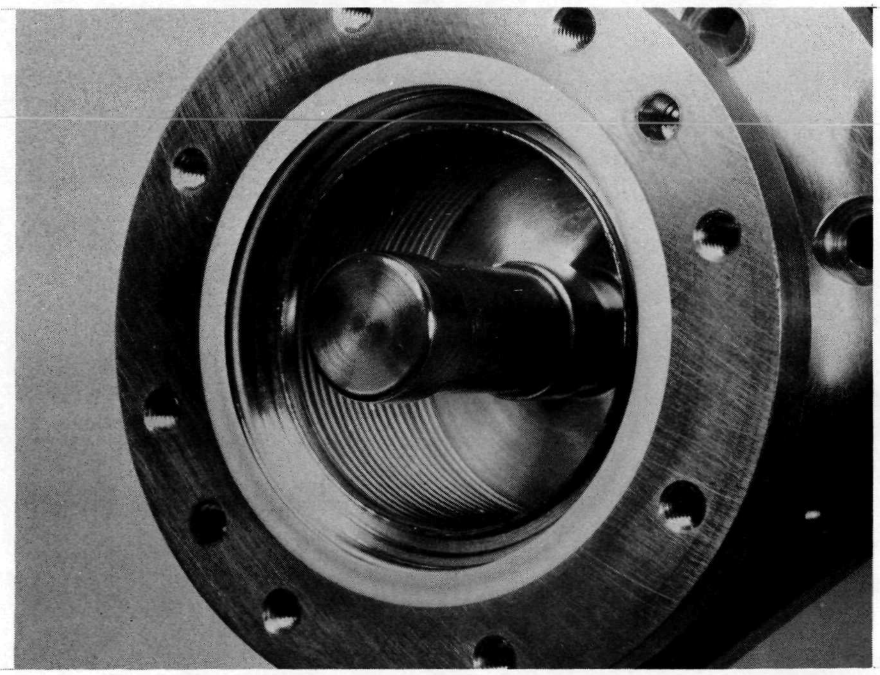
LF_2 Flow Test Setup

Figure 14

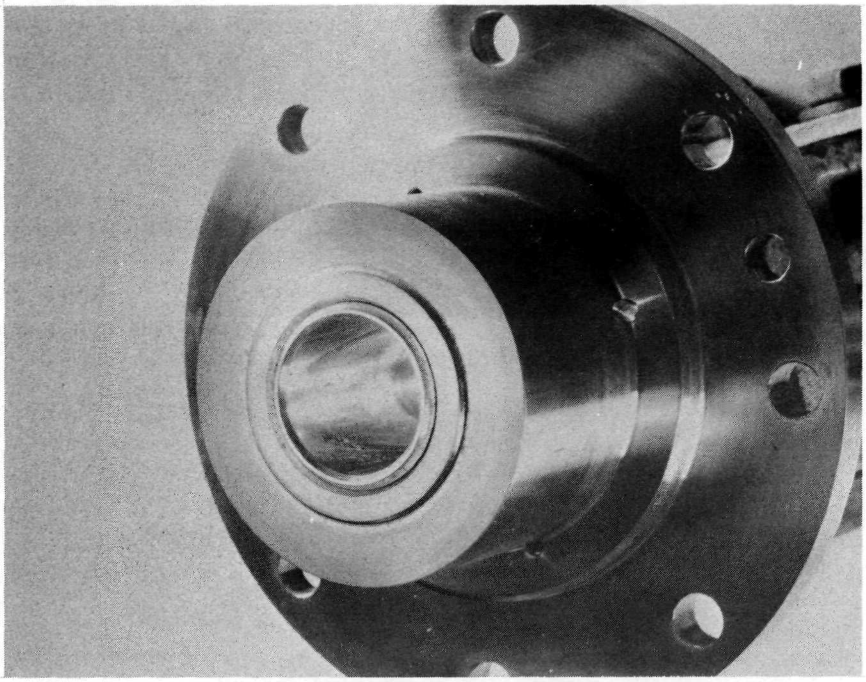


LF_2 Flow Test Setup

Figure 15



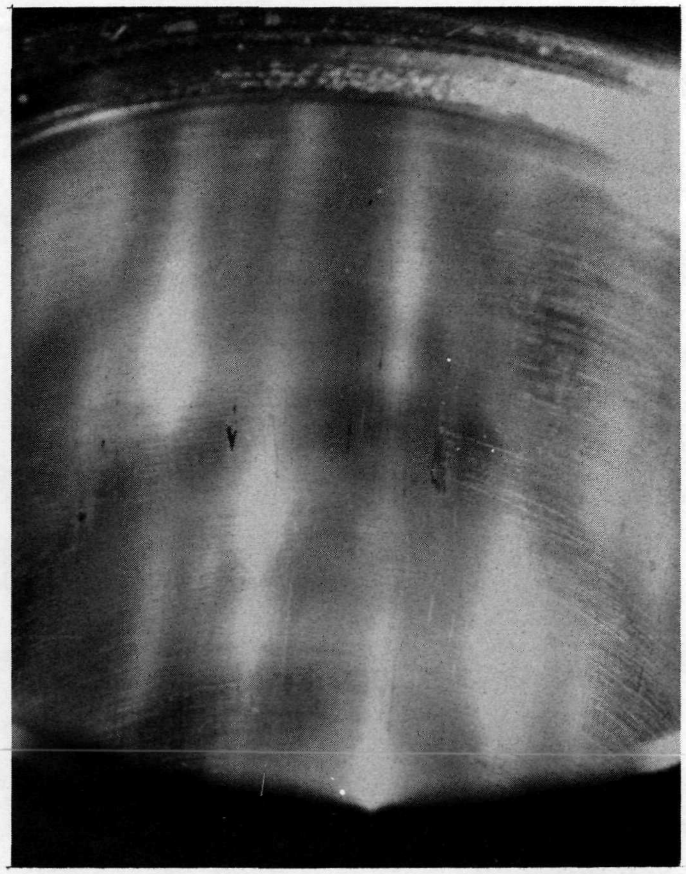
GUIDE POST 1 1/2 MAGNIFICATION



GUIDE BORE 1 1/2 X MAGNIFICATION

Actuator Guide, Post LF_2 Test

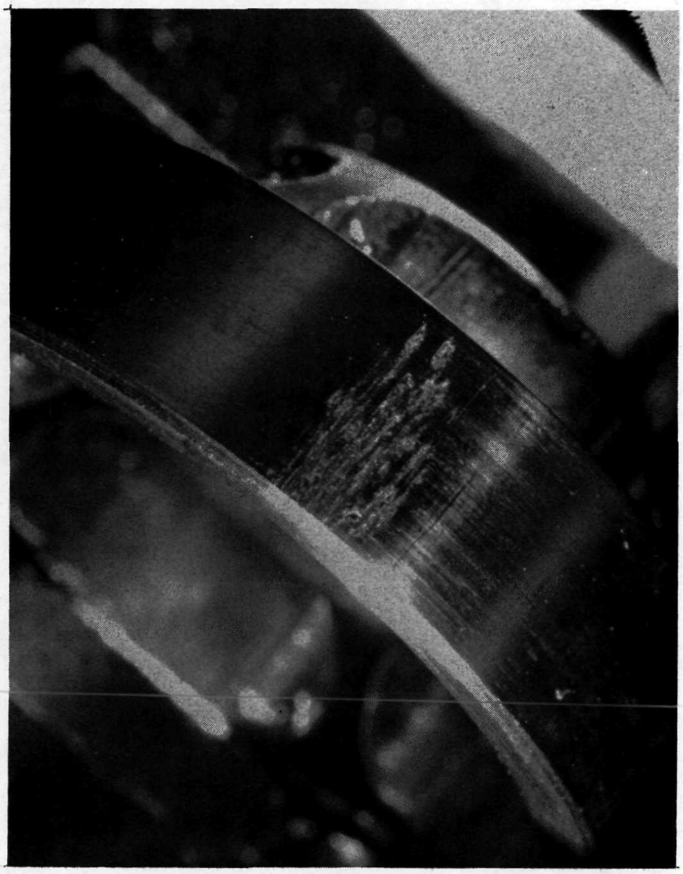
Figure 16



7 X MAGNIFICATION

Actuator Guide Bore Rub Marks

Figure 17

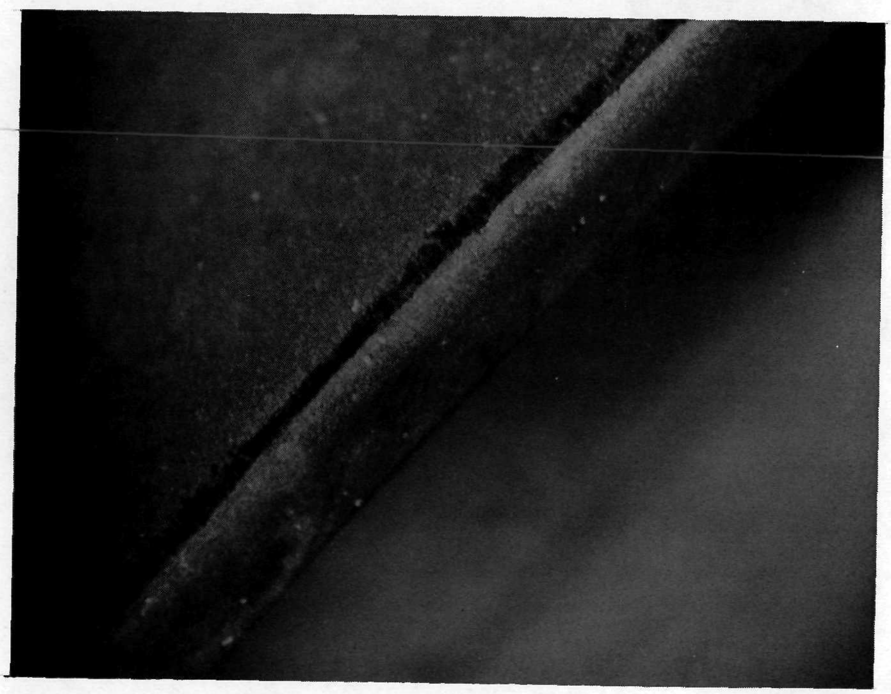


6 X MAGNIFICATION

Pintle Guide Scratches

Figure 18

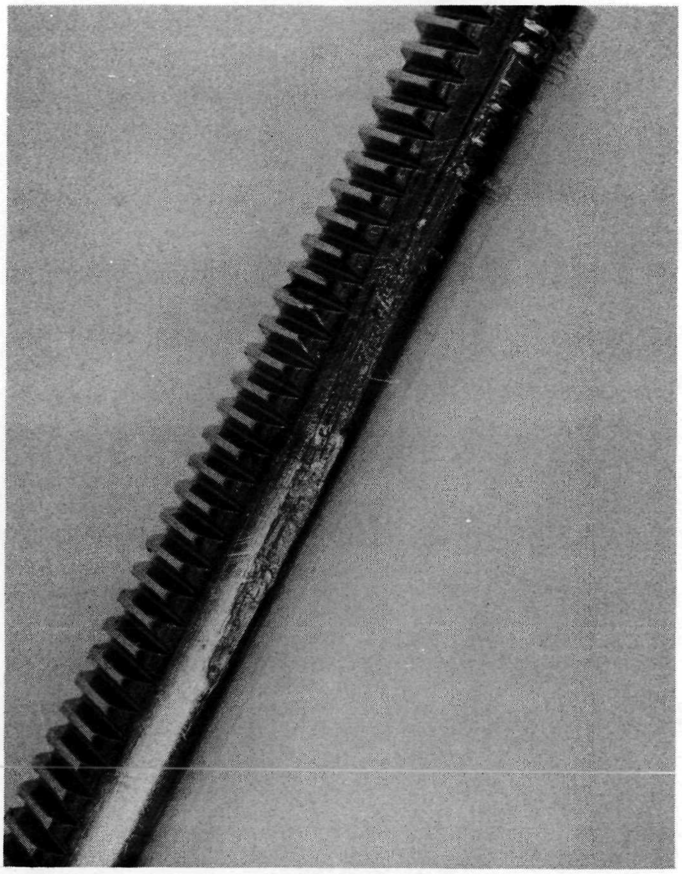
BERYLLIUM NICKEL
36 X MAGNIFICATION



BERYLLIUM COPPER
36 X MAGNIFICATION

Shut-off Seal Contact Areas

Figure 19



BERYLLIUM COPPER SEAL SIDE
5 X MAGNIFICATION

Potentiometer Drive Rack Rubbing and Gall Marks

Figure 20

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