NAS3-16744
D6-41119

(NASA-CR-134601) TESTING OF IMPROVED POLYIMIDE ACTUATOR ROD SEALS AT HIGH TEMPERATURE AND UNDER VACUUM CONDITIONS FOR USE IN (Boeing Commercial Airplane Co., Seattle) ~~50~~ 54 p HC CSCL 11A N74-21072 Unclas G3/15 35596

TESTING OF IMPROVED POLYIMIDE ACTUATOR ROD SEALS AT HIGH TEMPERATURES AND UNDER VACUUM CONDITIONS FOR USE IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS

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BOEING COMMERCIAL AIRPLANE COMPANY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-16744
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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-134601		
4. Title and Subtitle TESTING OF IMPROVED POLYIMIDE ACTUATOR ROD SEALS AT HIGH TEMPERATURE AND UNDER VACUUM CONDITIONS FOR USE IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS		5. Report Date May 1974
		6. Performing Organization Code
7. Author(s) B. K. Sellereite, A. W. Waterman, W. G. Nelson		8. Performing Organization Report No. D6-41119
		10. Work Unit No. YON 5816
9. Performing Organization Name and Address Boeing Commercial Airplane Company P.O. Box 3707 Seattle, Washington 98124		11. Contract or Grant No. NAS3-16744
		13. Type of Report and Period Covered Contractor report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Polyimide second-stage rod seals developed during the NAS3-14317 contract were evaluated to determine their suitability for applications in space station environments. The 6.35-cm (2.5-in.) K-section seal was verified for thermal cycling operation between room temperature and 478° K (400° F) and for operation in a 133 μPa (10^{-6} mm Hg) vacuum environment. The test seal completed the scheduled 96 thermal cycles and 1438 hr in vacuum with external rod seal leakage well within the maximum allowable of two drops per 25 actuation cycles. At program completion, the seals showed no signs of structural degradation. Posttest inspection showed the seals retained a snug fit against the shaft and housing walls, indicating additional wear life capability. Evaluation of a molecular flow section during vacuum testing, to inhibit fluid loss through vaporization, showed it to be beneficial with MIL-H-5606, a petroleum-base fluid, in comparison with MIL-H-83282, a synthetic hydrocarbon-base fluid.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Polyimides, Molecular flow section, Rod seals, Vacuum testing, Endurance life, Thermal cycling, High temperature	Unclassified—unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	50	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

The objective of the program conducted under NASA contract NAS3-16744 was to continue evaluation of polyimide second-stage rod seals, developed during the NAS3-14317 contract for application to advanced aircraft hydraulic systems. This objective was accomplished by verifying the 6.35-cm (2.5-in.) K-section seal capability in a hydraulic system for space application to provide effective sealing during alternating exposure to thermal cycling between room temperature and 478° K (400° F) and to a 133 μPa (10^{-6}mm Hg) vacuum environment.

Adequate wear life was verified in cycling of a linear hydraulic actuator with applied simulated loads during high-temperature excursions and during no-load cycling under high vacuum environment conditions. During completion of 96 thermal cycles between room temperature and 478° K (400° F), 3.74 x 10^5 linear actuation cycles were completed under simulated load using MIL-H-83282 as the test fluid. During 2491 hr of vacuum exposure at less than 133 μPa (10^{-6}mm Hg) pressure, 4.72 x 10^5 linear actuation cycles were completed under no-load operation. Both MIL-H-83282 and MIL-H-5606 fluids were used in vacuum testing for performance comparison. The test seal configuration demonstrated low leakage characteristics both during thermal cycling and vacuum testing. No structural degradation of either the upstream or downstream sealing elements occurred. Data were obtained on the performance of a molecular flow section downstream of the second-stage seal during vacuum tests. Data showed that some beneficial effect (less leakage) was obtained with the molecular flow section under specific test conditions. The effect was more apparent with the MIL-H-5606 petroleum-base fluid than with the MIL-H-83282 synthetic hydrocarbon-base fluid.

It was concluded from the testing completed during this program that polyimide seals have satisfactory operational capability over a wider range of environments than most seals in present usage. The test results demonstrated that polyimide second-stage rod seals can be made to satisfy the dynamic hydraulic actuator requirements of applications involving space storage and reentry.

Tests should be continued to evaluate the K-section and chevron second-stage seal configurations with other fluids and environments to further expand the field of knowledge regarding the application of these seals to satisfy the ever-expanding demands for reliable methods of fluid containment.

Development efforts should be increased toward standardization of a number of seal sizes for introduction to specific applications in industry. Cost reduction should be emphasized by investigating molding as a fabrication method.

INTRODUCTION

Development of advanced aircraft and space hydraulic systems requires consideration of new materials and design concepts. The higher fluid temperatures identified with these hydraulic systems preclude the use of many heretofore conventional seal design practices. The universal application of the elastomer to all hydraulic sealing applications is a thing of the past. The elastomers used in conjunction with polytetrafluoroethylene (PTFE) seal components will still have specific design applications, but critical dynamic sealing requirements will require new materials capable of long life at high fluid temperatures.

The material properties of polyimides are acceptable for the entire range of type III hydraulic system temperatures as well as for considerably higher temperatures, making these materials prime candidates for experimental seal research for advanced aircraft and space applications. Experimental investigations with polyimides to date have emphasized stable strength properties of these materials at high temperatures over long durations. NASA-initiated research was instrumental in the early development of new seal concepts using polyimides in exploratory tests to determine sealing characteristics under various operating environments. These efforts were conducted under the NAS3-7264, NAS3-11170, NAS3-14317, and NAS3-16733 contracts, references 1, 2, 3, and 4, respectively.

The program reported herein is a continuation of the above-mentioned seal development programs. It was intended to verify second-stage rod seal performance for thermal cycling and vacuum applications not previously considered. The developed seals were required to function under conditions representative of space station requirements with temperature excursions from room temperature to 478° K (400° F) and vacuum exposure to less than 133 μPa (10^{-6} mm Hg) pressures. Leakage characteristics of the seals under vacuum were examined using both MIL-H-83282 and MIL-H-5606 hydraulic fluids. Performance of a molecular flow section, downstream of the second-stage seal, was evaluated to determine its effect on reducing external leakage.

SEAL TESTS

The objective of this program was to continue the evaluation of the second-stage polyimide K-section rod seal design developed for advanced aircraft applications under contract NAS3-14317 and reported in reference 3. The continued testing was conducted to prove the applicability of the seal design to space environments. The tests consisted of alternating thermal cycling and vacuum tests to simulate repeated reentry heating and space vacuum storage while on station. The test plan is shown in table I. The same set of K-section seals were used for the entire series of tests.

Additional testing was performed to evaluate the molecular flow section described in appendix A. Comparison vacuum tests were conducted to determine the reduction in external leakage achievable by adding the molecular section and the effect that changing the fluid base had on molecular section efficiency.

SEAL CONFIGURATION

The test article was the 6.35-cm (2.5-in.) K-section second-stage seal as designed under NASA contract NAS3-14317 (see ref. 3 and app. B). The seal was fabricated from DuPont SP-21 polyimide material per Boeing drawing (ref. 5). The seal cavity was per reference 6 except for the piston rod diameter. The 6.347-cm (2.499-in.) rod diameter for the 6.35-cm (2.5-in.) seal was established for testing at 478° K (400° F). The increase in rod diameter from reference 6 specification was required to ensure an interference fit between the rod and seal at maximum test temperature, with the specific dimensions selected so that minimum overstressing of the seals would occur at room temperature. The change in rod diameter was accepted in preference to redesigning the seal for a test temperature of 478° K (400° F). The seal design temperature was 450° K (350° F).

The K-section seal was assembled in the module configuration designed under NASA contract NAS3-14317 (ref. 3). The module was installed in the 6.35-cm (2.5-in.) nominal rod actuator, as shown in figure 1.

THERMAL CYCLING TESTS

Thermal cycling tests 1 and 3 were conducted between room temperature and 478 K°(400° F), with intermediate cooling between cycles to 339° K (150° F). Rapid heating and cooling were required to complete a minimum of three heating-cooling cycles per 8-hr day. The actuator was cycled under simulated load representative of space shuttle actuator reentry conditions.

TABLE I.—TEST SCHEDULE, SECOND-STAGE K-SECTION SEAL AT 1.379 MPa (200 PSIA)

Test	Test fluid used			Molecular section evaluation conducted	Temperature range	Environmental pressure (a)	Test duration			
	MIL-H-83282 (ref. 8)		MIL-H-5606 (ref. 10)				Thermal cycling		Vacuum testing	
	Mobil XRM 206A-1	Mobil XRM 231A					Cycles completed	Loaded actuation hours	Vacuum exposure hours	No-load actuation hours
1	X				Cycling Amb. to 478° K (Amb. to 400° F)	Ambient	37	75		
2	X			Yes	Ambient	133 μPa (10^{-6} mm Hg)			934	217
3		X			Amb. to 478° K (Amb. to 400° F)	Ambient	59	129		
4		X		Yes	Ambient	133 μPa (10^{-6} mm Hg)			504	129
5			X	Yes	Ambient	133 μPa (10^{-6} mm Hg)			1053	237

[a]Where pressure other than ambient is shown, it is maximum pressure with chamber clean, dry, and empty.

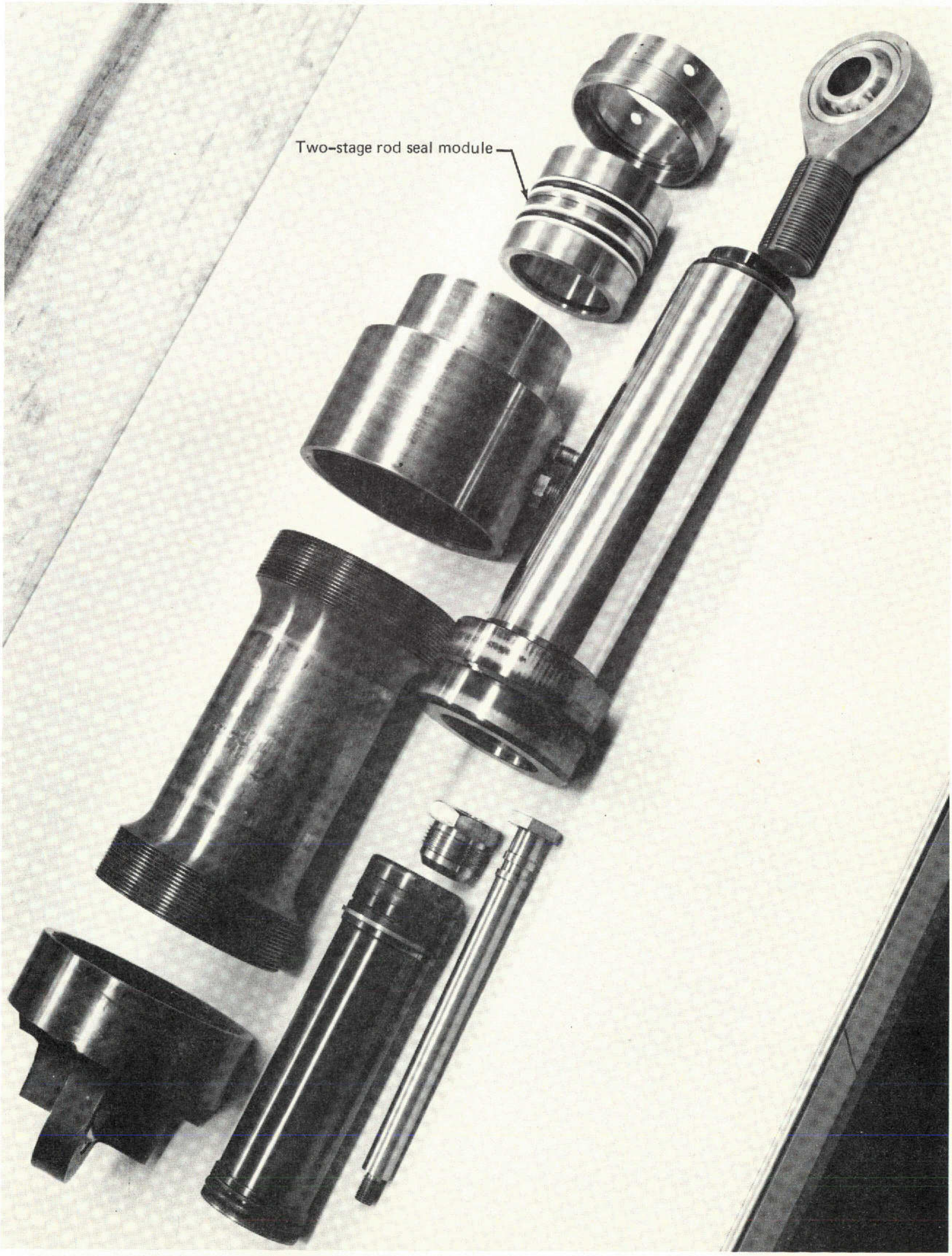


FIGURE 1.—6.35-CM(2.5-IN.) THERMAL CYCLING TEST ACTUATOR

Test Apparatus

Existing test actuator components were used to the greatest extent possible. The actuator is defined in reference 7 and shown in figure 1. A cast-iron contracting seal was used as the first-stage seal. Details of this seal design are shown in appendix C. The first-stage seal was not considered as a test article, although data on first-stage seal performance were obtained.

The thermal cycling test installation (fig. 2) was an existing rig developed primarily for testing linear actuator seals. The installation consisted of a load system, two hydraulic power supplies with their associated plumbing, and the control electronics. The major power and loading components were as follows:

- Oven—Dispatch, model 203
- High-temperature power supply—Auto Controls Laboratory, Inc., model 4586
- Standard power supply—Sprague, model 76217B
- Load fixture—Boeing laboratory equipment
- Filter—Microporous (25-micron-absolute)
- Relief valve—Vickers C-175-F
- Servovalve block—Boeing laboratory equipment
- Accumulator—Hydrodyne 68.95 MPa (10 000 psig)

The load system consisted of a torsion bar capable of providing resisting torque for the actuator. The torque bar length was adjusted to provide a torsional load such as to require a full system pressure of 27.58 MPa (4000 psig) at full actuator stroke. The force from the actuator was reacted to the torsion bar through a lever arm and bearing assembly to simulate a flight control surface hinge point. Self-aligning bearings were used for the actuator head-end and rod-end connection points. No additional side load other than bearing friction was applied. The mounting base of the load system and the actuator were installed in a test oven. This installation is shown in figure 3. Due to its size, the torsion bar extended through the back of the oven and was supported externally at the extreme end by a pedestal.

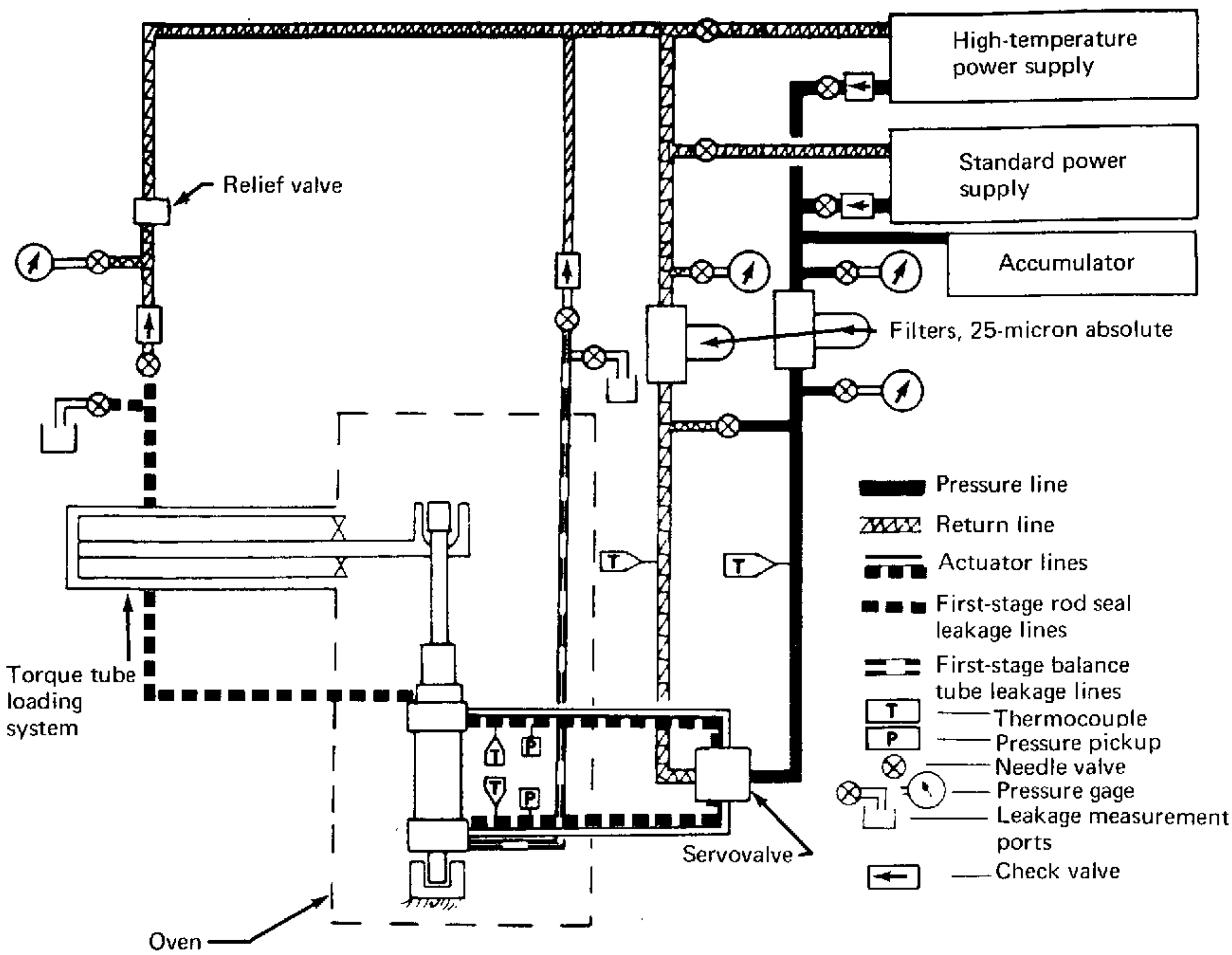


FIGURE 2.–HYDRAULIC INSTALLATIONS SCHEMATIC, THERMAL CYCLING TEST

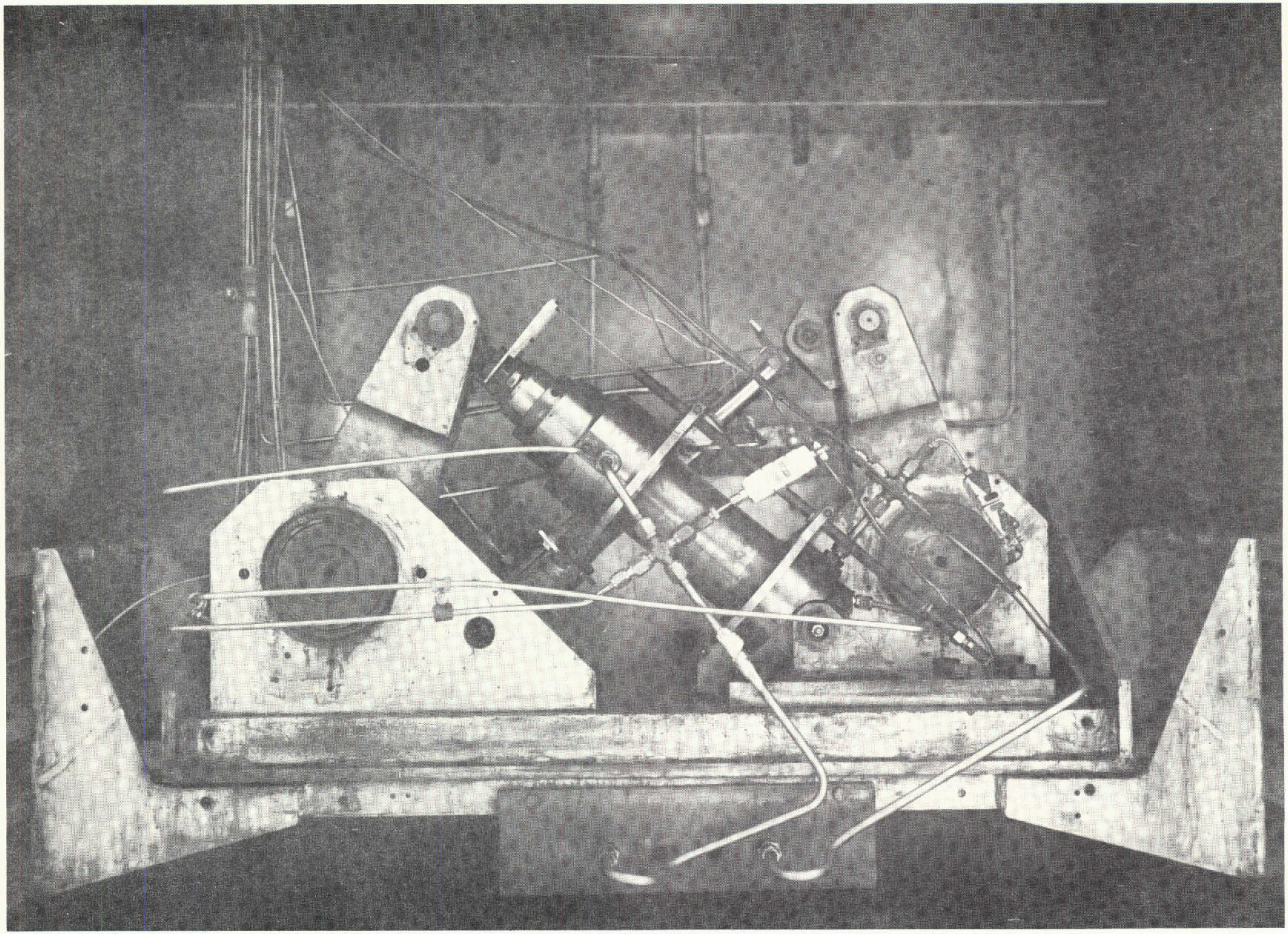


FIGURE 3.—ACTUATOR INSTALLATION, THERMAL CYCLING TEST

Hydraulic power was supplied by a 1.262-dm^3/s (20-gpm) Auto Controls Laboratory power supply and by a 0.631-dm^3/s (10-gpm) Sprague standard laboratory power supply. Each unit was complete with all pressure and temperature controls and supplied MIL-H-83282 (ref. 8) hydraulic fluid at 27.58 MPa (4000 psig) and the required test temperature. A 9.464-dm^3 (2.5-gal) accumulator was located in the supply line between the high-temperature power supply and the actuation rig. In addition to filtration within the power supplies, a 25-micron-absolute filter was located in the supply line downstream of the accumulator. The cavity between the first- and second-stage seals in the test actuator was vented to return through a relief valve to maintain second-stage seal pressure at 1.379 MPa (200 psig). Check and isolation valves allowed measurement of first-stage leakage without interrupting actuator cycling during test. Additional isolation valves were installed to allow fluid power to be supplied to the test rig from either of the two power supplies.

Control Electronics

The control of test operation cycling was provided by a closed-loop electrohydraulic flow control loop incorporating position feedback.

Components were arranged as shown in figure 4. The electrical loop consisted of the feedback transducer (LVDT), carrier amplifier, Boeing standard controller, and servovalve, with the total loop completed mechanically through the fluid-powered actuator rod. The servocontroller was driven with a function generator providing a sinusoidal cycle at the required period. The actuator stroke amplitude and position were set at the servocontroller command for the flow control servovalve.

Actuator head and rod-end cylinder pressures were measured and recorded on a direct-write oscillograph. The actuator position was also recorded on the oscillograph and monitored during test to ensure that proper position and stroke amplitude were maintained.

Oven ambient, oil, and component temperatures were recorded on a stamping-type temperature recorder.

Instrumentation and recorded data accuracies are reported in appendix D.

Test Operation

The unpressurized assembled test actuator was manually inspected for binding. A proof pressure was then applied and pretest leakage rates established for the first-stage seals at room temperature.

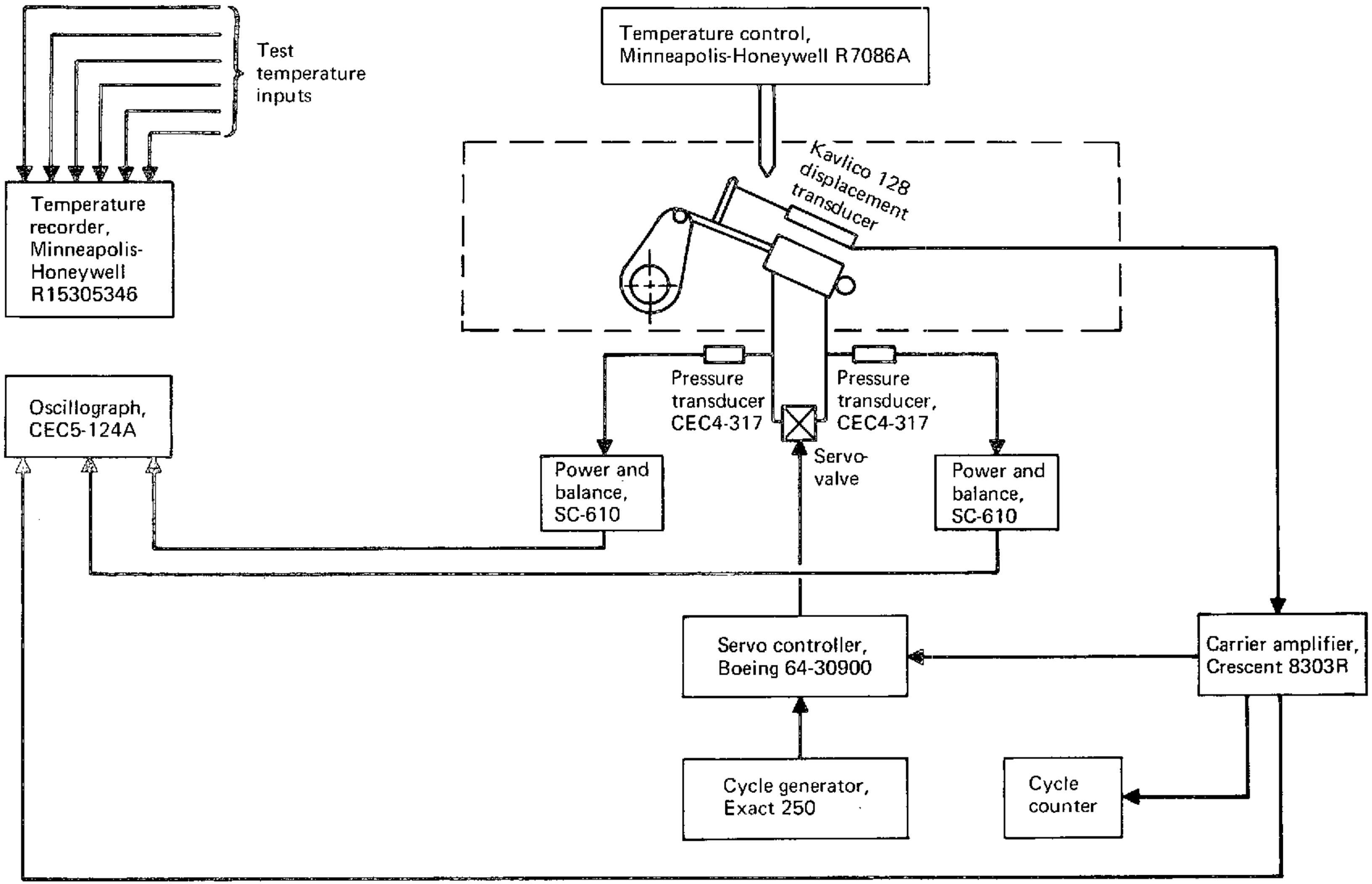


FIGURE 4.—ELECTROHYDRAULIC CONTROL LOOP, THERMAL CYCLING TEST

After the test actuator and data transducers were installed in the loading fixture, a reservoir pressure of 0.344 MPa (50 psig) was applied and air bled from the hydraulic system. A room temperature checkout was conducted, starting with a system pressure of 6.894 MPa (1000 psig) and increased in incremental steps to working pressure while cycling. The thermal cycling between room temperature and 478° K°(400° F) was performed while maintaining actuator stroke and rate, as shown in figure 5. The high-temperature power supply was operated at a nominal 478° K (400° F) continuously during testing. When the temperature of the test actuator operated by this supply reached 478° ±8° K (400° ±15° F), the high-temperature power supply was isolated from the test rig and fluid power supplied from the standard power supply, operated at approximately 310° K (100° F). If, upon completion of a full thermal cycle, time would not allow another full cycle to be completed before the end of the shift, actuator cycling using power from the standard power supply would be continued until the end of the day at 33% stroke and 0.6 Hz.

The test was conducted beginning with the heating portion of the cycle by adjusting:

- The high-temperature hydraulic power supply to 478° K (400° F) and 27.58-MPa (4000-psig) nominal working pressure.

- The oven controls to maintain the 478° K (400° F) test temperature for the mass of the actuator and fixture.

- The function generator to the cycle rate established in figure 5.

- The servocontroller to provide the desired actuator neutral cycling point and percent of rod stroke.

- The interstage relief valve to maintain 1.379 MPa (200 psig).

With the required test temperature reached, the high-temperature power supply isolated, and the standard power supply connected, cooling would start by adjusting:

- The function generator to the cycle rate established in figure 5.

- The servocontroller to provide the desired actuator neutral cycling point and percent of rod stroke.

During testing, first-stage leakage was measured by its collection in burettes. The second-stage leakage was measured by visual observation during the heating portion of the thermal cycle with the test actuator at approximately 478° K (400° F).

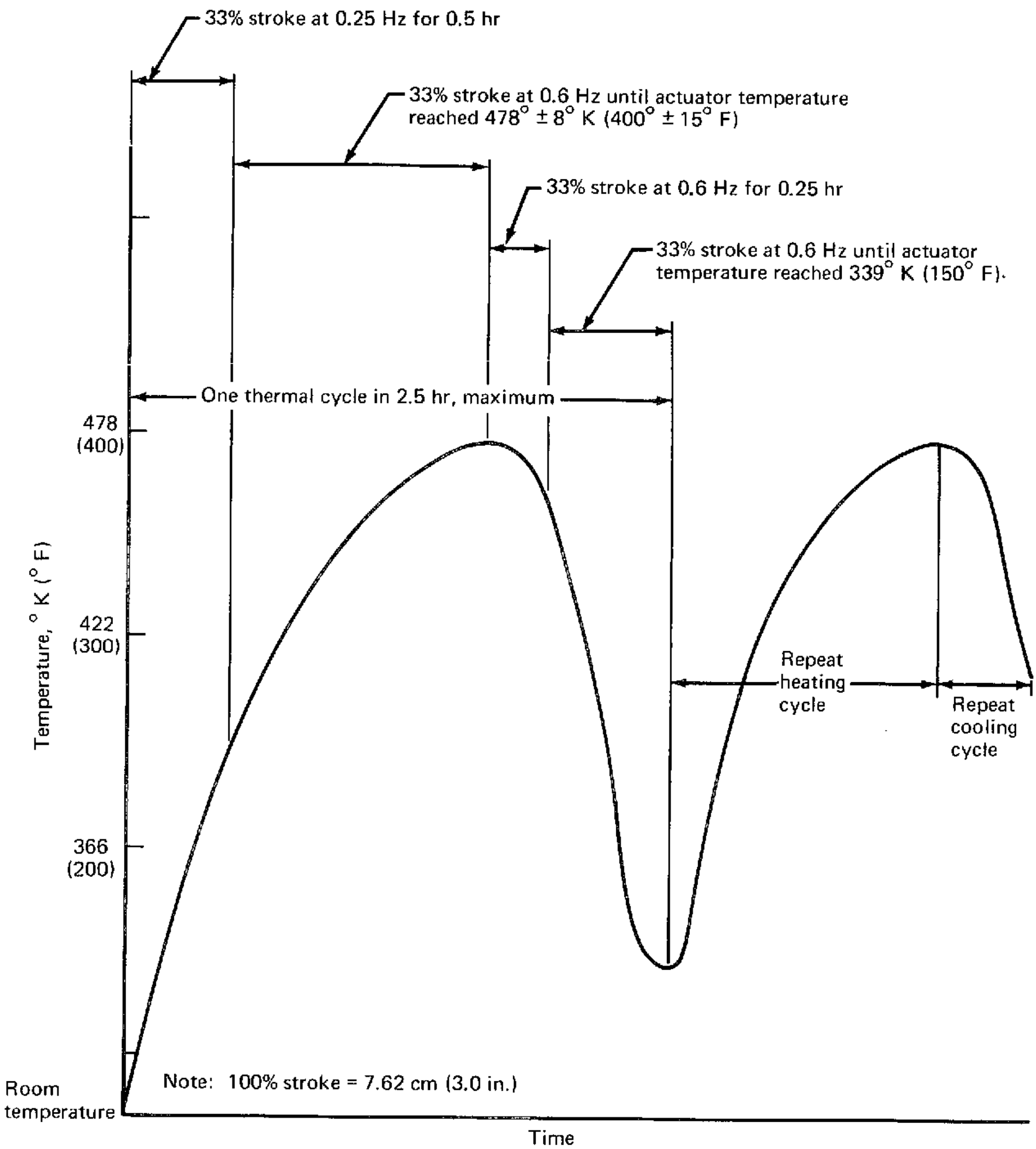


FIGURE 5.–ACTUATOR STROKE AND RATE SCHEDULE, THERMAL CYCLING TEST

Test Results

The test seals completed both test 1 and test 3 (see table I) of thermal cycling with no failures or deterioration in seal performance. The maximum leakage observed during any 5-min observation period was 1 drop. This corresponds to 180 actuation cycles per 50 mm^3 (1 drop) of leakage. The seals thus showed a level of performance 14 times better than the allowable.

First-stage seal leakage did not exceed 133 mm^3/s (2.7 drops/sec) during tests.

Room temperature leakage testing after completion of the thermal cycling tests revealed no second-stage leakage during the 15-min observation period.

Fluid thermal instability was encountered during test 1. Thermal cycling was discontinued after 37 of an originally planned 50 cycles due to breakdown of the Mobil XRM 206A-1 formulation of MIL-H-83282. This problem was corrected by the fluid supplier through a reformulation of the fluid additive package, resulting in an improved fluid designated XRM 231A and used in test 3.

VACUUM ENVIRONMENT TESTS

The vacuum environment tests 2, 4, and 5 (table I) were conducted to evaluate the suitability of the polyimide K-section rod seals for space shuttle applications requiring seal reliability during an extended period of continuous vacuum exposure to less than 133 μPa (10^{-6} mm Hg). In a typical space shuttle application the actuator rod seals would be exposed to periods of cyclic rod actuation alternated with periods when the actuator would be stowed or locked with the seals remaining pressurized. The tests simulated this environment to assess seal leakage variation as a function of changing actuation stroke and rate, fluid base, and the flow passage (molecular section) downstream of the K-section second-stage seal.

Test Apparatus

Existing actuator components were used to the greatest extent possible. The test actuator (fig. 6) included the rod-end cap and seal module tested by thermal cycling with the first-stage rod seal removed. This unit was assembled to a short cylinder and head-end cap. The rod-end cap containing the test seals was machined to accept a vacuum flange to allow attachment of the actuator to the vacuum chamber. A hollow, 40.64-cm (16-in.) long actuator rod without a piston section was installed through the end caps and was mechanically driven to provide a total actuation stroke of about 10.16 cm (4 in.). The rod end exposed to the vacuum was fitted with a vacuum plug

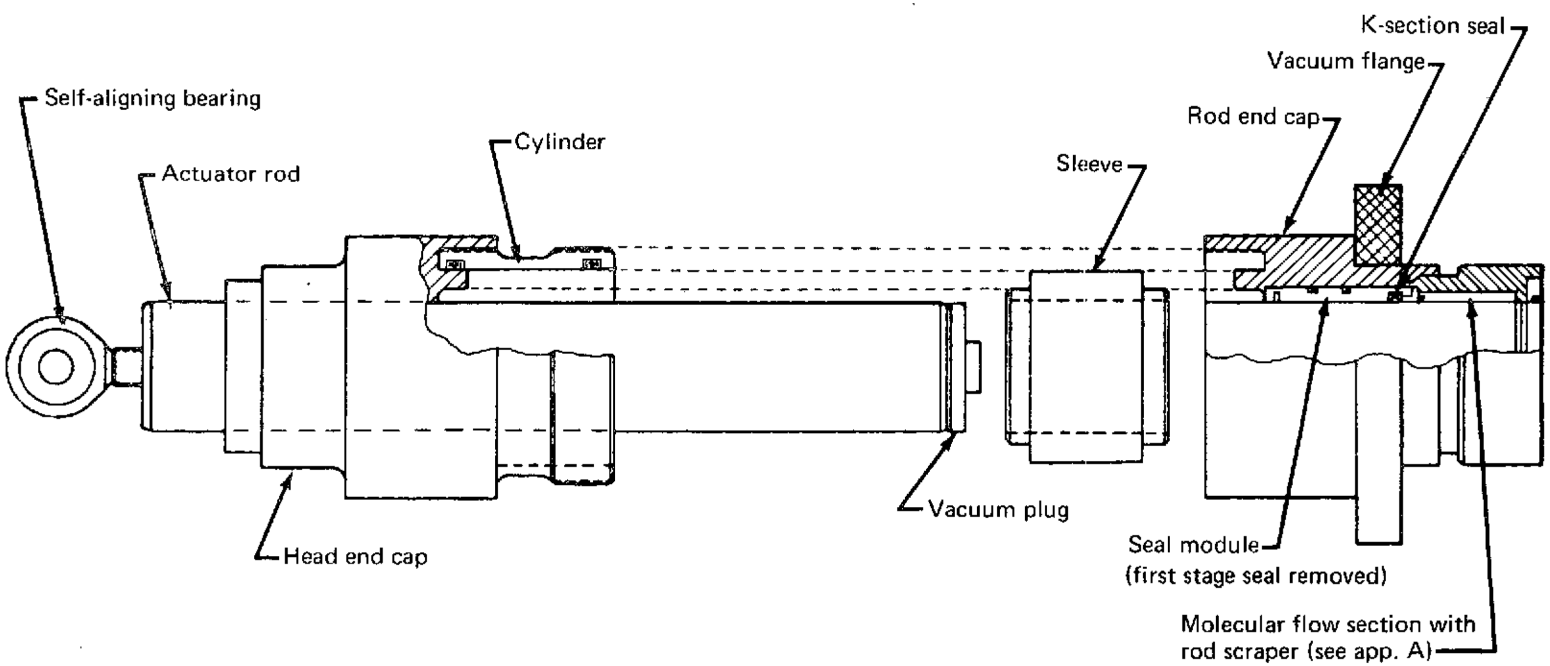


FIGURE 6.—6.35-CM (2.5-IN.) VACUUM ENVIRONMENT TEST ACTUATOR

and the opposite end with a self-aligning bearing for attachment to the external drive mechanism. A sleeve was included in the actuator cylinder to reduce the fluid volume, thus improving leakage instrumentation measurement accuracy. A molecular flow section was a removable installation downstream of the K-section seals. Details of this design are shown in appendix A, and reference 9 provides background information on the theory of the section.

The vacuum environment test rig is shown in figure 7. The installation consisted of the actuator with the test seals, static seal pressurization and leakage measurement device, rod drive mechanism, and vacuum chamber. The major components were:

- Variable-speed drive—Graham, 0-185 rpm, model 175 HMR 2.8
- Test stand, stroke adjustment wheel, and slider mechanism—Boeing laboratory equipment
- Leakage measurement device—Boeing laboratory equipment
- Pressure regulator—Apco, model 1B
- Mechanical stroke counter—Silver-King, model ARN5
- Vacuum chamber—Aero Vac, model ASB 1030H
- 10-in. oil-diffusion pump—National Research Corporation, type 0163
- 4-in. oil-diffusion pump—Consolidated Research Corporation, type PMC-720
- Mechanical pumps—Welch, model 1397 (0.5 m^3/min) and model 1403 (0.1 m^3/min)
- Liquid nitrogen cold trap—Aero Vac, model ATB10

The detail of the actuator rod drive mechanism is shown in figure 8. The variable-drive output speed was reduced by one-half through a sprocket/chain transmission to provide input to the stroke adjustment wheel. The rotary motion of the adjustment wheel was converted to linear motion via a push rod to the slider mechanism. Self-aligning bearings and installation alignment ensured that minimum side forces were transmitted to the actuator rod.

The seal pressurization and leakage measurement system used is illustrated in figure 9. It consisted of two calibrated capillary tubes, a hand pump, pressure regulator, relief valve, pressure gages, and shutoff valves. The tops of the capillary tubes were pressurized with nitrogen held at

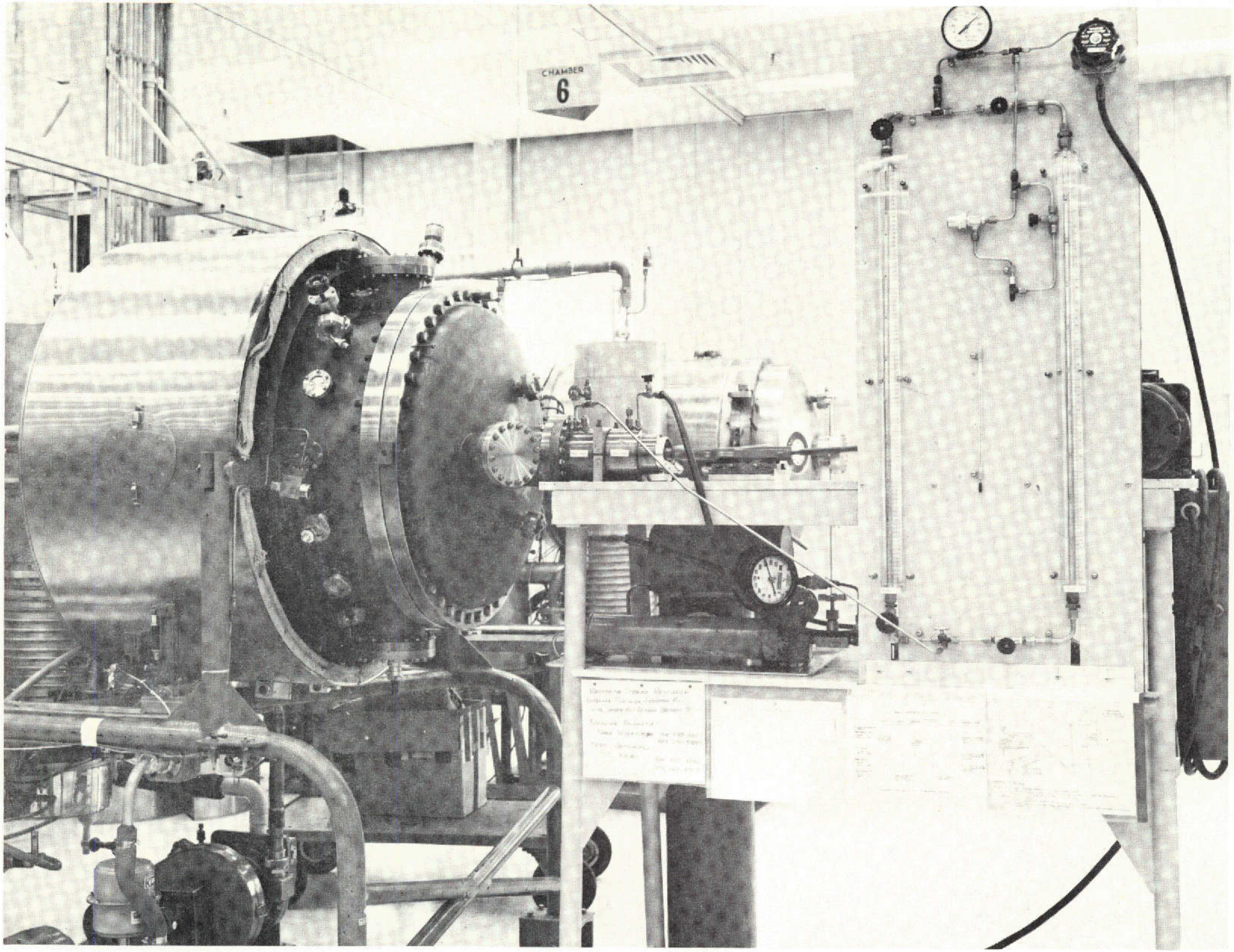


FIGURE 7.—VACUUM ENVIRONMENT TEST INSTALLATION

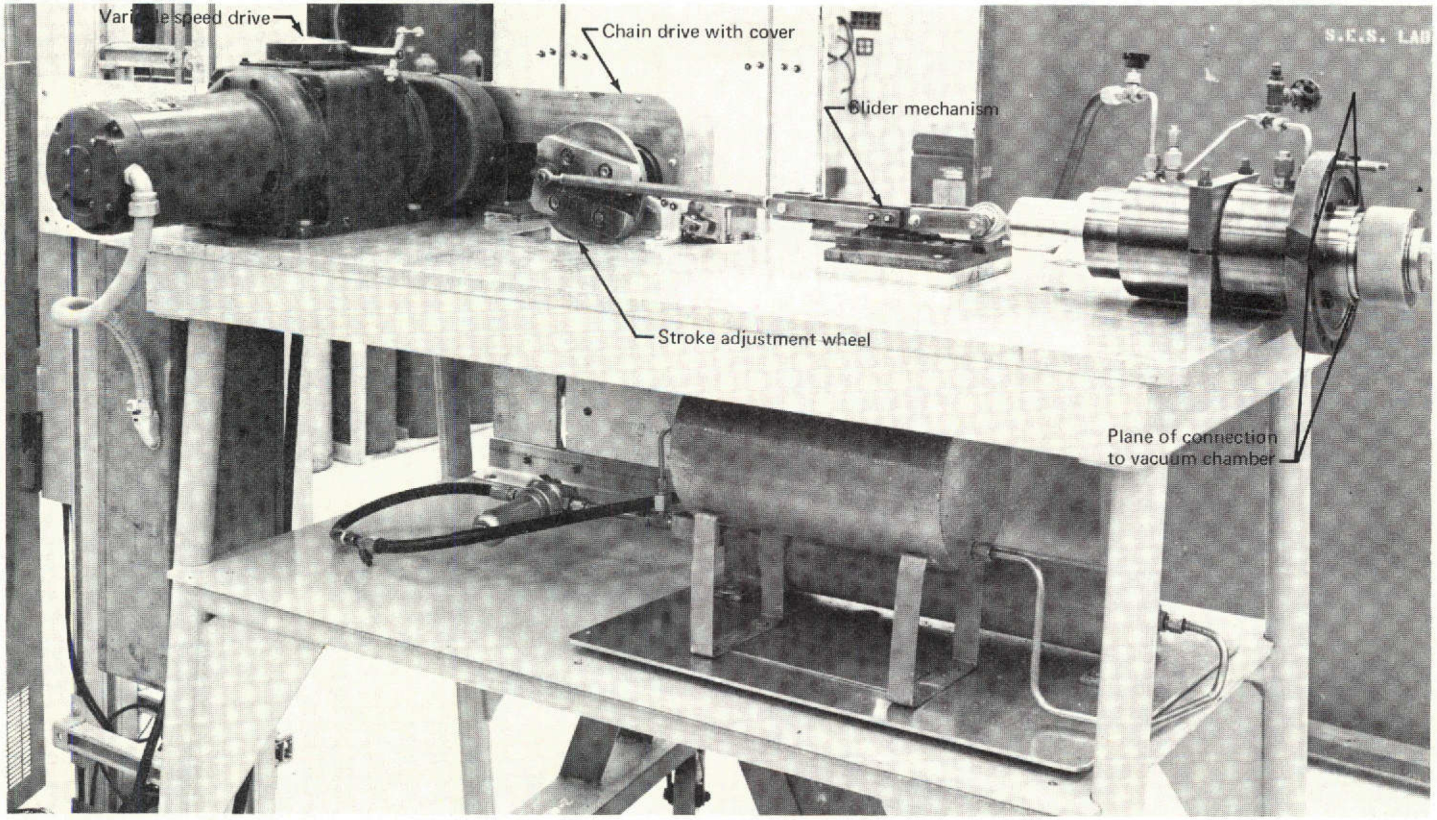


FIGURE 8.—ACTUATOR DRIVE MECHANISM, VACUUM ENVIRONMENT TEST

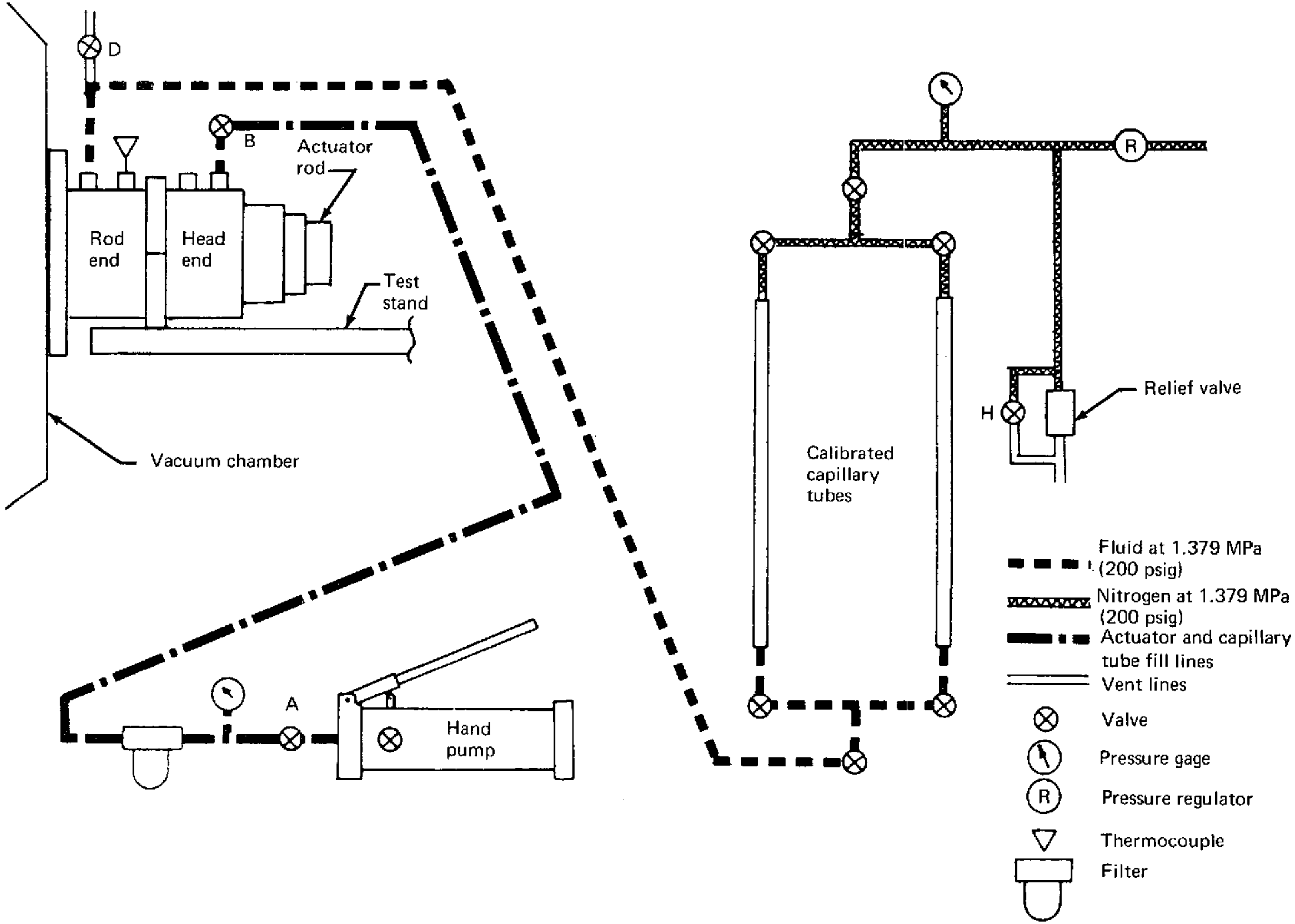


FIGURE 9.—PRESSURIZATION AND LEAKAGE MEASUREMENT SYSTEM SCHEMATIC, VACUUM ENVIRONMENT TEST

1.379 MPa (200 psig) by the pressure regulator, thereby maintaining the required seal pressure. The charging of the capillary tubing with hydraulic fluid was accomplished with the hand pump and connecting tubing.

A diagram of the vacuum chamber and pumping system is shown in figure 10. The chamber is an ultra-high-vacuum test chamber, 7.62 dm (30 in.) in diameter by 7.62 dm (30 in.) long, with an ultimate pressure capability of less than 13.3 nPa (10^{-10} mm Hg). It was pumped to the low micron pressure range by an 8.495-dm^3/s (18-cfm) mechanical pump. The two diffusion pumps were then used in series to achieve normal test pressures in the 133 μPa/13 μPa ($10^{-6}/10^{-7}$ mm Hg) range. A liquid nitrogen trap on the diffusion pump inlet prevented backstreaming of oil and provided high-speed pumping for condensibles such as water vapor. Repressurization at the end of test periods was done with clean, dry nitrogen.

Test Control and Data Recordings

Actuator stroke length and rate were controlled manually by setting the stroke adjustment and Graham drive speed. A set condition was established at the beginning of the first shift of each working day. The seal cavity pressure was held constant 24 hr a day throughout the test by the Apco pressure regulator (fig. 9). The vacuum pressure was maintained throughout the test by continuously operating the vacuum pumps. To permit unattended operation of the chamber during weekend periods, several chamber operating parameters were interlocked to the laboratory automatic alarm system. Alarms were provided for:

- Loss of vacuum
- Liquid nitrogen trap spillage
- Liquid nitrogen trap low level
- Power failure

Loss of power, which would shut down the primary pumps, also triggered an automatic transfer to a backup mechanical pump on the emergency power circuit.

The following data were recorded at regular intervals in the test log: fluid level in both capillary tubes, seal cavity pressure, actuator stroke length and rate, actuator cycles, laboratory ambient temperature, cylinder oil temperature, and vacuum pressure. Any leakage at the drive (atmospheric) end of the actuator was collected and measured. This leakage was subtracted from the total leakage to determine the leakage through the test seals into the vacuum chamber.

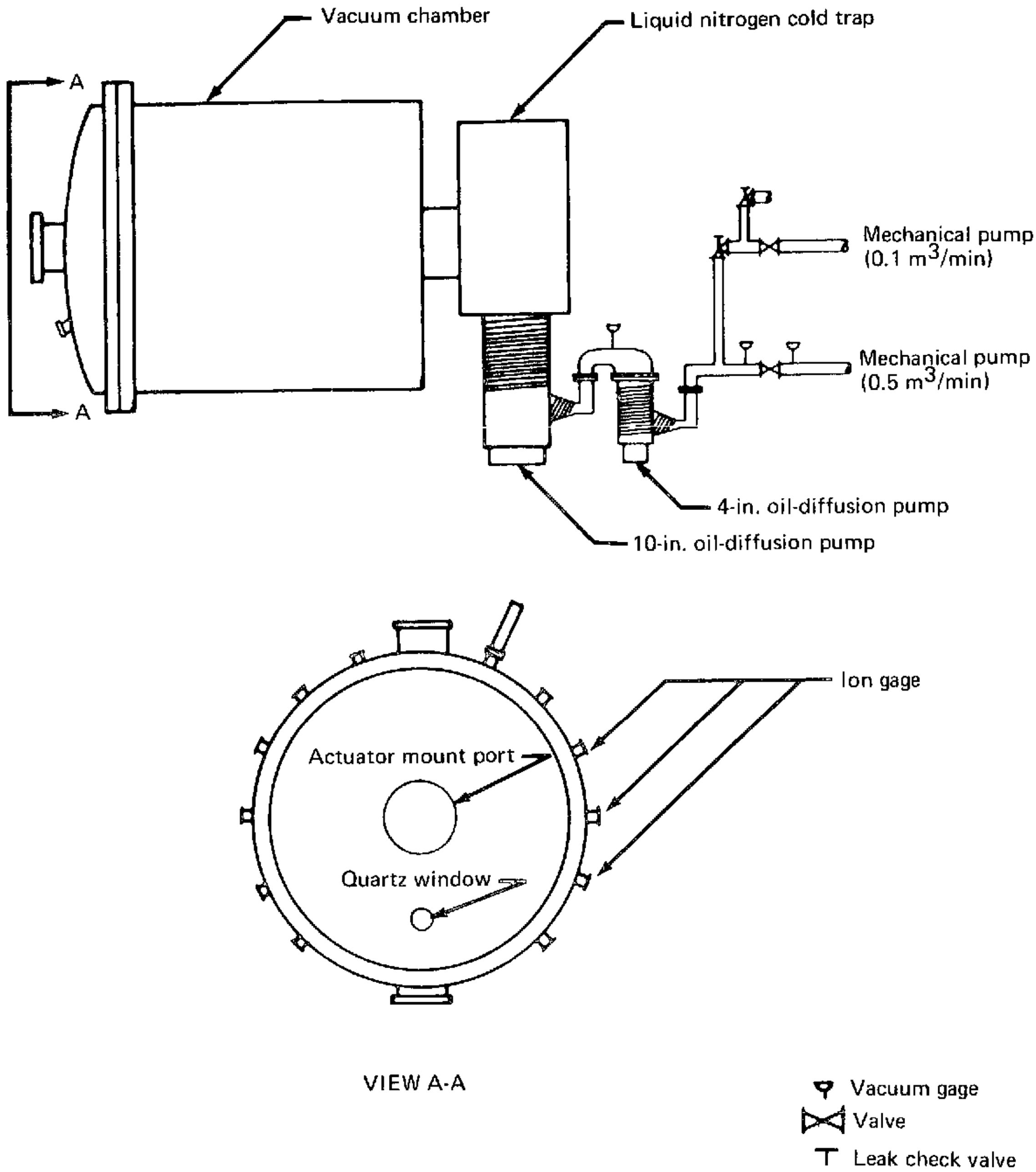


FIGURE 10.—VACUUM SYSTEM SCHEMATIC

Information and recorded data accuracies are reported in appendix D.

Test Operation

The test actuator was leak checked by applying a hydraulic fluid pressure of 1.379 MPa (200 psig) to the cylinder prior to the installation of the actuator in the test system. The hydraulic fluid loop was then connected and bled to eliminate air from the system. The system was filled to provide an appropriate level in the capillary tubes by operating the hand pump. The vacuum seals in the mounting flange and in the actuator rod-seal plug were subjected to a helium leak check using a special adapter mounted on the actuator vacuum flange. The leak check was conducted with the test system in the configuration shown in figure 8 and with 1.379 MPa (200 psig) of fluid pressure applied to the seal cavity. Helium was used in conjunction with a laboratory pumping cart and a Consolidated Electronics Corporation leak detector with a sensitivity of 200 $\mu m^3/s$ at standard conditions. All leak checks were conducted at room temperature. The test system was then attached to the vacuum chamber and the total installation was leak checked.

Testing commenced following chamber pumpdown to the 133 μPa (10^{-6} mm Hg) range. Actuator rod stroking was performed via the external drive mechanism for approximately 8 hr per working day. The actuator rod was stowed in the retracted position during off-hour shifts and on weekends. The highest possible vacuum was maintained throughout the test by operating the vacuum pumps continuously.

The daily test operation was conducted as follows, starting with first shift:

- Fill the capillary tubes, if required.
- Check actuator rod stroke setting.
- Start actuation and check actuation rate.
- Stop actuation at end of the manned shift.
- Adjust rod stroke to setting required for next day of testing.
- Fully retract actuator rod and stow for overnight (or weekend) period.
- Fill capillary tubes if required.

The capillary tubes were filled as required by operating the hand pump and opening valves A and B (fig. 9), thereby forcing hydraulic fluid through the actuator and connecting lines to the capillary tubes until the appropriate level was reached. The 1.379-MPa (200-psig) nitrogen pressure was maintained on the capillary tubes throughout the fill operation. If required, the filling operation would be performed during rod actuation. Rod stroke was set by adjusting the cranking arm length and the stroking rate by adjusting the drive output speed.

Three tests of seal performance in a vacuum environment were conducted (table I). Tests 2 and 4 were performed with MIL-H-83282, a synthetic hydrocarbon hydraulic fluid (ref. 8), and test 5 with MIL-H-5606, a petroleum-base hydraulic fluid (ref. 10).

Test 2 consisted of two sequences separated by the opening of the vacuum chamber to change the test configuration. The test was started with the molecular flow section installed downstream of the K-section seals. The second half of the test was conducted with the flow section removed and replaced by a retaining nut. Each sequence was run at a constant actuation rate of 0.27 Hz (16 cpm) of the crank arm and by testing at the stroke lengths of 100%, 75%, 50%, 25%, 100%, etc., on consecutive days to test termination. (100% stroke was equal to 10.16 cm (4 in.).)

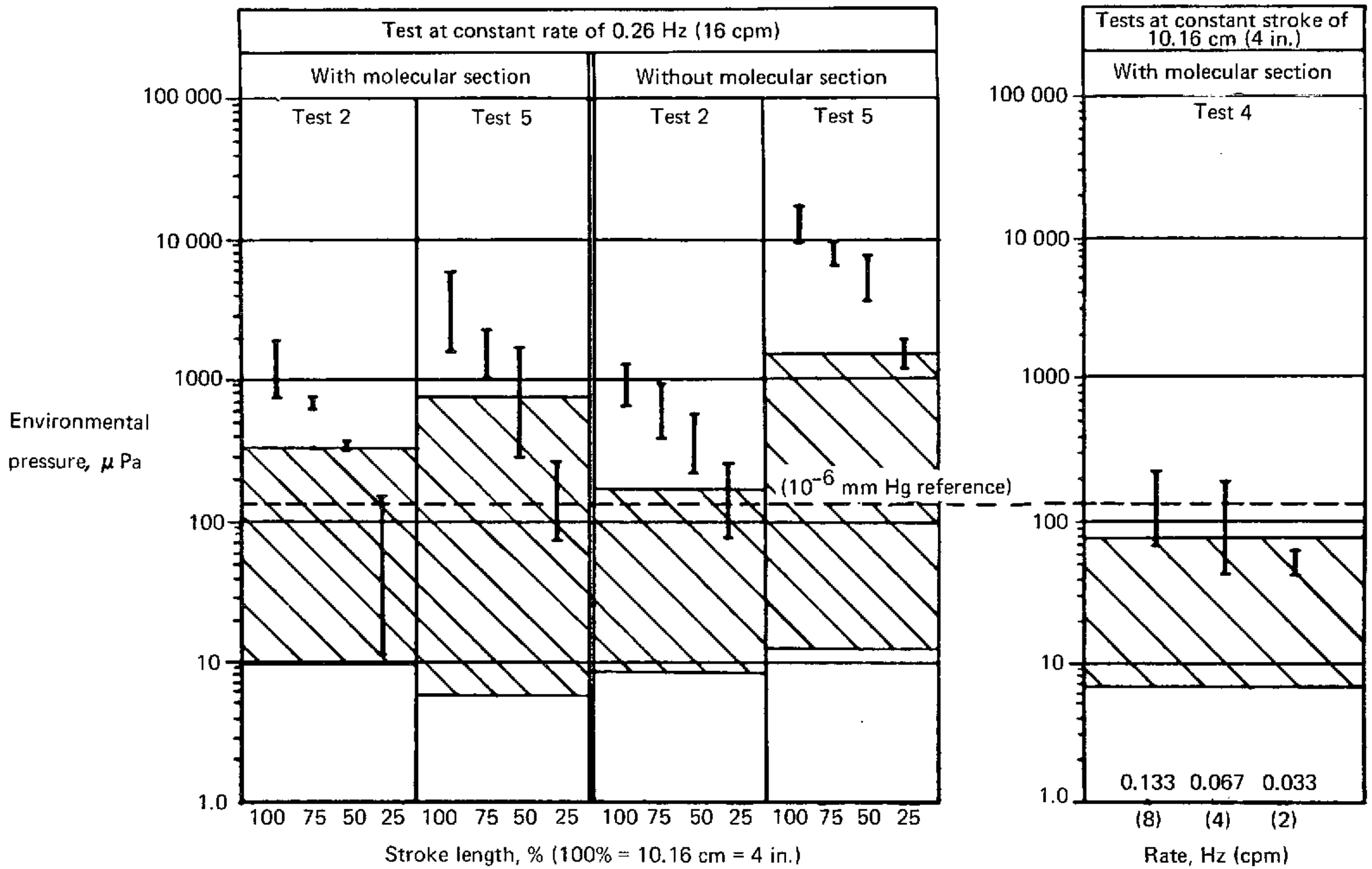
Test 4 was conducted with the molecular flow section installed. The actuation stroke was fixed at 10.16 cm (4 in.) and the actuation rate was varied. The rate was changed in the following sequence: 0.13, 0.13, 0.07, 0.03, 0.03, 0.07, 0.13, 0.13, 0.07, etc.,Hz (8, 8, 4, 2, 2, 4, 8, 8, 4, etc.,cpm).

Test 5 was conducted with MIL-H-5606 in the fluid loop. This test was otherwise a repeat of test 2 described above.

Test Results

Tests 2, 4, and 5, using MIL-H-83282 and MIL-H-5606 fluids, were completed with no failures or deterioration of the test seals. The seals were exposed to a total of 2491 hr under hard vacuum, 583 hr of these with the actuator rod being stroked for a total of 472 571 extend-retract cycles. See table II for a breakdown of these totals for each test. The vacuum pressures maintained during the tests are shown in figure 11.

Measured chamber pressures during actuation periods were higher than pressures when the actuator was stowed. This showed the effect of actuator external leakage on chamber vacuum maintenance. All chamber pressure measurements taken during testing were higher than the demonstrated 13.3 nPa (10^{-10} mm Hg) pressure of the chamber in its clean, dry, and empty condition.



Note: Crosshatched area shows range of vacuum pressure during storage

FIGURE 11.—RANGE OF CHAMBER PRESSURE DURING ROD ACTUATION IN VACUUM ENVIRONMENT

TABLE II.—VACUUM ENVIRONMENT TEST DURATION

Test sequence	Hours under hard vacuum	Actuator stroking hours	Actuator strokes
Test 2 (MIL-H-83282)			
With molecular section	446	105	100 269
Without molecular section	488	112	108 222
Test 4 (MIL-H-83282)			
With molecular section	504	129	37 001
Test 5 (MIL-H-5606)			
With molecular section	482	109.	104 148
Without molecular section	571	128	122 931
Totals	2491	583	472 571

Seal leakage was measured both during rod actuation and while the rod was in the stowed (retracted) position during overnight and weekend periods. Results are presented in table III showing the leakage during actuation reduced to an average loss per 8-hr shift. The maximum seal leakage during both actuation and stowage periods is shown in table IV.

A small quantity of hydraulic fluid was found inside the vacuum chamber following each vacuum test. About 8.1 cm^3 (0.494 $in.^3$) was taken from the chamber and below the actuator following test 2. Approximately 5.6 cm^3 (0.342 $in.^3$) of fluid was recovered similarly following test 4. Prior to test 4, a quartz window was installed in a port just below the actuator to allow observation of the fluid under vacuum. Fluid appeared in the port during the last day of actuation. No fluid movement (boiling) was observed.

At the midpoint of test 5 the chamber was opened to remove the molecular section. Approximately 0.25 cm^3 (0.015 $in.^3$) of fluid was recovered from inside the chamber. No additional fluid was observed at the completion of test 5.

POSTTEST INSPECTION

K-Section Seals

The test K-section seal shown in figure 12 was removed from the seal module for inspection only at the conclusion of all testing reported herein. The seal elements were noted to fit snugly on the actuator rod and in the seal cavity. Figure 13 shows the detailed condition of the seal elements upon removal from the module.

TABLE III.—SEAL LEAKAGE, VACUUM ENVIRONMENT TESTS

Constant rate of 0.27 Hz (16 cycles per minute)										
% stroke[a]	Run (b)	With molecular section				Without molecular section				
		Test 2[c]		Test 5[d]		Test 2[c]		Test 5[d]		
		cm^3/8 hr	Drops/ 8 hr	cm^3/8 hr	Drops/ 8 hr	cm^3/8 hr	Drops 8 hr	cm^3/8 hr	Drops/ 8 hr	
100	1	1.65	33	1.40	[e]28	3.50	70	6.60	132	
	2	0.70	14	1.80	36	2.55	51	5.90	118	
	3	0.65	13	2.30	46	1.50	30	6.50	130	
	4			2.30	46	0.65	13	5.55	111	
	5							6.50	130	
75	1	2.85	57	0.65	13	1.00	20	4.00	80	
	2	-0.75	[f]-15	1.70	34	0.85	17	3.15	63	
	3	0.25	5	1.45	29	-1.35	[g]-27	3.60	72	
50	1	0.00	0	1.55	31	1.50	30	2.75	55	
	2	0.85	17	1.10	22	1.10	22	2.10	42	
	3	-0.10	-2	0.85	17	0.40	8	1.80	36	
	4	0.30	6	0.50	10					
25	1	0.95	19	0.00	0	0.60	12	0.80	16	
	2	0.70	14	0.30	6	-0.10	-2	1.10	22	
	3	-0.05	-1	0.30	6	1.30	26	1.65	33	
	4					0.60	12			

Constant stroke at 10.16 cm (4 in.)			
Rate, Hz (cpm)	Run (b)	With molecular section	
		Test 4[c]	
		cm^3/8 hr	Drops/ 8 hr
0.13 (8)	1	0.50	10
	2	-0.15	-3
	3	0.45	9
	4	0.58	12
	5	0.10	2
0.07 (4)	1	0.15	3
	2	0.45	9
	3	-0.25	-5
	4	0.25	5
	5	0.10	2
	6	0.15	3
0.03 (2)	1	0.05	1
	2	0.10	2
	3	0.25	5
	4	0.10	2

[a]100% = 10.6 cm (4 in.)

[b]Sequence of runs was 100%, 75%, 50%, 25%, 100% . . . stroke conditions in tests 2 and 5; and 0.13, 0.07, 0.03, 0.13 Hz . . . (8, 4, 2, 8 . . . cpm) rate in test 4.

[c]Test fluid: MIL-H-83282 (ref. 8)

[d]Test fluid: MIL-H-5606 (ref. 10)

[e]Leakage for half-day actuation

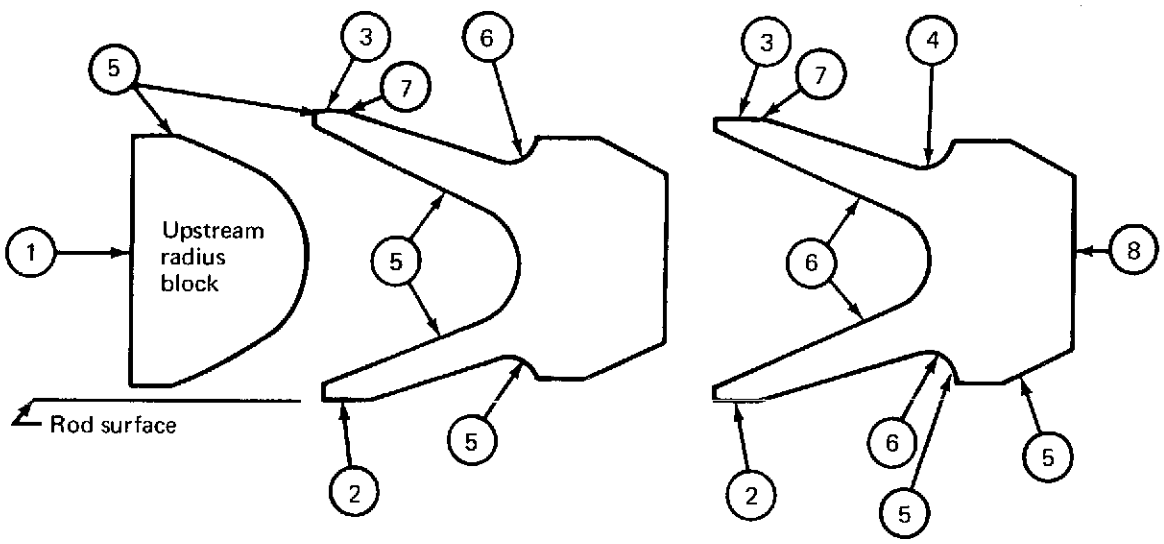
[f]Negative leakages result from applying correction factors to adjust for environmental temperature variation. All negative leakages, except this value, are within instrumentation-allowable tolerance. The high magnitude of this individual measurement is not readily explainable.

[g]Leakage following capillary tube overfill

TABLE IV.–MAXIMUM LEAKAGE, VACUUM ENVIRONMENT TESTS

Test	Test fluid used			Molecular section evaluation conducted	Time per condition, hr			Leakage				
	MIL-H-83282 (ref. 8)		MIL-H-5606 (ref. 10)		No-load cycling	Overnight storage	Weekend storage	Total condition		Total/hour		Cycles per 50 mm^3 (one drop)
	Mobil XRM 206A-1	Mobil XRM 231A						Cm^3	(Drops)	Cm^3	(Drops)	
2	X			Yes	8			2.85	(57)	0.356	(7)	134
						16		3.65	(73)	0.228	(5)	–
							64	0.35	(7)	0.006	(0)	–
				No	8			3.50	(70)	0.438	(9)	113
						16		0.40	(8)	0.025	(1)	–
							64	0	(0)	0	(0)	–
4		X		Yes	8			0.58	(12)	0.072	(1)	360
						16		0.95	(19)	0.059	(1)	–
							64	2.05	(41)	0.032	(1)	–
5			X	Yes	8			2.30	(46)	0.288	(6)	167
						16		2.30	(46)	0.144	(3)	–
							64	0.60	(12)	0.009	(0)	–
				No	8			6.60	(132)	0.825	(17)	58
						16		0.70	(14)	0.044	(1)	–
							64	1.10	(22)	0.017	(0)	–

FIGURE 12.—K-SECTION SEAL AT TEST COMPLETION



The test seal was inspected only at the conclusion of all testing. Inspection showed the following at the indicated locations:

(1) No contact was noted, indicating that the gland was long enough so that the thermally expanding seal did not completely fill the cavity.

(2) Highly polished across entire surface, indicating wear had produced an extension of machined flat to approximately 20% greater than the original dimension.

(3) Light contact area noted.

(4) Seal element free of deposits.

(5) Fluid residue clinging to seal surfaces had black grease-like consistency showing evidence of time at temperature. Bronze suspended particles were evidence of wear on molecular flow section.

(6) Heavy fluid residue over approximately 25% of circumference.

(7) Three bronze particles less than 150 μm (0.005 in.) across were observed imbedded in polyimide with the exposed faces flush to the seal surface.

(8) One bronze particle 270 μm (approximately 0.01 in.) across was observed imbedded in polyimide with exposed face protruding up from seal surface.

FIGURE 13.–6.35-CM (2.5-IN.) K-SECTION POSTTEST INSPECTION

Microscopic inspection of the seal elements revealed no surface cracks. The dynamic sealing surfaces at the tips of the inner legs of the K-sections were highly polished. The downstream element appeared more polished and the width of the surface was 0.127 to 0.254 mm (0.005 to 0.010 in.) wider than the same surface on the upstream element. In comparison, this surface on the inner leg was 70% wider than the contact surface on the outer leg, which is not subject to dynamic wear. Some clearly defined streaks in the direction of rod movement were noted across the dynamic sealing face of both elements. The streaks were more clearly defined than the normal wear band from rod stroking and may have been caused by bronze particles similar to those observed imbedded in the seals (see fig. 13). The fluid residue found on the seal elements was black in color and grease-like in consistency, indicating it was most probably trapped and resided in the seal cavity some time during thermal cycling. The residue could easily be washed from the seals with solvent.

Molecular Flow Section

The molecular flow section was examined at the completion of each of the vacuum tests (tests 2, 4, and 5). Polished surface areas were noted at each end of the inner surface of the section and diametrically opposed. This wear pattern indicated minor sideloading that resulted in surface wear. At the completion of each successive test the wear area was increased. At the conclusion of test 5 nearly one-half of the circumference at each end of the section indicated wear (see fig. 14). Maximum wear depth at the conclusion of testing was measured as 0.0025 mm (0.0001 in.).

A polyimide first-stage rod seal (ref. 3) was used as a scraper in the molecular flow section (see app. A). The rubbing surface on the scraper showed only a slight indication of wear, including some axial surface streaks similar to those observed on the K-section seals. The wear was not considered excessive since the seal dimensionally remained within new seal tolerances at the completion of all vacuum testing.

Test Actuator Rods

The actuator rod used during thermal cycling was inspected at the conclusion of each thermal cycling test (tests 1 and 3). The rod exhibited only superficial longitudinal marks in the seal running area. There was no buildup of hard, baked-on or varnish deposits on the rod using MIL-H-83282.

The actuator rod used during vacuum testing was inspected at the conclusion of vacuum testing (following test 5). The rod surface showed a series of overlapping superficial longitudinal marks in the areas swept by the K-section seal, molecular flow section, and polyimide scraper at the various strokes. Other external inspections of the actuator rod during the vacuum tests showed the rod to be clean of deposits or fluid residue following tests 2 and 4. When the molecular section was removed during test 5 there was a dark, sticky residue on the exposed rod that easily wiped clean. A

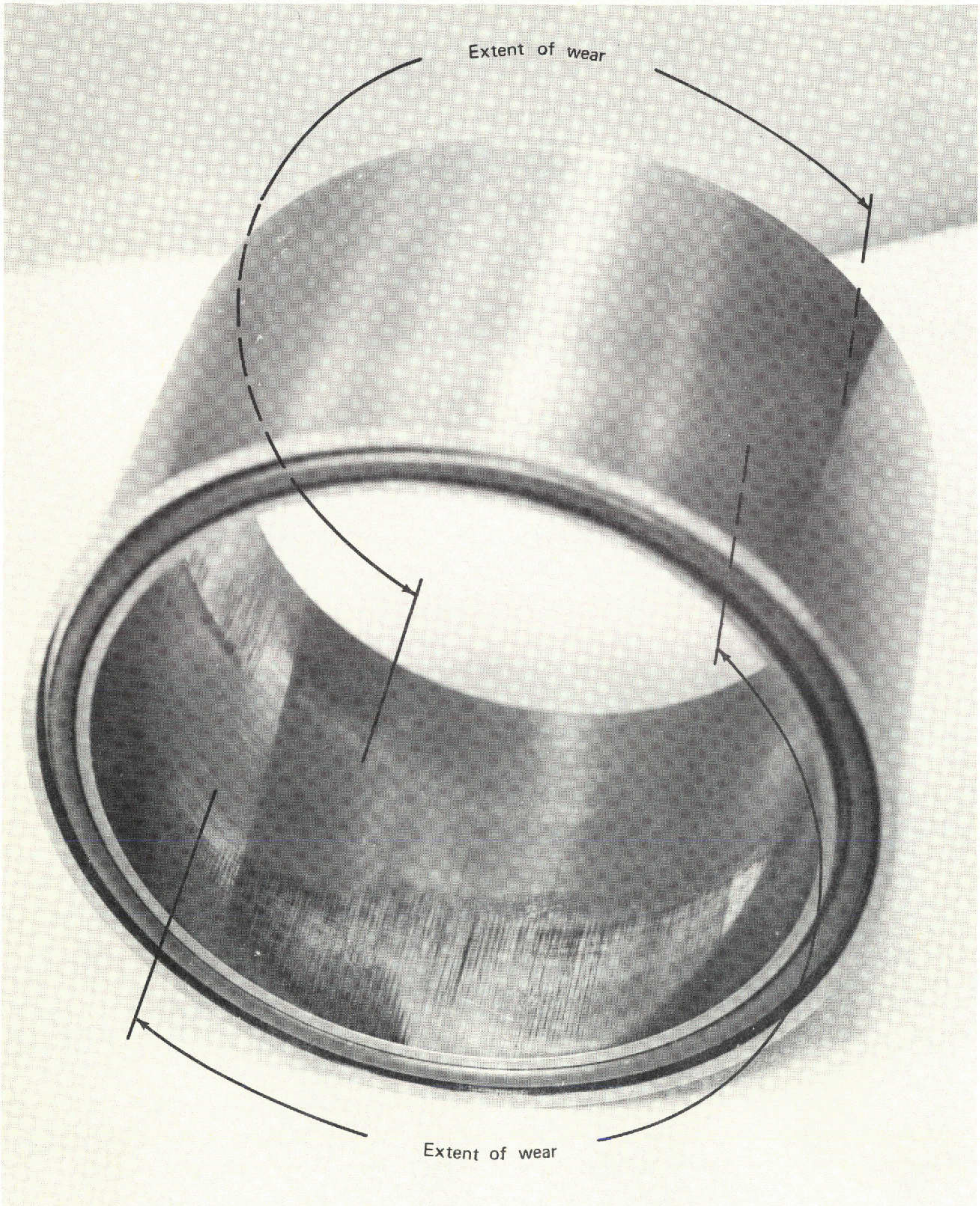


FIGURE 14.—MOLECULAR FLOW SECTION AT TEST COMPLETION

similar film in a 12.5-mm (0.5-in.) band appeared on the rod at the completion of test 5. This residue or film was also found during other tests using MIL-H-5606 fluid in vacuum, as described in reference 11.

DISCUSSION OF RESULTS

The same set of 6.35-cm (2.5-in.) K-section seals was used throughout the thermal cycling and vacuum tests to obtain seal exposure typical of space shuttle on-station (actuation and stowage) and reentry conditions. Seal performance with two fluids was evaluated during vacuum testing to show leakage variation between a petroleum-base fluid and a synthetic hydrocarbon-base fluid. Under these combined conditions a total of 8.50×10^5 cycles were accumulated on the one set of polyimide seals.

THERMAL CYCLING TESTS

The 6.35-cm (2.5-in.) K-section seal was operated for a total of 3.74×10^5 long-stroke, extend-retract cycles during 96 thermal cycles accumulated by 205 hr of testing. These results indicate the ability of this seal to withstand cyclic stresses imposed by the differences in thermal expansion between the polyimide seal and the steel actuator materials. Such temperature excursions as those tested would be expected once per flight during reentry of a space shuttle; thus a seal minimum life of approximately 100 flights could be anticipated.

The visual observation method of measuring second-stage leakage at the high test temperatures cannot account for fluid lost due to fluid film vaporization. Experience indicated the volume of vaporized fluid to be negligible. Even if an assumed vaporized volume were added to the measured leakage, the low leakage demonstrated would be well within the acceptable leakage requirements for a linear rod seal in an aircraft application or during reentry of a space shuttle vehicle.

The absence of cracks in either the upstream or downstream seal element indicated that the fatigue life for the seal assembly was not exceeded during these tests. Previous experience with the seal design showed that sealing integrity can be maintained by the downstream element of the assembly in the event that the upstream element fails (ref. 3). The satisfactory condition of the seal contact surfaces and corresponding cycling area on the actuator rods demonstrated the compatibility of the polyimide seal materials and the hard chrome surface for future system applications.

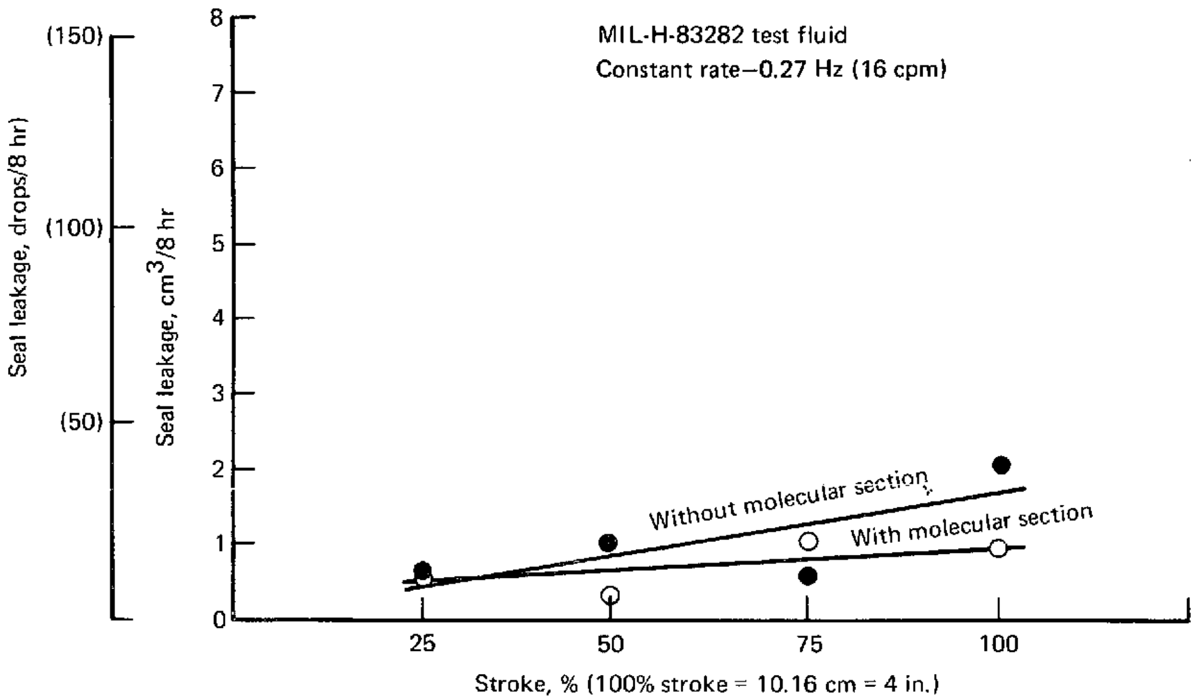
The hard chrome actuator rod used for these tests was hand burnished lightly with polyimide SP-21 material after the final grinding to 6 to 7 rms. The actuator rod was in better condition after test than the unburnished actuator rods used during the reference 3 contract, which had the same machine finish. Due to the limited samples and differences in testing conducted, it is not known whether the better performance can be attributed to the burnishing operation. Additional material compatibility and wear tests would be required to verify the advantages of burnishing with polyimide.

Some deposits were noted on the exposed portion of the actuator rod. These deposits were not baked on, probably because the maximum exposure at any given stroke was on the order of 1 hr. The deposits were therefore effectively removed by the spring-loaded polytetrafluorethylene (PTFE) scraper with 15% graphite fill during longer stroke actuation. This is in contrast to the results from endurance testing at 478° K (400° F) (ref. 4), where short-stroke cycling for 188 hr allowed accumulation of hard residue on the rod that required manual removal.

VACUUM ENVIRONMENT TESTS

The polyimide K-section second-stage rod seal was designed for use in 450° K (350° F) and higher temperature aircraft hydraulic systems. The MIL-H-83282 leakage measured during actuation in a vacuum environment was well within the allowable established for the intended rod seal design in an advanced vehicle application. The maximum leakage recorded during an 8-hr period of actuation was 3500 mm^3 (70 drops), corresponding to 113 extend-retract rod cycles per 50 mm^3 (1 drop) of leakage. This was nine times better than the allowable under design conditions. The highest average leakage rate recorded for an overnight or weekend period was 228 mm^3/hr (5 drops/hr). This leakage was not considered representative of leakage during a stowed condition since it occurred at the start of the test and was much higher than during any other comparable period. The next highest average leakage rate recorded was 59 mm^3/hr (1 drop/hr). The MIL-H-5606 fluid leakage measured during actuation in the vacuum environment was also within the design allowables. Maximum leakage in an 8-hr period was 6600 mm^3 (132 drops), corresponding to 58 extend-retract rod cycles for 50 mm^3 (1 drop) of leakage. This was five times better than the allowable under design conditions. The highest average leakage rate recorded for an overnight or weekend period was 144 mm^3/hr (3 drops/hr).

The tests with the molecular flow section showed some reduction in seal leakage over the comparable test with the flow section removed. The result was general over all stroke and rate conditions evaluated as shown on figure 15, but was less definable using MIL-H-83282 than with MIL-H-5606. The average leakage at constant actuation rate shows only minor slope variation between MIL-H-83282 data, with or without the molecular flow section, and MIL-H-5606 data with the molecular section. The performance without the molecular section using MIL-H-5606 fluid was significantly degraded, giving evidence of the advantage of this section with a petroleum-base fluid. The advantage of the molecular section with a synthetic hydrocarbon-base fluid (MIL-H-83252) was not considered sufficiently adequate to suggest its use to provide superior sealing performance.



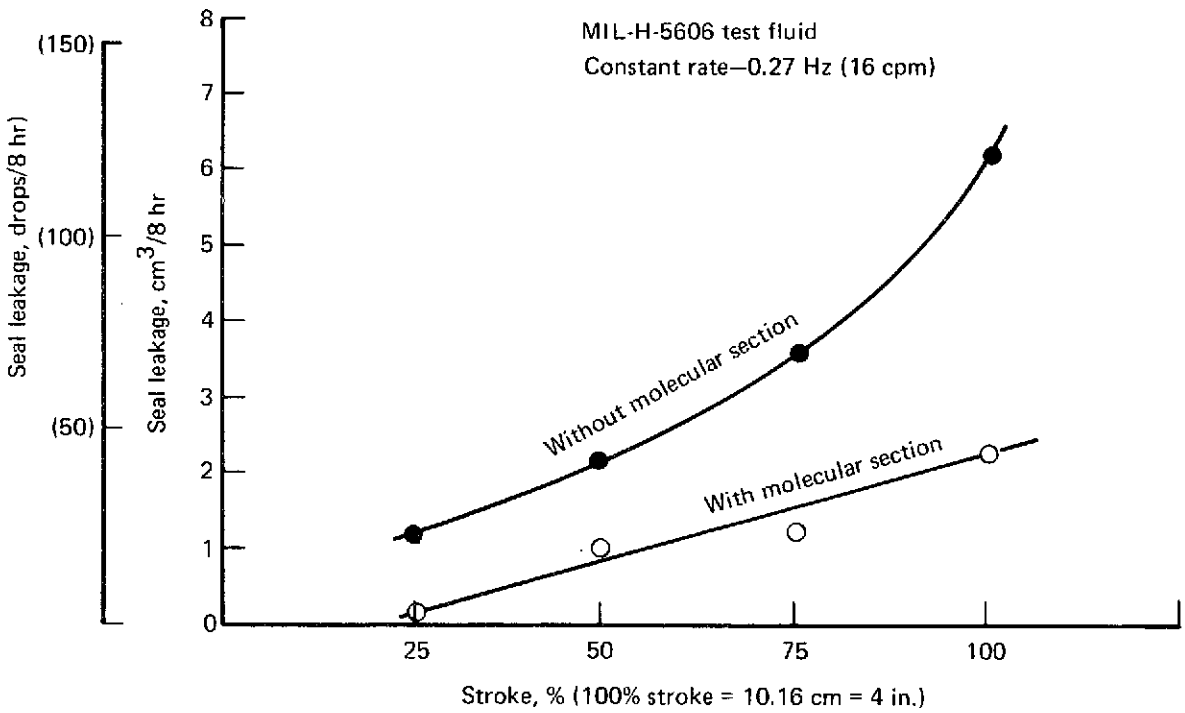


FIGURE 15.—CONSTANT-RATE ACTUATION SEAL LEAKAGE—VACUUM ENVIRONMENT TESTS

Testing at variable rate and constant stroke was performed using only MIL-H-83282 fluid. Figure 16 shows the relative leakage as a function of rate in cycles per minute to be a straight line. This confirms that the leakage in vacuum is a direct function of the time/area exposure of the wetted rod in the vacuum environment.

A comparison of seal leakage during vacuum storage between test 2 with MIL-H-83282 and test 5 with MIL-H-5606 showed that the leakage was less with the synthetic fluid (MIL-H-83282). Leakage during storage in test 2 was insignificant and independent of use of the molecular section except for a transition period at the start of testing and a period of approximately an accumulated 200 hr under vacuum. Leakage during the initial transition period was attributed to not having had a sufficient period of seal-to-rod wear-in. The 0.40 cm^3 (8 drops) loss at approximately 200 hr has no apparent explanation, this having occurred during an overnight period with no manual monitoring.

A definite leakage pattern during storage was recognized with MIL-H-5606 fluid. With the molecular flow section in use the fluid leakage rate was 0.01 cm^3/hr (0.2 drop/hr). Without the molecular section the leakage was doubled—0.02 cm^3/hr (0.4 drop/hr)—indicating the effectiveness of this section during actuator storage when used with a hydrocarbon-base fluid.

Allowable rod seal leakages for space shuttle applications have not been specified for comparison with the test results. An analytical comparison can be made to the definition of "leaktight" as 0.1 mm^3/s of helium under standard atmospheric conditions. This condition is achieved only by supermachining and press fitting of mating parts, which is inconsistent with the functioning of a rod seal. Thus a leaktight rod installation can be achieved only by employing the best practical linear seals in conjunction with a rod-end bellows to prevent external release of the seal leakage obtained.

The test data for leakage measurement showed scatter and the presence of negative leakage. The scatter was primarily due to inexact knowledge of the temperature distribution over the fluid volume under test coupled with an inexact knowledge of the fluid volume within the limits of component parts dimensional tolerances. Any variation in ambient or fluid temperature resulted in a change in system fluid volume, which in turn manifested itself in a change in capillary fluid level. Fluid temperature variations were produced by friction between the rod and seals and at the rod bearings in the end caps. A discussion of the leakage measurement confidence level is contained in appendix D. This shows that the variation is on the order of less than 500 mm^3 (10 drops), 0.1% of the maximum volume in the test system.

Overall leakage for each test (arithmetic sum) was in very close agreement with the capillary tube fill volume. This means that the positive leakages calculated are somewhat conservative (high). For all tests with the molecular flow section, the leakage volume and capillary tube fill volumes

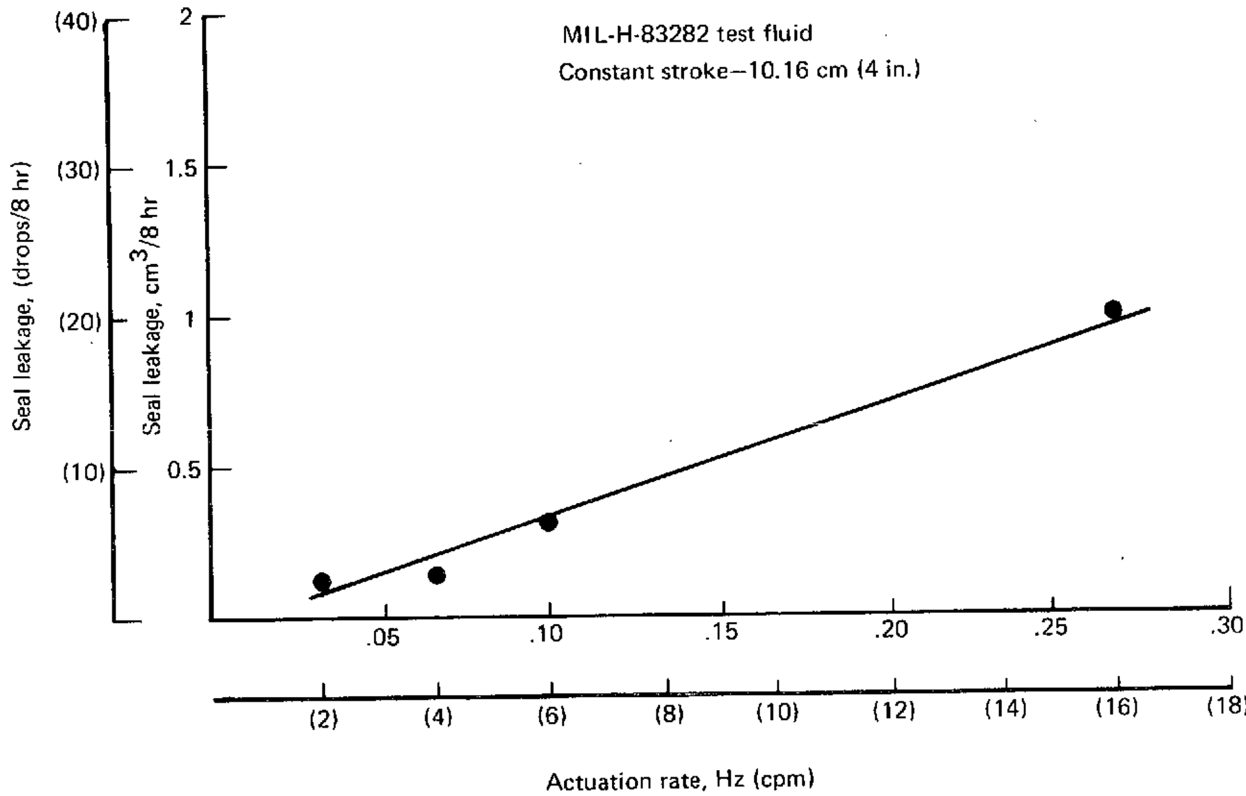


FIGURE 16.—CONSTANT-STROKE ACTUATION SEAL LEAKAGE— VACUUM ENVIRONMENT TESTS

agreed within 2% and were within 10% for the test without the flow section. An inadvertent overfill of the capillary tubes during the test without the molecular flow section accounts for the poorer leakage/fill volume agreement.

The hydraulic fluid that collected in a port just below the actuator mounting port during MIL-H-83282 testing was subjected to differential infrared analysis. The analysis revealed that the fluid exposed to vacuum contained less fluid additive components than did the new fluid. These are the more volatile components of the fluid that were evacuated from the vacuum chamber, leaving a fluid with a higher boiling point in the chamber. This accounts for the fact that no fluid movement (boiling) was noted through the quartz window.

CONCLUSIONS

The 6.35-cm (2.5-in.) K-section second-stage rod seal was proved capable of maintaining seal integrity during alternate exposures to thermal cycling and vacuum environments while installed in a hydraulic system simulating conditions of a space shuttle mission.

The demonstrated wear life of the SP-21 polyimide material at 478° K (400° F) was greater than the expected wear based on published wear data as a function of temperature. It appears, therefore, that the material allowables used in the seal design analysis for fatigue life were very conservative estimates.

Seal leakage during test was well within allowable tolerances for advanced aircraft applications and probably is as low as can be expected for the seal design tested. Any further reduction in actuator external rod leakage will probably necessitate use of a bellows connecting the rod end to the actuator housing and covering the exposed rod.

The molecular flow section showed some advantage from an overall system viewpoint. The advantage was more pronounced with the use of MIL-H-5606 fluid than with MIL-H-83282. The leakage reduction achievable with the molecular flow section is a function of the section length. The effectiveness of a given length must be traded for each application against the added actuator weight necessary to incorporate such a section. Weight increases will include a longer actuation rod, addition of the molecular section, and an extension of the actuator end cap to retain the molecular section.

The polyimide seal development progress has been concentrated on two sizes—2.54 cm (1.0 in.) and 6.35 cm (2.5 in.). During the reported contract, only the 6.35-cm (2.5-in.) size has been evaluated. This procedure has been acceptable for development testing to prove seal design feasibility. Such feasibility is now proved and efforts should be concentrated on providing design characteristics for a family of seal sizes that would be important to the acceptance of the seal in practical industry applications. In conjunction with determining these characteristics, emphasis should be placed on cost reduction by molding, rather than machining, the seals.

APPENDIX A

MOLECULAR FLOW SECTION

The molecular flow section installed in the test actuator during some of the vacuum environment testing was a close-tolerance sleeve fitted on the actuator rod downstream of the K-section seal. The sleeve was contained in a housing for the molecular flow section and was attached to the rod-end cap, as shown in figure 17.

The theoretical background for the design of the flow section is covered in reference 9. In general, the smaller the radial rod-sleeve clearance and the longer the sleeve, the lower the predicted leakage through the flow section. A rod-sleeve clearance of 12.7 μm (0.0005 in.) on the diameter was considered the smallest practical for normal machining practice. Further reduction of the clearance would probably require the rod and sleeve to be manufactured as a matched set.

Since an existing actuator was adapted for the vacuum testing, some envelope constraints were placed on the design presented here. For example, the sleeve length was limited to 5.08 cm (2 in.) to obtain the desired rod-stroke length of 10.16 cm (4 in.). See figure 17 for details of the design and installation of the flow section in the test actuator. The flow section was designed to free-float on the rod within the flow section housing. The upstream end of the flow section was sealed with an O-ring face seal, thereby forcing any fluid that leaked past the second-stage K-seal to pass through the clearance between the rod and the flow section. The downstream end of the flow section housing was fitted with a two-piece, contracting polyimide wiper loaded with a wave washer.

The flow section was manufactured from AMS 4640 Al-Ni-Bronze. No axial or spiraling tooling marks were allowed. The rod-sleeve clearance for the finished parts was 1.016 to 1.27 μm (0.0004 to 0.0005 in.), with a sleeve inside diameter finish of 16 rms.

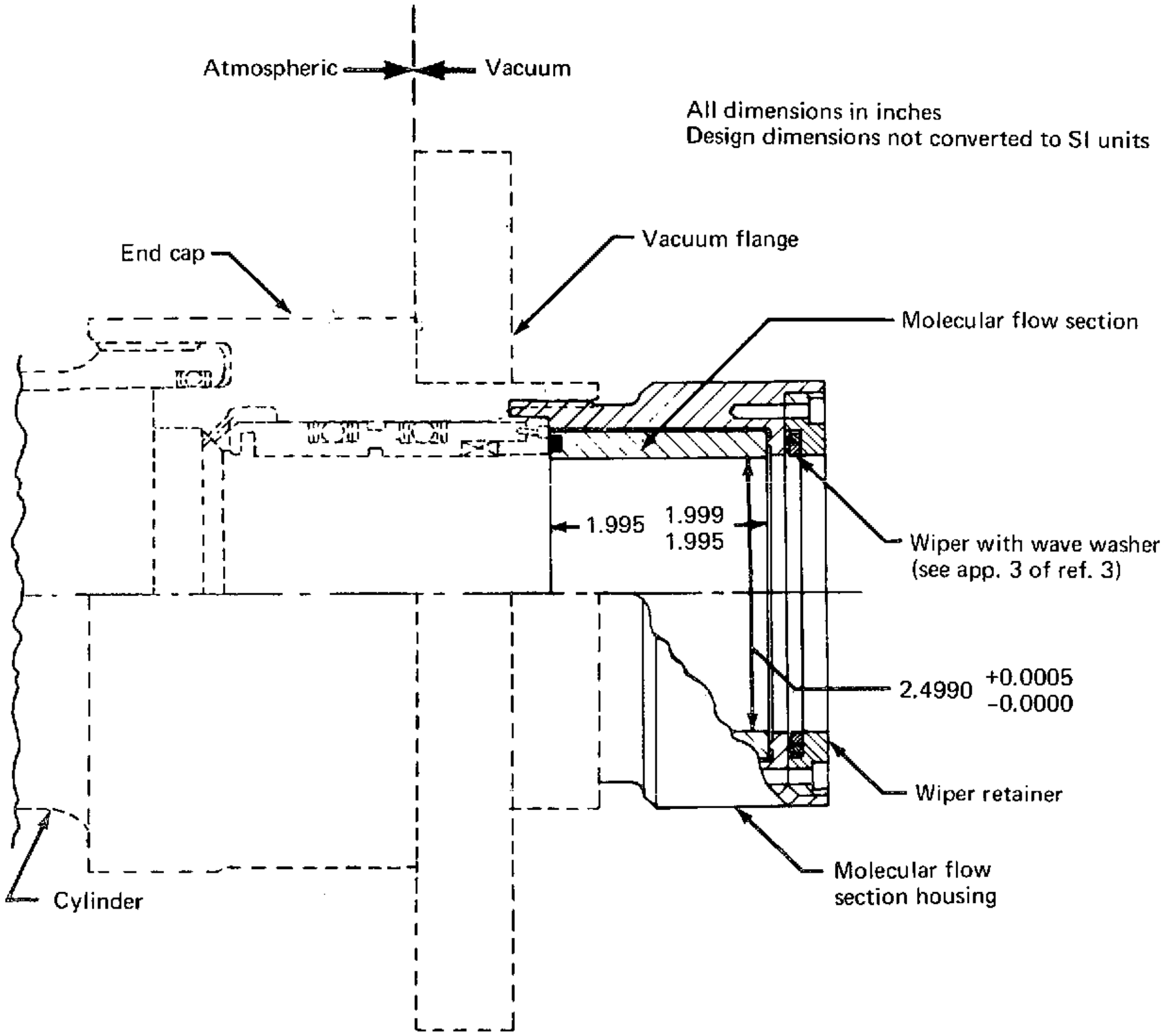


FIGURE 17.—MOLECULAR FLOW SECTION INSTALLATION

APPENDIX B

SECOND-STAGE ROD SEAL ASSEMBLY

Figure 18 shows the design details of the 6.35-cm (2.5-in.) K-section seal configuration.

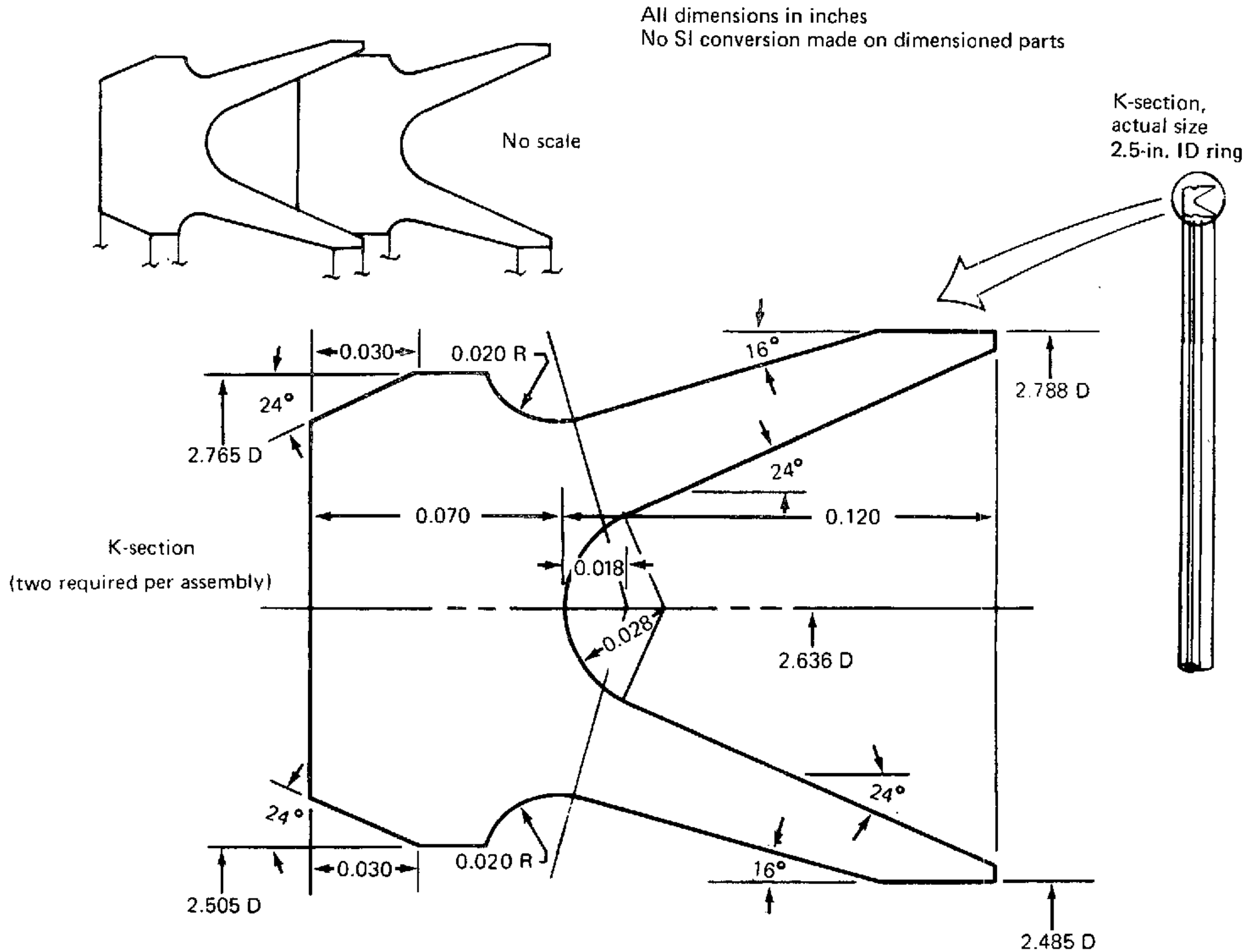
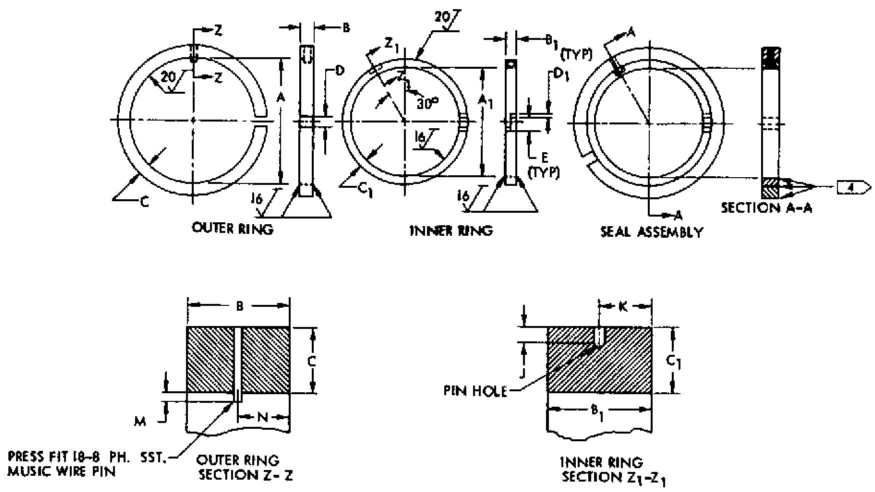


FIGURE 18.—SECOND STAGE ROD SEAL ASSEMBLY, 6.35-CM (2.5-IN.) K-SECTION

APPENDIX C

BOEING STANDARD, SEAL ASSEMBLY, ROD, METALLIC

(First-Stage Seal)



TOLERANCES: ±.005 UNLESS OTHERWISE SPECIFIED

BOEING STD. NO. BACS11AM	KOPPERS PART NUMBER	OUTER RING A	OUTER RING B ±.0005	OUTER RING C	OUTER RING D [2]	OUTER RING D [2] TOL	INNER RING A_1	INNER RING B_1 ±.0005	INNER RING C_1	INNER RING D_1 [1]	INNER RING D_1 [1] TOL	E +.030 -.000	J +.005 -.000	K	M	N ±.001	PIN DIA	PIN HOLE	D [3]
112	56695	.538		.023-.027	.115		.496		.019-.023										.047-.077
113	56698	.600		.023-.027	.115		.558		.019-.023										.047-.077
114	56701	.667		.025-.029	.115	-.000 +.020	.621		.021-.025	.020	+.005 -.000	.074							.047-.077
115	56704	.729		.025-.029	.115		.683		.021-.025				NO PIN						.047-.077
116	56707	.792		.027-.031	.125		.746		.021-.025										.052-.082
211	56710	.854		.027-.031	.125		.808		.021-.025										.052-.082
212	56713	.917		.028-.032	.135		.871	.0610	.028-.033										.060-.090
213	56716	.979	.0620	.028-.032	.135		.933		.028-.033										.060-.090
214	56719	1.041		.030-.035	.135		.996		.028-.033										.060-.090
216	56722	1.172		.035-.040	.150		1.121		.028-.033			.105	.013						.062-.102
218	56725	1.303		.040-.045	.170		1.246		.028-.033	.035					.009 .012				.072-.112
220	56728	1.434		.045-.050	.185		1.371		.029-.034					.0295 .0325		.031	.015	.025	.080-.120
222	56731	1.565		.048-.053	.200		1.496		.032-.037										.087-.127
326	56734	1.698		.053-.058	.220		1.621		.036-.041										.092-.142
327	56737	1.829		.057-.062	.240		1.746		.039-.044	.040		.136							.102-.152
328	56740	1.955		.057-.067	.255		1.871		.041-.047		+.015 .000				.012 .017				.110-.160
329	56743	2.080		.057-.067	.255		1.996		.041-.047				.018						.110-.160
330	56746	2.217		.067-.077	.295		2.121		.043-.053					.0445 .0475					.130-.180
331	56749	2.342	.0920	.067-.077	.295		2.246	.0910	.043-.053	.050						.046	.020	.035	.130-.180
332	56752	2.479		.074-.084	.320		2.371		.049-.059										.142-.192
333	56755	2.614		.078-.088	.320	-.000 +.030	2.496		.054-.064			.167							.142-.192
334	56758	2.741		.084-.094	.360		2.621		.055-.065										.157-.217
335	56761	2.874		.088-.098	.375		2.746		.059-.069	.055									.165-.225
336	56764	2.999		.088-.098	.375		2.871		.059-.069										.165-.225
337	56767	3.135		.097-.107	.415		2.995		.065-.075										.185-.245
338	56770	3.260		.097-.107	.415		3.120		.065-.075				.022		.015 .020				.180-.250
339	56773	3.397		.106-.116	.450		3.245		.071-.081								.025	.040	.197-.267
340	56776	3.522		.106-.116	.450		3.370		.071-.081										.197-.267
341	56779	3.655		.115-.125	.485		3.495		.077-.087										.215-.285
342	56782	3.784	.1235	.115-.125	.485		3.620	.1225	.077-.087		+.020 -.000	.190		.0600 .0630					.215-.285
343	56785	3.923		.123-.133	.520		3.745		.084-.094							.0615			.232-.302
344	56788	4.048		.123-.133	.520		3.870		.084-.094										.232-.302
345	56791	4.185		.133-.143	.560		3.995		.090-.100	.060									.242-.332
347	56794	4.447		.141-.151	.590		4.245		.096-.106										.257-.347
349	56797	4.709		.150-.160	.625		4.495		.102-.112				.037						.275-.365
427	56800	4.972		.159-.169	.660		4.744		.109-.119						.030 .035				.277-.397
429	56803	5.234		.168-.178	.710		4.994		.115-.125		+.030 -.000	.220							.302-.422
431	56806	5.484		.168-.178	.710		5.244		.115-.125								.030	.052	.302-.422
433	56809	5.748		.181-.191	.765	-.000 +.040	5.494		.122-.132										.332-.452
435	56812	5.998		.181-.191	.765		5.744		.122-.132										.332-.452

DATE 18 MAR 70 REV.

1	— —	2	— —

LIST OF ACTIVE SHEETS

CODE IDENT NO. 81205

BAC S11AM SH 1 OF 2

SEAL ASSEMBLY, ROD, METALLIC

BAC S11AM SH 1 OF 2

BOEING STANDARD

PAGE 60.15.6.8.1

1. END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A_1" ±.0005 DIAMETER.
2. END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A" ±.0005 DIAMETER.
3. TENSION CONTROLLED BY OUTER RING GAP, RING IN FREE STATE.
4. I.D. EDGES OF INNER RING MAY HAVE A RADIUS OF .003 MAX FOR SIZES THROUGH BACS11AM345. SIZES LARGER THAN 345 MAY HAVE A RADIUS OF .005 MAX. O.D. EDGES OF OUTER RING MAY HAVE A RADIUS OF .015 MAX. INNER RING O.D. AND OUTER RING I.D. EDGES SHALL BE SHARP. ALL EDGES SHALL BE FREE OF BURRS.

MATERIAL: INNER: KOPPERS K-6E, ALLOY GREY IRON PER AMS 7310 EXCEPT CHROMIUM AND MOLYBDENUM ALLOYING ELEMENTS ADDED.
OUTER: 17-4PH CRES PER AMS 5643 OR AMS 5398, HARDNESS - R_c30-40.
PIN: 18-8 CRES PER AMS 5688.

FINISH: INNER RING ONLY. PARCO LUBRITE NUMBER 2 PER BAC5810, CLASS 1. THE RING SHALL THEN BE IMMEDIATELY IMMERSED IN HYDRAULIC FLUID WHICH MEETS THE REQUIREMENTS OF BMS3-10 AND PACKAGED WHILE DRIPPING WET WITH FLUID.

SURFACE ROUGHNESS: 63 RHR PER USAS B46.1 UNLESS OTHERWISE SPECIFIED. ROUGHNESS TO BE MEASURED PRIOR TO PARCO LUBRITE TREATMENT.

MARKING: EACH PACKAGE SHALL BE MARKED WITH THE SUPPLIER'S NAME, TRADEMARK OR CODE NUMBER, THE SUPPLIER'S PART NUMBER, AND THE BOEING STANDARD NUMBER.

CLEANING: PER KOPPERS COMPANY SPECIFICATION E-3803 TITLED "CLEANING AND PACKAGING PARTS TO BE USED IN PRECISION SEAL APPLICATIONS." CHLORINATED SOLVENT SHALL NOT BE USED IN THE CLEANING PROCESS.

PACKAGING: RING SETS CONSISTING OF AN OUTER AND INNER RING IN MATCHED SETS SHALL BE INDIVIDUALLY PACKAGED IN A HEAT SEALED POLYETHYLENE BAG. THE BAG SHALL THEN BE PLACED IN RIGID OR SEMI-RIGID BOXES.

INSPECTION: 100% INSPECTION BY THE MANUFACTURER. ASSEMBLY TO BE 100% LIGHT TIGHT BETWEEN INNER RING AND GAGE IN A GAGE OF "A_1" ±.0005 DIAMETER, AND 100% LIGHT TIGHT BETWEEN INNER AND OUTER RINGS FOR A DISTANCE EXTENDING 20° EITHER SIDE OF INNER RING STEP JOINT. LIGHT WHICH CAN BE PRESSED OUT WITH A RADIAL FORCE NOT EXCEEDING 5 LBS/INCH OF RING DIAMETER SHALL NOT BE CAUSE FOR REJECTION. EACH ASSEMBLY SHALL BE INSTALLED IN A TEST FIXTURE WITH A ROD FINISH OF 8 RHR AND A DIAMETER EQUAL TO THE MINIMUM ALLOWABLE PER MIL-G-5514, TABLE I, COLUMN "B". THE FOLLOWING TESTS SHALL BE CONDUCTED: MAXIMUM STATIC LEAKAGE USING MIL-F-7024, TYPE II AT ROOM TEMPERATURE AT 750 AND 4000 PSI SHALL NOT EXCEED 10 CC/MIN UP TO 2.500 INCH ROD DIAMETER, 25 CC/MINUTE FOR RODS 2.501 TO 5.000 INCH AND 50 CC/MINUTE FOR RODS OVER 5.000 INCH DIAMETER.

PROCUREMENT: KOPPERS COMPANY INCORPORATED, METAL PRODUCTS DIVISION, BUSH AND HAMBURG, BALTIMORE, MARYLAND 21203 (CODE IDENT NO. 75370)

THE SUPPLIERS LISTED AND THEIR AUTHORIZED DISTRIBUTORS ARE THE ONLY APPROVED SOURCES FOR THE ABOVE QUALIFIED PRODUCTS. CHANGES IN PRODUCT DESIGN OR QUALITY WITHOUT PRIOR BOEING APPROVAL MAY RESULT IN SUPPLIER DISQUALIFICATION. SUPPLIERS OF COMPETITIVE PRODUCTS MAY APPLY TO A MATERIEL DEPARTMENT OF THE BOEING COMPANY FOR QUALIFICATION.

USAGE AND APPLICATION INFORMATION

THESE SEAL RINGS ARE INTENDED AS ROD SEAL RINGS IN HYDRAULIC ACTUATORS WITH FLUID PER BMS 3-10 AT OPERATING TEMPERATURES OF 350° WITH EXCURSIONS TO 500°F. THESE SEALS TO BE USED WITH GROOVES PER BACD2040. THESE SEALS ARE NOT INTENDED FOR ZERO LEAKAGE APPLICATIONS.

SEE PREFACE FOR GENERAL USAGE NOTES.

APPENDIX D

INSTRUMENTATION CALIBRATION AND DATA ACCURACY

Test instrumentation equipment calibrations are traceable through the Boeing flight test calibration laboratory to the National Bureau of Standards. Strain gage bridge-type transducers were calibrated to determine nonlinearity, hysteresis, and R-shunt calibration transfer values. Position transducers were end-to-end calibrated in place by a calibrated scale/visual technique.

Thermal Cycling Test

Pressure

Transducer accuracy within	±0.75% full scale
Power and balance/conditioning within	±0.1% full scale
Oscillograph accuracy within	±2.0% full scale
Pressure-measuring-system accuracy (RSS) within	±2.1% full scale

Displacement

Transducer accuracy within	±0.1% full scale
Signal conditioning within	±0.1% full scale
Oscillograph accuracy within	±2.0% full scale
Displacement-measuring-system accuracy (RSS) within	±2.0% full scale

Temperature

Thermocouple accuracy within	±1.11° K (±2° F)
Temperature recorder within	±2.2° K (±4° F)
Temperature-measuring-system accuracy (RSS) within	±2.5° K (±4.5° F)

Vacuum Environment Test

Fluid Pressure

Pressure gage	±5% full scale

Ambient Temperature

Direct read thermometer	±1.11° K (±2° F)

Fluid Temperature

Thermocouple	±1.11° K (±2° F)
Reference temperature	±0.55° K (±1° F)
Readout	±0.55° K (±1° F)
Temperature-measuring-system accuracy (RSS) within	±1.36° K (±2.45° F)

Vacuum Pressure

Ion gage	
Pressure of 1.33 cPa - 1.33 μPa (10^{-5} to 10^{-8} mm Hg)	±15%
Readout	
Pressure of 13.3 cPa - 133 μPa (10^{-4} to 10^{-6} mm Hg)	±8%
Pressure of 13.3 μPa - 0.133 nPa (10^{-7} to 10^{-10} mm Hg)	±9%
Pressure-measuring-system accuracy (RSS) for	
Pressure of 13.3 cPa - 133 μPa (10^{-4} to 10^{-6} mm Hg)	±17%
Pressure of 13.3 μPa - 0.133 nPa (10^{-7} to 10^{-10} mm Hg)	±17.5%

Capillary Tube Volume

Large-bore capillary tube	±0.8% full scale
Small-bore capillary tube	±1.4% full scale
Readout large-bore capillary tube	±0.5% full scale
Readout small-bore capillary tube	±0.9% full scale
Fluid-level-measuring-system accuracy (RSS), large-bore tube within	±0.9% full scale
Fluid-level-measuring-system accuracy (RSS), small-bore tube within	±1.7% full scale

LEAKAGE MEASUREMENT CONFIDENCE LEVEL

The capillary tube measurement accuracies listed above can be applied directly to obtain leakage measurement accuracies if the fluid level measurements were made at the same temperature. This results in an accuracy of 1.27% for the large-bore tube and 2.4% for the small-bore tube leakage corresponding to a maximum error of ±60 mm^3 (±1.2 drops) and ±65 mm^3 (±1.3 drops), respectively, and ±62.5 mm^3 (±1.25 drops) when both tubes are used simultaneously.

Because the fluid temperature was not the same at all times when fluid level was measured, the measurements were corrected to a common reference temperature prior to establishing leakage volume. This was required to correct for the thermal expansion of the trapped fluid volume. The correction is influenced by the total fluid volume, the coefficient of thermal expansion, and the difference between the temperature at the time of measurement and the reference temperature. The fluid volumes of the actuator and connecting tubing were calculated based on drawing dimensions. The coefficient of thermal expansion for MIL-H-83282 was provided by Mobil and was considered accurate within ±10%. The coefficient for MIL-H-5606 was obtained from published data. Temperature accuracies are listed above. The "fluid temperature" readings were used for actuator volume correction and "ambient temperature" readings for connecting tubing volume corrections. The calculated fluid volume correction factors are listed below:

Test 2	
Actuator correction factor	
Maximum	130 mm^3/°K ±10% (2.6 drops/°F ±10%)
Minimum	120 mm^3/°K ±10% (2.4 drops/°F ±10%)
Connecting tubing	25 mm^3/°K ±10% (0.5 drop/°F ±10%)

Prior to test 4, a sleeve was manufactured and installed to reduce the test actuator fluid volume and thereby reduce the magnitude of the correction factor determined above. Subsequent correction factors for the MIL-H-83282 fluid used in test 4 and for the MIL-H-5606 fluid used in test 5 were identical within the accuracy of calculation and are as follows:

Tests 4 and 5	
Actuator correction factor	
Maximum	35 mm^3/°K ±10% (0.7 drop/°F ±10%)
Minimum	30 mm^3/°K ±10% (0.6 drop/°F ±10%)
Connecting tubing	25 mm^3/°K ±10% (0.5 drop/°F ±10%)

The corrections were made on the assumption of no variation in the temperature throughout the fluid volume.

Assuming an ambient temperature accuracy of ±1.11° K (2° F) and a fluid temperature accuracy of ±1.36°K (2.45° F) in establishing the differential temperature between two readings, the following confidence of leakage correction was calculated for a temperature change of 5.5° K (10° F) between the two leakage measurements.

Test 2

Actuator	±449 mm^3 (±8.97 drops)
Connecting tubing	± 75 mm^3 (±1.50 drops)
Overall (RSS)	±455 mm^3 (±9.09 drops)

Tests 4 and 5

Actuator	± 86 mm^3 (±1.72 drops)
Connecting tubing	± 75 mm^3 (±1.50 drops)
Overall (RSS)	±142 mm^3 (±2.84 drops)

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