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TECHNOLOGY REPORT

VALVE LIPSEALS

M-1 SLEEVE-TYPE THRUST CHAMBER VALVE

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ABSTRACT

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The design investigation reported was undertaken in an attempt to develop a zero leakage dynamic cryogenic seal. Background theory, seal evaluation, and design and development method are discussed. The results of this investigation indicated that an advance in the technology of dynamic cryogenic seals had been made; however, further work to optimize the design is feasible and is recommended.

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I. SUMMARY

Candidate cryogenic dynamic seals were tested prior to initiating M-1 engine contract work. From this testing it was determined that existing seals would not meet the zero leakage requirements for the M-1 thrust chamber valves and that a seal development effort would be required. The work accomplished in designing and developing seals for the M-1 thrust chamber valves is presented in this report.

Although two types of thrust chamber valves were involved, only the sleeve-type configuration was completely fabricated and tested. The sleeve-type thrust chamber valve is shown in Figure 1. In the sleeve-type thrust chamber valve, two different sizes of lipseals were used to seal high pressure cyrogenic fluids (liquid oxygen and liquid hydrogen). One of these seals was the actuating shaft seal (1.25-in. nominal diameter), and the other was the sleeve-gate lipseal (11.0-in. nominal diameter). This report deals primarily with the larger seal because it constituted a major portion of the development effort. This large sleeve-gate lipseal was used in the valve as an upper sleeve seal which remained in constant contact with the sleeve and as a lower shut-off seal which disengaged with the sleeve during valve opening and re-engaged during valve closure.

The seal that showed the best potential for development was a Kel-F flanged lipseal. The performance of this lipseal was well known from its use in the Titan I liquid oxygen thrust chamber valve. The Kel-F flanged lipseal configuration was adapted to the M-1 thrust chamber valve sleeve-gate and shaft for both the liquid oxygen and liquid hydrogen valves. Leakage rates of less than 1 cc/min were achieved for these valve seals at pressures of up to 1800 psig; however, these leakage rates were not consistent. The average leakage rate for the large 11-in. seal was approximately 500 cc/min, thus indicating the need for design refinement. Also, this type of seal is very critical with respect to seal quality, sealing-surface finish, mating-surface, lubrication, and test-fluid contamination.

During the seal development, the optimum seal design became a compromise between good sealing and structural strength. The best pressure-sensitive seals were too flexible to withstand high pressure. Even the best compromise configuration failed structurally at 2400 psig. Therefore, the design was modified to incorporate a steel support ring within the seal flange inner diameter. This device permitted satisfactory seal performance beyond the required operating limits. The seal sustained a test pressure of 3000 psig without structural damage.

The control of frictional drag is a lipseal design problem. High unit pressure is essential for good sealing at the seal contact area. A typical seal friction for a 11-in. diameter seal, using liquid nitrogen as test fluid, ranged from 200-lb force at zero pressure differential to 2300-lb force at 1400-psig pressure across the seal. However, the design with the steel backup ring limits seal pressure sensitivity. With liquid nitrogen, the friction peaked at 1460-lb force at 800-psig pressure and then decreased as the pressure increased.

The general design and development method used was to adapt an existing seal design for application in the M-1 thrust chamber valve. The seal was then

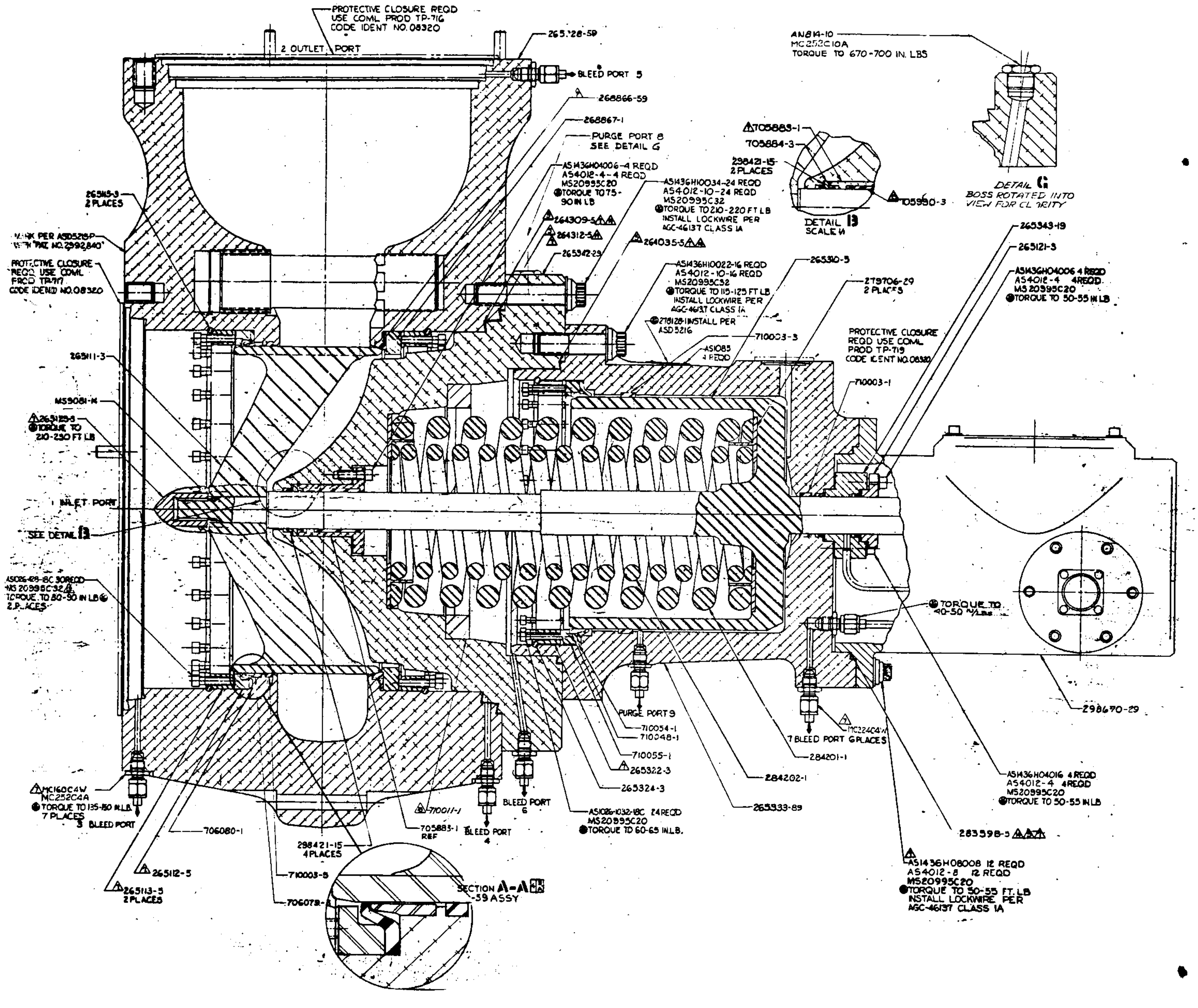

Figure 1

Thrust Chamber Valve, Sleeve-Type, P/N 705520 tested to determine what design modifications were required to meet the more severe conditions (i.e., zero leakage in liquid oxygen and liquid hydrogen at leak test pressures up to 1800 psig). Zero leakage for internal seals was defined as being less than one gas bubble/min at standard pressure and temperature, which is equivalent to 1×10^{-3} cc/min.

II. INTRODUCTION

A precontract search coupled with testing of candidate dynamic cryogenic seals revealed that no adequate seal existed for the zero leakage requirements of the M-1 engine thrust chamber valves. However, the basic design of the flanged seal (Kel-F) used in the Titan I liquid oxygen thrust chamber valve showed development potential. Seals designed for the M-1 Program included the configurations shown in Figure 2 (Configurations A, B, C, D, and E).

The purpose of the seal investigation was to find and/or develop a seal with zero leakage capability. In the M-1 Program, zero leakage was defined as being 1×10^{-3} cc/min.

The cross-section and general configuration of the seals designed for the M-1 engine thrust chamber valves were based upon the indicated Titan I seals. The program approach to improve seal performance was to test and then modify this design as test results dictated. When a seal design performed well at ambient temperature, cryogenic (liquid nitrogen and liquid hydrogen) testing was performed to evaluate the seal in its operating environment. An anlytical design approach to modify Titan I seals was unsuccessful because the seal stress patterns were too complex and material properties data for Kel-F at cryogenic temperatures were too limited.

The development test results are summarized and presented herein. They represent the data collected during the development testing of the M-1 engine thrust chamber valve shaft and sleeve-gate seals; however, primary emphasis is placed upon the larger (11-in. diameter) sleeve-gate seal. A more detailed presentation of the data and a discussion of test results has been provided in another report(1).

III. BACKGROUND THEORY

In general, sealing theory is based upon the concept of two material surfaces coming in close contact to prevent the flow of a gas or liquid between the two surfaces. In a sliding valve seal, the two surfaces continuously touch and move against each other in a shearing mode.

If the plane, spherical, cylindrical or conical surfaces that are in contact are absolutely congruent in a mathematical sense, no flow path exists. Leak tightness is attained without the use of high contact forces between the surfaces.

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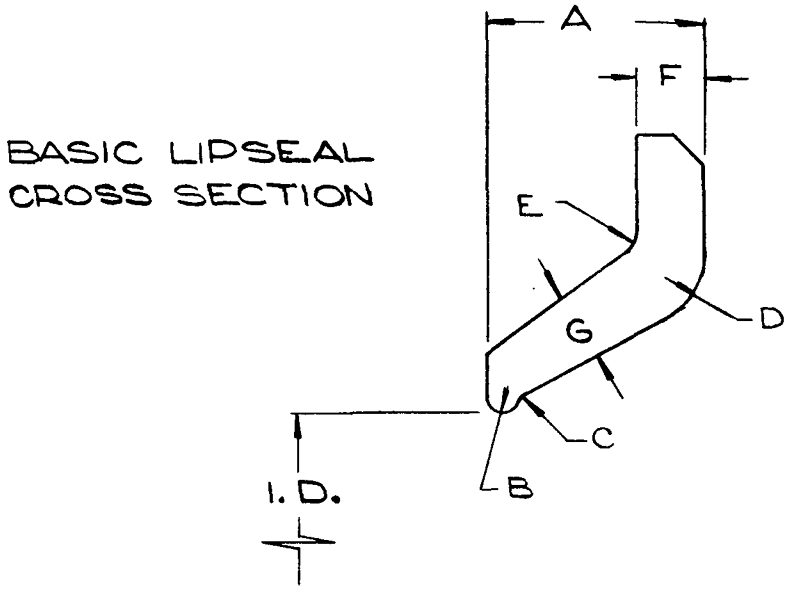
(1) Henson, Floyd M, An Evaluation of Gaskets, Seals, and Joints for Aerospace Hardware, Aerojet-General Report AGC 8800-39, March 1966 (To be subsequently published as a NASA Contractor Report)



CONFIGURATION	SEAL PART NO.	I. D. ±.005	A	B	C	D	E	F	G	ASSY BURST STRENGTH PSIG
A	265114-F									
	-1&-7	10.830	.410	.030	.030	.030	.060	.125	.100	2,400
	-3&-11	10.820	↕	↕	↕	↕	↕	↕	↕	↕
	-5&-13	10.810	↕	↕	↕	↕	↕	↕	↕	↕
	-15	10.800	↕	↕	↕	↕	↕	↕	↕	↕
	-17	10.790	.410	.030	.030	.030	↕	↕	.100	↕
B	704631	10.830	.300	.050	.050	.050	↕	↕	.150	↕
	705013	10.830	.380	SQ	.100	.050	.060	.125	.150	↕
C	705458-B									↕
	-1	10.800	.375	.050	.300	.035	.060	.125	.100	↕
	-5	10.810	↕	↕	↕	↕	↕	↕	↕	↕
	-7	10.820	↕	↕	↕	↕	↕	↕	↕	↕
	-11	10.830	.375	.050	.300	.035	.060	.125	.100	2,400
D	706080									
	-1	10.820	.375	.050	.050	.150	.125	.125	.090	3,000
	-3	10.810	.375	.050	.050	.150	.125	.125	.090	3,000
E	298421									
	-15	1.215	.200	.030	.030	.050	.050	.055	.050	3,000

Figure 2

Comparison of Lipseal Configuration Dimensions

If the surfaces are not congruent, or if contamination particles are entrapped, a geometric leak path is created. To obtain a tight seal, the resulting crevice must be closed under a force that is capable of deforming the sealing surface and/or the contaminant particle until an uninterrrupted line of contact is established.

Conventional manufacturing methods, including the best lapping and diamond dust polishing, are not capable of producing a perfectly smooth surface of monomolecular dimensions. Instead, there are surface irregularities consisting of somewhat evenly distributed asperities of various heights and occasional random disturbances (e.g., nicks and scratches).

Fundamentally, using existing technology and fabrication techniques, there must be a definite unit loading of the seal against the sealing surface to have an effective dynamic seal. The unit loading must be increased when leakage allowances are reduced or when sealing against higher pressures is required. This additional unit loading results in a greater seal friction force. The contact area is another parameter affecting the force required to move a component past the seal.

IV. LIPSEAL DEVELOPMENT METHOD

A. EVALUATION

1. Aerojet-General Flange Seal Design AS1023

The AS1023 flange seal made of Kel-F (Figure 3) was the first seal of this type to be designed at Aerojet-General for the dynamic sealing of rods or shafts which have a rotary or reciprocating motion in rocket engine controls hardware. The operating principle of this seal is to load the seal lip with sufficient force to maintain its positive contact with the rod or shaft during dynamic as well as static conditions. This seal has been used successfully in sizes up to four inches in diameter for both cryogenic and storable propellant applications. A typical application for this standard seal design was its use as a shaft seal for the thrust chamber butterfly valves and as a rod seal for the gas generator oxidizer valves on the Titan I. Both of these valves were used in liquid oxygen systems which operated at pressures of approximately 900 psig.

There are four forces loading seals of this configuration in a cryogenic application. These forces are: preload, pressure, thermal contraction, and flow.

a. Preload Force

Preload force results from the interference fit between the internal sealing diameter of the plastic seal and the dynamic rod (shaft) against which the seal makes contact. Preloading is essential to ensure sealing at low pressures. An example of the interferences provided in typical AS1023 seals, the nominal 0.125-in. diameter seal has a 0.010-in. diametral interference fit with the rod and the 4.00-in. seal has a 0.119-in. diametral interference.

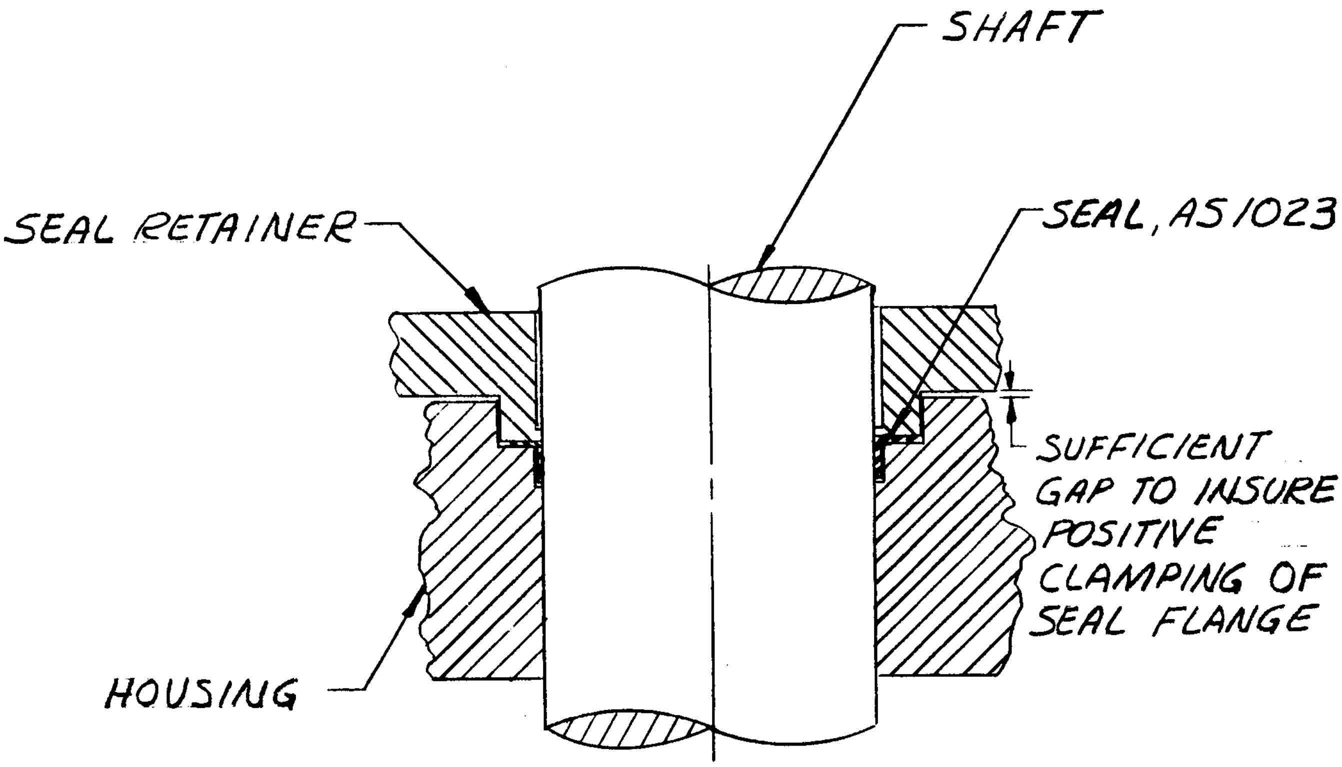


Figure 3

AS1023 Flanged Seal Installation

b. Pressure

If the pressure force is defined as F = PA, with P denoting the pressure on the seal, the only remaining difficulty is to calculate the effective area, A. The effective area for a similar seal has been derived as $A = 0.75 \pi d l$.(2) In this formula, "d" is the rod diameter and "l" is the seal contact length, which is measured from the seal bend radius to the end of the seal lip.

c. Thermal Contraction Force

This force results from differential relative contraction between the seal (supported by the valve body, component housing, etc. usually fabricated of aluminum material) and the rod or shaft which is usually fabricated from steel. The contraction effect occurs during childown in the cryogenic system. In general, the contraction force increases as the temperature decreases.

d. Flow Force

This force is the result of the fluid moving at high velocity and impinging upon the seal. The flow force can be considered directly proportional to the magnitude of the fluid density and velocity for a given seal size.

2. Lipseal Influence Factors

Experience at Aerojet-General with the AS1023 seal indicated that excessive friction would result from attempting to use the basic design at high pressures but with larger seal diameters (greater than four inches). Thus, when the Titan I thrust chamber valve gate lipseal was designed with nominal diameters ranging from three to five inches, an attempt was made to achieve line contact with the valve gate, instead of the large contact area characteristics of the AS1023 design.

The larger-size lipseals for Titan I liquid oxygen thrust chamber valves, which were designed to operate in a cryogenic environment, were shaped to minimize the contraction force by keeping adequate clearance at the knee of the seal. The clearance provided is sufficient to prevent the knee of the seal from contacting the valve gate, regardless of the seal shrinkage at low temperatures. In this manner, seal contact with the mating dynamic part is limited to "line" contact at the sealing lip only.

3. Titan I Liquid Oxygen Thrust Chamber Valve Gate Seal

The gate seal for the Titan I liquid oxygen thrust chamber valve, with a design based upon the concepts described in Section IV.A.2., is shown in Figure 4. This final seal configuration evolved during the associated valve

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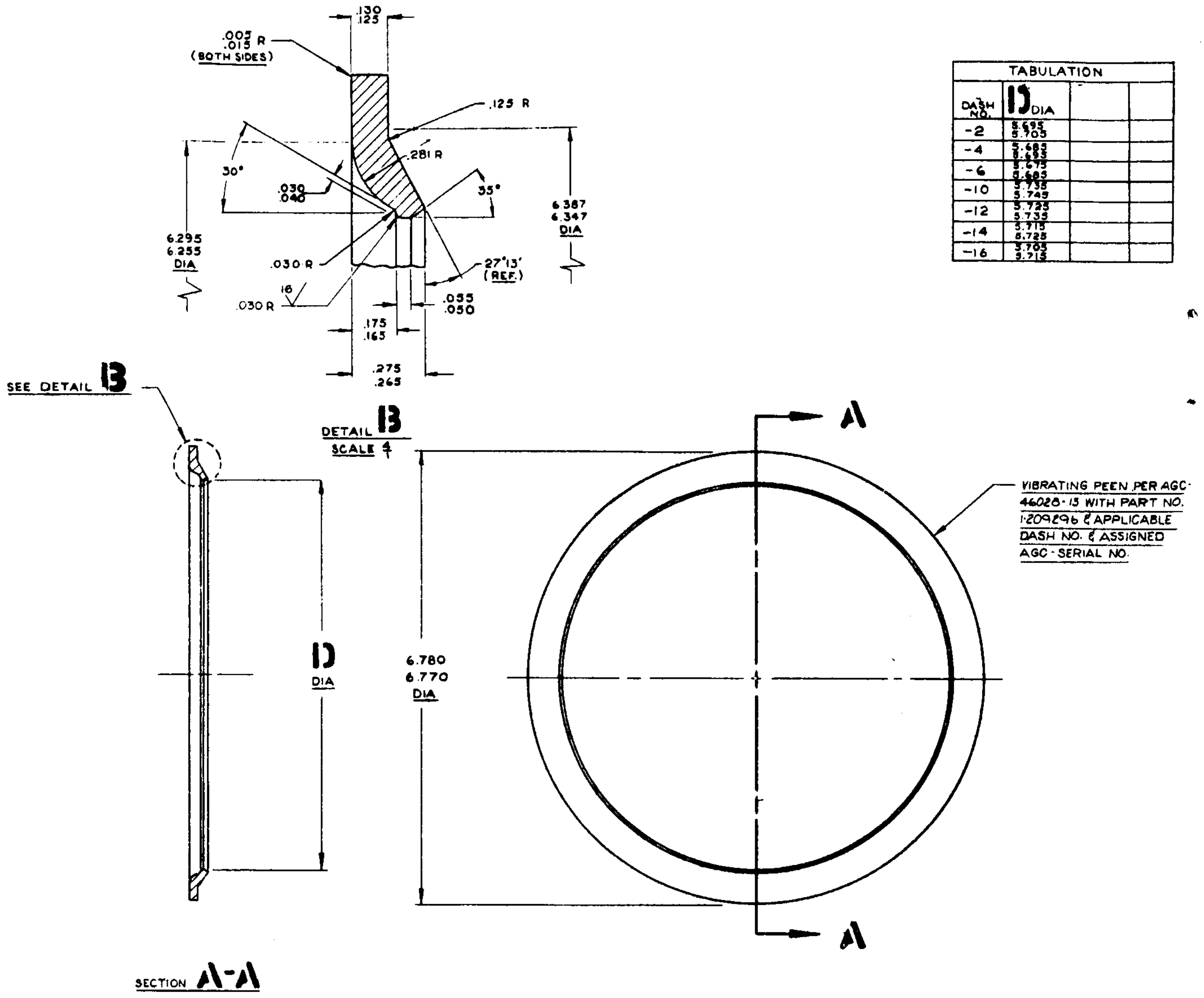
(2) Pearson, G.H.; The Design of Valves and Fittings, Second Edition, Sir Issac Pitman and Sons, Ltd., 1964, p. 333.



TABULATION			
DASH NO.	D DIA		
-2	5.695 5.705		
-4	5.685 5.695		
-6	5.675 5.685		
-10	5.735 5.745		
-12	5.725 5.735		
-14	5.715 5.725		
-16	5.705 5.715		

NOTES
1. REMOVE ALL BURRS AND SHARP EDGES.
2. ALL SURFACES OF SEAL TO BE FREE OF SCRATCHES, INDENTATIONS, & CRACKS.

Figure 4

Titan I Thrust Chamber Oxidizer Valve (5-in. Seal) development program. Preceding variations of the initial design were tested and modified as necessary to achieve optimum sealing and low friction with a structural (proof) capability to 1980 psig. This seal was ultimately capable of "bubble tight" leakage with liquid nitrogen at pressures up to 1410 psig.

B. DESIGN AND DEVELOPMENT OF VALVE SEALS FOR M-1 ENGINE

1. Design and Development Approach

The approach to lipseal design and development for the M-1 thrust chamber valves was based upon the Titan I oxidizer (liquid oxygen) thrust chamber valve lipseals and test experience. The cross-section of the lipseals for the M-1 valves was designed to give theoretical line contact with the reciprocating mating parts to minimize the rubbing area and corresponding friction forces. In actuality, a small flat developes on the seal lip at the contact line because of the cold flow characteristic of the plastic (Kel-F) material.

The M-1 thrust chamber valve seals were designed to be pressure sensitive to increase seal loading and to maintain adequate sealing at the higher pressures. This feature minimizes the seal preload required for initial installation. Minimizing the seal preloading results in a lower total friction in the low pressure range than would otherwise exist if the seal were designed for a preload sufficiently high to seal at high pressure, without being pressure sensitive.

A seal backup ring was ultimately provided in the sleeve-gate lipseal design for seal Configuration D, where operating pressures ranged from 1000 to 1500 psig and sealing diameters were relatively large. This design for the shut-off seal application is illustrated in Figure 5. The back-up ring (see Figure 6) which is located immediately beneath the seal, provides structural support to prevent excessive deflection and possible seal failure. A secondary benefit of the support ring is that it significantly restricts the installed, minimum diameter of the seal lip, thereby facilitating the insertion of the mating shaft or rod during component assembly and/or operating conditions.

The primary disadvantage of pressure-sensitive seals is that a design for pressure sensitivity is at cross purposes with a design for minimal friction. It is in this aspect that a back-up ring beneath the lipseal can serve to minimize friction throughout the entire pressure range while satisfying adequate sealing requirements. This can be accomplished with a back-up ring design by thinning the seal cross section to provide good pressure-sensitive sealing at the low end of the pressure range; and by dimensioning the ring to restrict pressure sensitivity above a predetermined pressure threshhold by limiting the amount of seal deflection that can occur above this pressure level.

Lipseal development experience has proven that thermoplastics are the only lipseal materials suitable for adequate performance in cryogenic applications. Elastomers are too brittle at the extremely low temperatures. Metals have too high a modulus of elasticity, which makes it impossible to

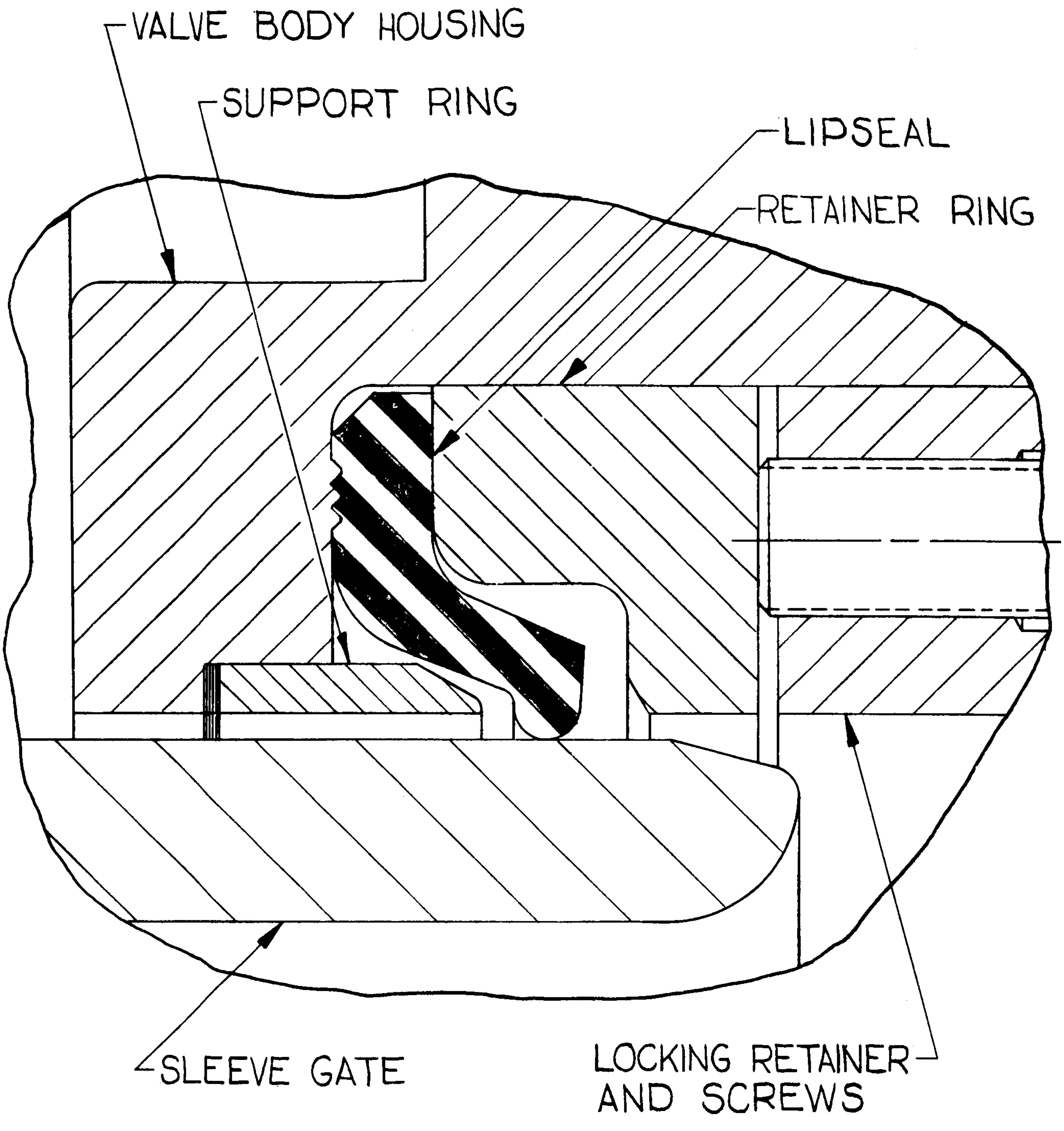


Figure 5

Installed Position of M-1 Sleeve-Type Thrust Chamber Valve Lipseal P/N 706080

NOTES:

1. REMOVE ALL BURRS & SHARP EDGES EQUIV TO .005/.015 R UNLESS OTHERWISE NOTED.
2. INTERPRET DRAWING PER STANDARDS PRESCRIBED IN MIL-D-70327
3. CLASSIFICATION OF CHARACTERISTICS PER MIL-W-9411 DENOTED BY: ●(CRITICAL) ●(MAJOR) & NO SYMBOL (MINOR)
4. SURFACE ROUGHNESS ▽ UNLESS OTHERWISE NOTED.
●5. MAGNETIC PARTICLE INSPECT PER AGC-STD-4817 TYPE OPTIONAL. ACCEPTANCE PER AGC-STD-4006. CLASS I
6. CLEAN PER MSFC-SPEC-164, TYPE II, CLASS I, OXYGEN SYSTEM.
7. PRESERVE & PACKAGE PER MSFC-DWG NO. 10419900, OXYGEN SYSTEM.
8. PENETRANT INSPECT PER AGC-STD4814 TYPE OPTIONAL. ACCEPTANCE PER AGC-4005 CLASS I.

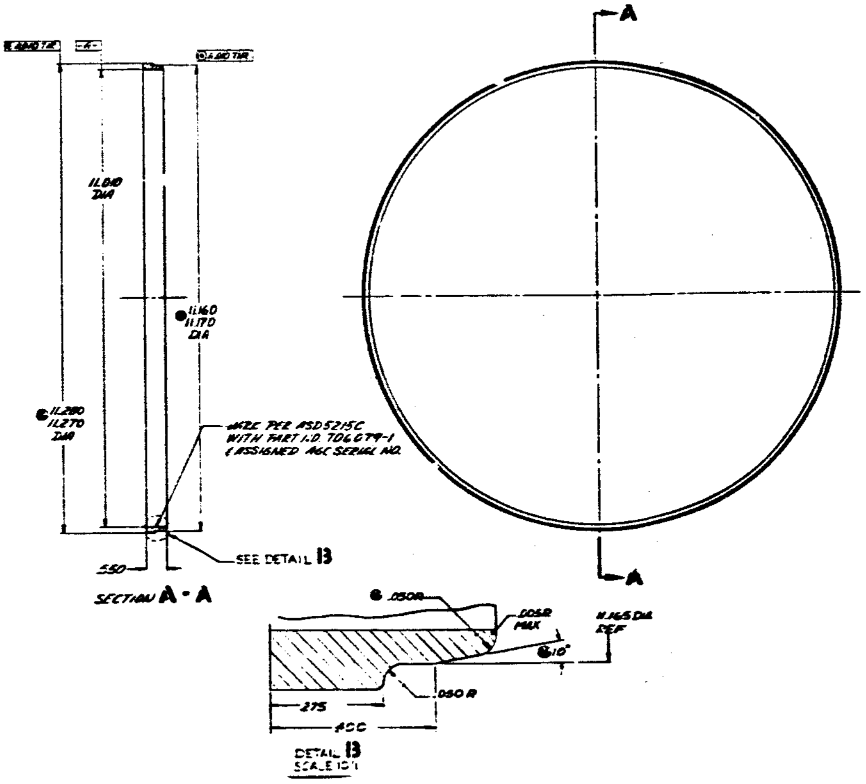


Figure 6

Back-Up Ring

manipulate design tolerances for adequate control of friction/sealing balance and still retain a feasible tolerance range for fabrication.

The most suitable of the various candidate materials evaluated for cryogenic use was Kel-F; therefore, this material was selected for use in the M-1 valve lipseals. Kel-F has the most acceptable physical properties at extremely low temperatures and exhibits less cold flow at ambient temperature than Teflon, which is the second best material. The resistance of Teflon to cold flow can be improved through the use of additives, but even in this improved condition Teflon is considered inferior to Kel-F. A qualitative comparison of those thermoplastics initially considered as potential lipseal materials is presented in Table I. The physical properties of the four most promising materials are shown in Table II. Other materials such as Kynar and Mylar were evaluated. Kynar showed extreme fragmentation when exposed to a high pressure differential at cryogenic temperatures. Mylar, although of interest, is available only in thin sheets (less than 0.010-in. thick) that are not suitable for fabricating large single-piece lipseals.

2. Method of Design and Development

Certain basic stress considerations, in combination with applicable experience and accumulated data, are used in establishing initial seal design configurations. Final seal configurations are developed through appropriate sequential test, performance analysis, and redesign cycles.

An unsuccessful analytical approach to seal design utilizing a computer technique was attempted during the M-1 thrust chamber valve seal development program. The implementation of computerized methods in seal design will require more engineering data about cryogenic seals and Kel-F material under combined moment, tensile, and shear stress than currently exist.

V. DEVELOPMENT TEST RESULTS

A. LEAKAGE

A major portion of the sleeve-gate lipseal development testing was conducted using seal testers, which were designed for the valve and valve seal development programs. Figure 7 shows the seal tester installed in the liquid nitrogen fixture for functional testing. Final development testing and refinement of seal configuration was accomplished using the valve itself.

Several hundred leakage tests with 20 different seal configurations were conducted on both the thrust chamber valve and valve seal tester. Although extensive details of this over-all effort are not reported herein, some specific information is included. Table III is a list of the various seals tested. Seal Configuration A was the original basic sleeve inlet lipseal and was considered as the standard comparative development tool. The standard actuator shaft seal was Configuration E. During development testing, the seals were usually subjected to leakage measurements under the following pressure sequence:

TABLE I

SUITABILITY OF CANDIDATE SEMI-RIGID SEAL MATERIALS

Material	Propellants	
	LO_2	LH_2
(TFE/AGC-44028 (Kel-F)	Suitable	Suitable
Teflon (100X) FEP/ AGC-44081 & AGC-44113	Suitable	Suitable
Kynar/AGC-44140	Questionable - Possible Detonation	Questionable - Insufficient Property Data
Mylar (.010 Sheet)	Unsuitable - Sensitive to Detonation	Suitable
Nylon/AGC-44002	Unsuitable - Sensitive to Detonation	Unsuitable - Thermal Shock Crazing
Polypropylene AGC-44089	Unsuitable - Sensitive to Detonation	Questionable - Insufficient Property Data
TFE/AGC-44087 (Teflon-7)	Suitable	Suitable

TABLE II

Properties of Various Thermoplastic Materials

TABLE II PROPERTIES OF SOME THERMOPLASTIC MATERIALS

ENCL (2)
SH'T 1

MATERIAL	MOLDED THICKNESS INCHES	HARDNESS	GROSS CRYSTAL %	TEMP OF	ULT TENSILE PSI x10³	TENSILE YIELD PSI x10³	YIELD OFFSET PSI x10³/%	ULT ELONG %	YIELD ELONG %	ELASTIC MODULUS PSI x10⁵	FLEX STRENGTH PSI x10³	FLEX MODULUS PSI x10⁵	COMPR. STRENGTH PSI x10³	COMPR MODULUS PSI x10⁵	MODULUS OF RIGIDITY PSI x10⁵	IZAD IMPACT FT-LB
1. FLUORINATED ETHYLENE - PROPYLENE (FEP)																
TEFLON FEP FILM	≥ .090		< 50	160												
(AGC-44081)				75±5	2.5		1.0/.2	250								
TEFLON 100/110	> .5	SHORE D55	< 45	160												
(AGC-44113)				75±5	3.4		1.8/5	350		0.7	2.5	2.0	1.0	0.8	0.2	NO BREAK
				-320	17.5	19.0		10		6.5	25.0	6.5	30.0	9.0		
				-423	23.5	23.0		4	2	8.0	35.0	7.2	35.5	9.3	8.6	
			> 45	160												
				75±5	3.0		1.9/5	300		0.6	2.6	2.0	1.0	0.7	0.2	NO BREAK
				-320	17.0	18.5		10		4.0	2.70	6.6	32.0	9.0		1.5
				-423	22.5	23.0		4	2	6.0	35.0	7.3	33.5	9.5	6.6	1.5
2. POLYCHLOROTRIFLUOROITHYLENE (CTFE)																
KEL-F81 GRADE III	≤ .125	SHORE D77	< 40	160	2.5	1.5	1.0/.2	300		0.5	3.0	0.8				
(AGC-44028)		KHN8.5		75±5	5.6	4.5	2.0/.2	150	10-16	1.5	7.0	1.8 3.8	7.4	2.6	5.0	3.0
				-320	21.0	24.5		4	4	10.9	40.0	18.0	31.0	14.8	22.0	
				-423	23.0	28.0		1	1	12.0				16.7	23.5	
	.125-.375	SHORE D80	40-60	160	3.0	2.5	1.5/.2	300		0.9	5.0	1.3				
		KHN9.7		75±5	5.0	5.2	3.0/.2	125	7.5-10	1.9	10.0	2.4 5.0	7.6	2.7	5.5	3.0
				-320	17.0	15.0		2	2	7.5	36.0	17.0	35.0	15.0	18.5	
				-423		20.0				9.0					20.0	
	> .375	SHORE D80	60-80	160		1.5										
		KHN10.4		75±5	4.5	4.5		100	7.0-7.5	2.2	13.0	4.8	8.5	3.3	6.0	1.0
				-320	15.0	13.0		1.5	1.5	7.2	34.0	16.5	35.0	16.5	18.5	
				-423	19.0	17.0		0	0	7.5				14.7	23.0	
X-CTFE	≤ .125	SHORE D75	< 40	75±5		4.1		80	10		7.4					
(AGC-R&D)		KHN7.2		-320							31.2					
3. POLYETHYLENE TERAPHTHALATE																
MYLAR FILM	≤ .010		< 20	160												
				75±5	20.0	12.5		85		6.0					7.5	
				-320	38.0	37.5		25		15.0					11.0	
				-423	41.5	41.0		4		17.2					44.0	
4. POLYTELRAFLUOROETHYLENE																
TEFLON 7																
(AGC-44087)	< .065		< 50	160												
				75±5	4.4		1.9/5	300		0.5	3.0	1.3	2.5	0.7	0.2	
				-320	17.2	15.5		7.5	7.5	4.7	30.0	7.1	19.5	7.5	2.2	
				-423	19.2	19.0		1	1	5.5	33.0	7.6	29.5	8.2	2.5	
	.065-.125		50-60	160												
				75±5	4.1		1.8/5	350		0.7	3.0	1.5	3.5	1.1	0.2	1.1
				-320	15.0			5.0	5.0	4.7	23.5	6.7	20.5	8.0	1.8	1.2
				-423	18.5			2	2	6.0	25.0	7.2	31.0	9.0	2.6	1.3
	> .125		60-70	160												
				75±5	4.0		1.75/5	325		0.9	3.7	1.8	4.0	1.4	0.25	2.7
				-320	11.0	10.0		3.0	3.0	4.0	21.5	6.2	21.0	8.4	1.8	1.3
				-423	15.0	15.0			0	6.0	220	6.7	32.5	9.7	3.3	1.5

TABLE III

SUMMARY OF SLEEVE-GATE LIPSEAL DEVELOPMENT TEST RESULTS

Seal Cross-Section Configuration	Shutoff Seal P/N And Interference P/N	Shutoff Seal P/N And Interference Untorqued/ Torqued	TCFV S/N	Date	Inlet Seal P/N And Interference P/N	Inlet Seal P/N And Interference Untorqued /Torqued	Max. Leakage Recorded @ LN2 Temp. CC/MIN @ PSIG * Bleed in Leakage CC/Min	@ PSIG Temp	Before Actuations CC/Min	@ PSIG	After Actuations CC/Min	@ PSIG	Max. Leakage Recorded @ LH2 Temp. CC/MIN @ PSIG Bleed in Leakage	Before Actuation CC/Min	@ PSIG	After Actuation CC/Min	@ PSIG	Remarks
 KEL-F	265114-1	.105/.112	2	10/29/63	265114-1	No Record	0	20-30	250 50	300 500	420	500						Inlet pressure range was zero-500 psig. The 420 cc/min was recorded after 50 sleeve actuations.
	265114-1	No Record/ .110	1	10/12/63	265114-1	No Record/ .110	0	- - -	1050	800	730	800						Max. inlet pressure was 1400 psig 1 actuation.
	265114-1	No Record/ .110	1	10/16/63	265114-1	No Record/ .110	200	10-30	8	1000	20	400						Same buildup as above, after dehydration pressure higher than 1000 psig were not attempted due to excessive shaft seal leakage.
	265114-3	No Record	1	11/4/63	265114-3	No Record/ .114	No Record	- - -	185	1000	525	400						11 actuations.
	265114-5	.135/.137	2	12/2/63	265114-5	.145/No Record	0	- - -	225	1600	215	1400	0	1170	800	24,400	1000	6 actuations at LN_2 temp., 5 actuations at LH_2 temp. Shutoff lipseal ruptured during LH_2 test.
	265114-5	.115/.120	1	11/11/63	265114-5	.112/.119	No Record		275	1200	800 200	200 1800						17 Actuations at LN_2 temp.
	265114-15	.137/.145	2	12/16/63	265114-5	.124/.125	0		0	- -	Excessive	- -						Shutoff seal ruptured during the first 5 sleeve actuations.
	265114-15	.135/.138	2	12/10/63	265114-15	.130/.139	No Record		0	- -	740	1800						6 actuations at LN_2 temp.
	265114-15	No Record/ .090	2	12/14/63	265114-15	No Record/ .065	1000	50-100	800	200	2400 580	400 1800						Same seals as tested on 12/10/63, 6 additional sleeve actuations at LN_2 temp.
	705458-1	.140/.142	2	12/21/63	705458-1	.140/.142	0		0	- -	1250	1000	0	0		27,200	800	5 actuations at LN_2 temp, 5 actuations at LH_2 temp. Valve did not completely close. Contamination found on and around seals following the LH_2 test.
	705458-1	.125/No Record	1	12/26/63	705458-15	.132/.135	0	- - -	0	- -	585 0	1200						Sleeve did not close after actuating. Sleeve did close later during 2nd bleed-in. Leakage rate after closing was zero up to 1800 psig. Lipseal failed during 4 additional actuations.
	705458-5	.132/.130	2	1/7/64	705458-5	.133/.135	No Record		0	- -	0 700	0-1200 1800						Seal ruptured after 2nd series of actuations.
LEXAN	705458-1	.100/.116	2		705458-5	No Record	No Record		Excessive Zero to	1600								Lexan seal ruptured at 1600 psig.
KEL-F	268866-5	Surface Contact	HYB-3	5/23/64	704631-1	.090/.118	0	100,-250	0	1500	0	1500				6000	1800	5 actuations 20 actuations; supported lipseal.
	268866-5	"	HYB-3	6/3/64	706080-1	.115 AVG.	0	100,-250	375	1670	750	1670	100	450	1800	3000	1800	40 actuations; supported lipseal.

*Converted to STD cc/min 14.7 psi @ 70°F

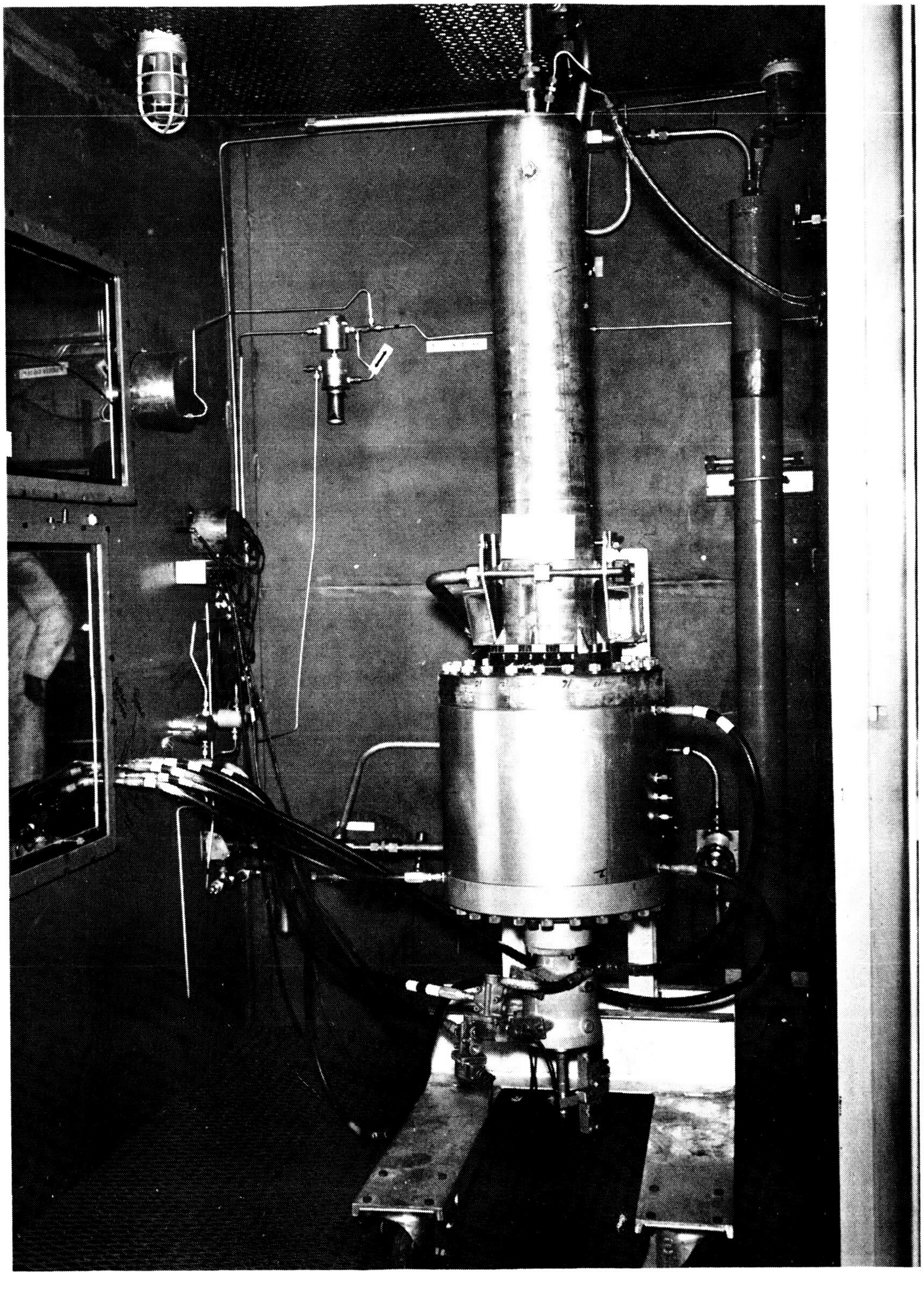


Figure 7

Test Installation of M-1 Thrust Chamber Valve Seal Tester

1. Zero to 500 psig with ambient gaseous nitrogen.

2. Zero to 1800 psig with liquid nitrogen in 200-psi increments at temperatures below -250°F.

3. Six actuations with 500 psig inlet pressure.

4. Zero to 1800 psig and return to zero psig in 200-psi increments at temperatures below -250°F with liquid nitrogen.

5. Five actuations with 500 psig inlet pressure.

6. Zero to 1800 psig and return to zero psig in 200-psi increments at -250°F or below with liquid nitrogen.

The results of these tests were not entirely conclusive, but the general trend in leakage indicated that for any given seal design, less leakage was obtained with greater amounts of interference between the lipseal and mating dynamic part (sleeve). However, friction also increased with interference, ultimately necessitating a trade-off between leakage and friction. Seals were fabricated and tested with diametral interference ranging from 0.080-in. to 0.150-in. on a nominal 11.0-in. diameter seal.

Sleeve-gate lipseals were used most extensively during the development testing. The sequence in which they were tested was Configuration A, C, and D. Lipseal Configuration D, commonly called the supported lipseal, was used in conjunction with a support ring and was found to give the most satisfactory over-all results. The supported lipseal test results indicated a maximum liquid nitrogen bleed-in leakage of 180 cc/min of gaseous nitrogen. After 26 sleeve actuations at liquid nitrogen temperature, the leakage rate was zero at inlet pressures up to 1600 psig and a maximum leakage rate of 65 cc/min of gaseous nitrogen at an inlet pressure of 1800 psig. Visual inspection after disassembly of the valve revealed that the lipseal did not show any evidence of excessive wear.

B. FRICTION

Frictional forces were determined for the various internal sleeve-gate lipseals (nominal 11.0-in. diameter) by using the seal tester. Friction force analysis became increasingly more significant as the seal development emphasis shifted from an unsupported to a supported lipseal configuration. The exact values of friction loads acting upon the various seals could not be completely obtained with absolute precision using the seal tester because of minute differences in the actuation system and body designs. However, trends could be reliably predicted and the over-all magnitude of the forces could be determined.

1. Standard Sleeve-Gate Lipseal (Configuration A)

The first friction tests were conducted with the original unsupported-sleeve lipseal (Configuration A). An extensive series of tests was conducted with this seal at both ambient and liquid nitrogen temperatures. The results of these tests indicated that the total friction force generated by the lipseals increases as the inlet pressure increases. This increase in friction is the combined result of plastic lipseal deformation, an increase in contact gripping area, a possible change in coefficient of friction, and an increase in unit loading on the contact area. Dynamic friction tests to determine the effect of actuation velocity upon break-away and sliding forces indicated that a slight increase in break-away force occurred with an increase in velocity, but sliding force remained constant as velocity increased. This seal was used as the standard for further friction evaluation of other seal designs.

2. Supported Lipseal (Configuration D)

A seal tester was assembled, tested with liquid nitrogen, and subsequently sent to the Cryogenics Laboratory for friction tests under liquid hydrogen conditions. This assembly included the supported lipseal (Configuration D), two supplementary internal Omniseals to isolate lipseal leakage, and two tandem shaft seals (Configuration D). The friction tests of the supported lipseal represented the first attempt to correlate the effects of different cryogenic fluids. Although the supplementary Omniseals contributed additional friction, a comparison of the frictional forces encountered with both liquid nitrogen and liquid hydrogen was possible. Figure 8 is a comparison of curves representing total forces and independent lipseal forces which were obtained with the supported lipseal and the standard lipseal with both liquid nitrogen and liquid hydrogen. The independent lipseal friction forces were derived by subtracting the curve of total forces without the lipseal at liquid nitrogen conditions from the curve of total forces obtained during testing with the lipseal at both liquid nitrogen and liquid hydrogen conditions. As a result of these factors, the derived independent lipseal force with liquid hydrogen is actually in error by some unknown positive amount because total forces without the lipseal at liquid hydrogen conditions would probably be somewhat higher than experienced with liquid nitrogen. Despite this difference, the trend is demonstrated.

Test results indicate that the frictional forces with liquid nitrogen are greater for the supported lipseal than for the standard nonsupported lipseal. As a result of having a thinner cross-sectional area in the flexible arm and larger radii at the bending area, the supported lipseal is more pressure sensitive at inlet pressures from zero to 900 psig. The unique feature of the supported lipseal is that friction forces diminish rapidly after 900 psig and are considerably less than the conventional seal at inlet pressures above 1000 psig. This same phenomena was experienced under liquid hydrogen conditions; frictional forces diminished rapidly above 600 psig, and a projected cross-over point with the standard seal occurred at approximately 1200 psig. One possible theory for the reduction of frictional forces above a certain inlet pressure is that the pivot point of the flexible lipseal shifts from its own bending radius to the contact area on the support ring. When sufficient contact is made, the moment arm changes and the effective or normal load acting along the lipseal-sleeve contact arm is reduced as the resultant pressure load is transmitted mostly into the support ring.

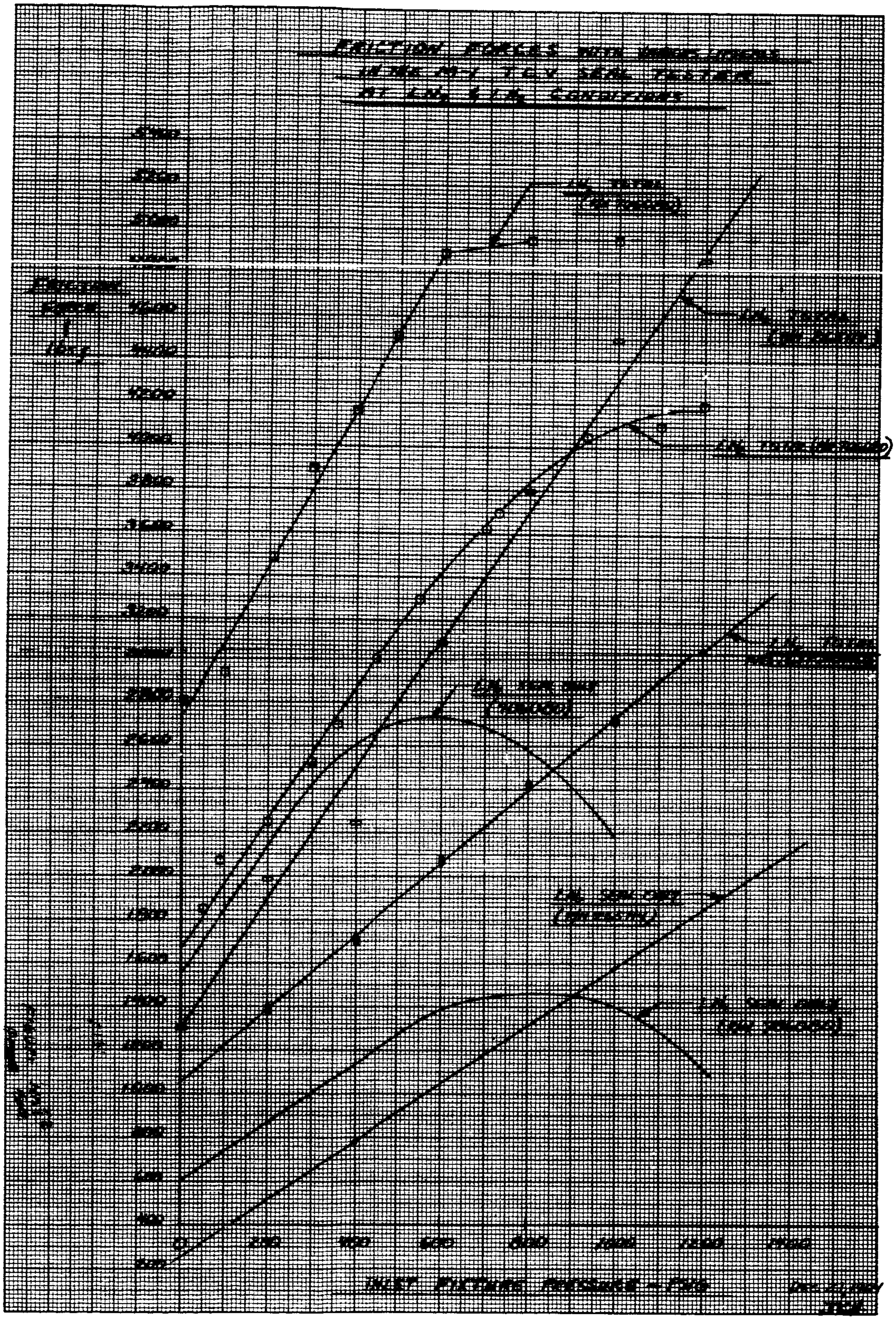


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Figure 8

Friction Forces in the M-1 Seal Tester

3. Lipseal (Configuration C)

A seal friction test was conducted using a thrust chamber valve incorporating a lipseal (Configuration C). This test was to determine the force required to insert the sleeve into the lipseal initially (lipseal used as shut-off seal) and the running force required to move the sleeve through the seal once the sleeve has been inserted. At ambient temperature, the force required to start the sleeve through the seal was 714 lb. After insertion, the force required to maintain the continuous motion of the sleeve in the opening direction was 513 lb. The force required to move the sleeve in the closing direction was 656 lb. At liquid nitrogen temperature, the force required to continuously move the sleeve in the opening direction was 780 lb. The force required to move the sleeve in the closing direction was 1048 lb. The lipseal-to-sleeve interference was 0.097-in.

C. STRUCTURE

Critical dimensions of the various lipseal designs are presented in Figure 6. Kel-F was found to be structurally more sound than Lexan and more resistant to cold flow than Teflon. Intentional pressurization of various seals to failure revealed that a seal support ring was required to provide the lipseal with a satisfactory margin of safety above the maximum dynamic system pressure of 2200 psig. Several seal failures occurred in the associated thrust chamber valve at an estimated pressure of 2400 psig. Static laboratory tests demonstrated the structural integrity of the supported lipseal at pressures up to 3000 psig and established the failure limit of the standard lipseal to be 2400 psig.

D. TEFLON SUPPORT AND GUIDE BEARINGS

One of the primary causes of lipseal leakage is scratching or wearing of the sealing surface of the seal. This usually occurs because of imperfections, in-service damage, or deterioration of the mating, dynamic metal sealing surface. The use of Teflon bearings in the thrust chamber valve body to support and to guide the sleeve-gate and shaft improved lipseal performance and longevity by protecting the mating sealing surface from metal-to-metal contact and resultant damage. This arrangement proved very successful in both the thrust chamber valve seal tester and the valve assembly.

E. LIPSEAL TECHNOLOGY SUMMARY

Over-all development experience indicates that the supported lipseal design, as used for the 11-in.-diameter thrust chamber valve seal, exhibits definite advantages over unsupported configurations of the same size. This seal (Configuration D) has a burst strength 25% higher (3000 psig maximum) than the conventional or standard design (Configuration A); its leakage rates are comparable with other seals; and has a unique friction-to-inlet pressure characteristic curve. Leakage less than 1 cc/min with liquid hydrogen and liquid nitrogen was occasionally achieved with the nominal 11-in.-diameter lipseal; however, the average leakage was approximately 300 cc/min. Leakage rates with the smaller 1.25-in. diameter, unsupported shaft lipseal (Configuration E) ranged from zero to approximately 50 cc/min.

This shaft seal successfully withstood proof pressures up to 3000 psig at liquid nitrogen conditions and up to 2500 psig at ambient conditions without structural failure.

VI. CONCLUSIONS

A. The Aerojet-General lipseal design, as used in M-1 thrust chamber valves, is a potentially successful cryogenic seal for dynamic applications.

B. Development work to date concerning the subject lipseals is limited but results indicate the feasibility of design optimization.

VII. RECOMMENDATIONS FOR DEVELOPING AN OPTIMUM SEAL

A. A thorough analysis of test results to date should be made.

B. An analytical design method should be developed.

C. The method and design should be made optimum by means of an advanced development program.

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