Seal Testing of Large Diameter Rocket Motors

N. Bruce Moore* and John W. Hellums†
Cameron Offshore Engineering, Houston, Texas 77079
Thomas Bechtel‡
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
and
Ken Kittredge§ and Craig Crossfield¶
Teledyne Brown Engineering, Huntsville, Alabama 35807

This investigative program examines leakage testing of elastomeric O-ring seals for a solid rocket casing and provides direction towards an improved nondestructive postassembly test. It also details test equipment for the Space Shuttle systems solid rocket boosters (SRB). The results are useful to designers of hardware for pressure containment vessels which use O-ring seals. However, testing of the SRB seal is complicated because the bore of the SRB cannot be pressurized to working pressure prior to launch; thus specialized seal test procedures are required. Using several subscale seal and groove configuration test fixtures equipped with either two or three O-ring seals in series, seal integrity is investigated with both a pressure decay and flowmeter methods. Both types of test equipment adequately detect the practical range of expected seal leak rates of 1 to 1×10^{-4} sccs. The flowmeter leak test equipment appears to reduce testing time substantially. Limited seal leakage testing is performed on full-sized rocket motor segment seals, a pre-Challenger short stack, providing comparison of bore seals to test specimen bore and face seals. The conclusions are that seal reliability, verified via a performance pressure test, can be affected by temperature, quantity of grease, test pressure, and seal pressure load direction. Potential seal failure scenarios including contamination, seal damage, and sealing surface damage are discussed. Recommendations are made for an improved test procedure.

I. Introduction

SUBSEQUENT to the Challenger Space Shuttle solid rocket booster (SRB) failure, considerable effort was launched to understand O-ring seal behavior. NASA, aided by several contractors, began investigations into O-ring seal performance using a variety of analytical and experimental tools. Although O-rings are successfully used for a wide variety of applications in many industries, testing SRB joints present unique leak testing problems because of seal configuration and inability to pressurize the SRB before launch.

The two primary areas of concern for the SRB seal applications are seal performance and seal leak testing verification. Moore[1] reports on O-ring response and sealing of a pressurized shell structure with specific applicability to Space Shuttle SRB. Earlier, the effects of surface defects, surface contaminations, and compression were reported.[2] Commercially available information defines typical O-ring seal parameters and some types of failures.[3] Others have investigated stresses in O-ring gaskets.[4] A general review of leak testing of pressure vessels is available.[5]

A data base specific to the Space Shuttle SRB was needed to address the key issues affecting an SRB joint seal leak test procedure. This data base could allow the establishment of a seal acceptance criteria for the SRB joints. These results are applicable to O-ring seals used in other applications ranging from hatch door seals on the Space Station to seals used in subsea drilling equipment and many other high-reliability sealing applications.

This paper presents the approach and results from several phases of investigation into O-ring seal integrity and verification. The investigation involves four different experimental configurations—a subscale barrel seal test fixture, two flat plate fixtures, and a full-sized SRB joint (short stack).

The investigations of grease blockage, O-ring extrusion, O-ring flaws, seal contaminations, and seal surface damage are discussed. Comparisons are made of full-scale to subscale test specimens. Confidence in the experimental techniques and the test equipment is developed.

Fig. 1 Barrel test fixture.

Received Feb. 17, 1989; revision received July 31, 1989.

*Vice President.

†Project Engineer.

‡Branch Chief.

§Thermal Analyst.

¶Design Engineer.

II. Test Apparatus

All three types of test fixtures are designed to Challenger case joint gland dimensions; flight quality O-rings are used for all tests.

A barrel test fixture (see Fig. 1) with two parallel serpentine O-ring grooves is used to simulate the length of the SRB case joint. The length of the seal was approximately 19 ft, which is equivalent to half the circumference of an SRB motor case. This is the worst case for gas (nitrogen) communication through a grease-filled seal annulus. Five equally spaced pressure ports are provided along the length of the groove 5 ft apart.

Two grease evaluation test (GET) flat plate fixtures of the same design and dimensions (see Fig. 2) are manufactured to perform grease evaluation testing. Duplicate fixtures allow simultaneous tests to be performed. The GET fixtures consist of two concentric O-ring grooves machined into a circular, flat plate (Fig. 2). Subsequently, the fixtures were modified to contain three concentric rings. The seals are labeled from the outside inward as the barrier (B), primary (P), and secondary (S) seals. The nomenclature is identical to SRB redesign nomenclature. The top plate provides the other sealing surface for the O-ring. The low and high tolerance extrusion gaps of 0.004 in. and 0.014 in. are achieved by placing brass shims between the plate faces during assembly. Eight equally spaced test ports are located circumferentially between the primary and secondary seals and similarly eight ports between the barrier and the primary. An alternate 1-in.-thick transparent acrylic top plate is provided for the GET fixtures. This allows visual examination and video taping of the seal system during testing.

A truncated pre-Challenger SRB case joint, short stack, is used to verify the subscale test results. The short stack has two O-ring grooves without a capture feature. The absence of the SRB field joint style of capture feature limits the maximum pressure to 200 psig between the primary and bore seal.

Additional materials included Conoco HD-2 grease, Viton O-rings, and 5 micron-filtered dry nitrogen.

To measure the communication of pressure at the various test ports, pressure transducers are placed in the ports. The 0–15 psig and 0–50 psig ±0.1% full-scale pressure transducers are used for the leak rate calculations. The 0–50 psig and 0–1000 psig ± 0.252% full-scale pressure transducers are used to monitor test pressures. Type K thermal couples and, later, 1000-ohm resistance temperature detectors (RTDs) are used to monitor the test fixture and gas temperatures. Data acquisition is performed using a Hewlett-Packard HP85 with a HP3497A data acquisition control unit and a Compaq Portable III equipped with an analog to digital conversion card and software. For low temperature tests, the fixtures are placed in a Tenny environmental chamber at Cameron Test Laboratory facility.

III. Grease Blockage Tests

The grease blockage test series focuses on the effects of grease within and between the seal glands. Initial tests are performed to determine if filling the area between the O-rings with grease prevents pressure communication to the portions of the seal most remote from the inlet port. Tests are performed to determine if the grease can mask detection of contaminants and damaged seal surfaces. Both the serpentine barrel fixture and the GET fixture are used.

The serpentine barrel fixture is used to determine if grease blockages can prevent the pressurized nitrogen from reaching portions of the O-ring seal during a leak test. A 0.005- to 0.010-in. layer of grease is applied to the seal area of the test fixture. The test is started at a temperature of 32°F with 30 psig applied to test port 1. The test pressure is increased, and the temperature is raised over an extended period of time before pressure arrives at test port 6. The final temperature is 90°F, the final pressure is 500 psig, and total elapsed time is 3 h before the grease flowed sufficiently to penetrate to test port 6.

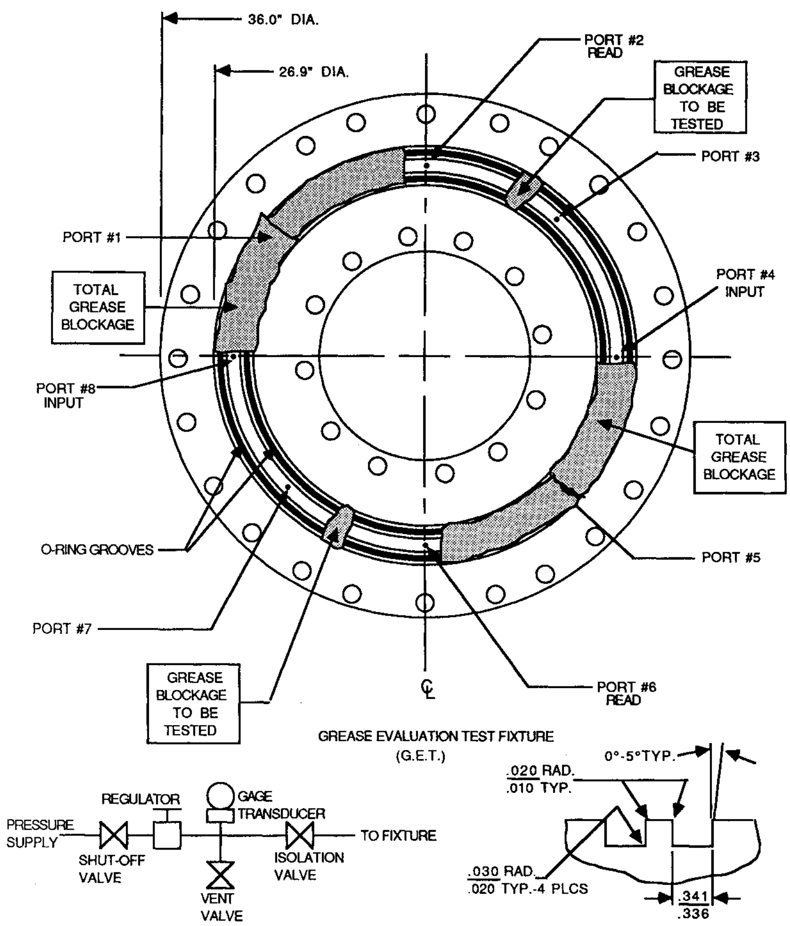

Fig. 2 Grease evaluation test fixture.

The GET fixtures, with three concentric face seals, are used to test the effects of the grease on pressure communication to seals. Prior to assembly, grease blockages of various lengths are applied to the O-rings, the O-ring grooves, and the land separating the grooves. Pressure is applied to the upstream side of the grease blockage, and the time duration required for the pressure to be sensed downstream is recorded. For each grease blockage length, a corresponding elapsed time, temperature, and pressure at penetration are recorded. These tests are performed at temperatures of 30, 50, 70, and 90°F. Test pressures are 30, 50, 100, 200, 500, and 1000 psig at extrusion gaps of 0.004, 0.007, and 0.014 in. The gaps chosen correspond to potential gaps for the Shuttle SRB.

Results show grease concentrations in the O-ring glands and connecting annulus reduce the effectiveness of an internal pressure test. As shown in Figs. 3–5, with sufficient pressure and time, grease blockages can be penetrated.

IV. Damaged Seal Testing

These tests examine the sealing of cut O-ring seals and determine if grease masking will prevent damaged O-ring detection with a pressure test. Using the GET fixture, pressure is applied between the barrier (B) and primary (P) seal and pressure increase measured between the primary (P) and secondary (S) seal. The leak rate of a flawed seal is calculated using perfect gas laws and the increase of pressure. Leak rates are determined by pressure rise method or with flowmeters. The primary O-ring seal is installed with a flaw. Pressure is applied to the damaged primary (P) O-ring seal. Tests are performed with test pressures from 30 to 1000 psig, at ambient temperatures without grease. By trial and error effort, an O-ring is cut producing a leak rate within the range of the instrumentation (see Fig. 6).

The dominant performance characteristic of the cut O-ring is the healing effect of the seal with increasing pressure. The energization of the seal by the increasing pressure results in leak rate reduction.

Additional O-rings are tested to determine if a cut O-ring can leak at a low pressure and seal at a high pressure. Three additional cases were tested which leaked at low pressures, 30 to 200 psig, but when subjected to high pressure, 1000 psig, sealed completely.

The damaged seal tests are repeated with the application of Conoco Calcium HD-2 grease to the O-ring flaw. The application of the grease simulates the grease accumulation caused by assembly of an SRB joint. A thin layer of grease, approximately 0.002 to 0.005 in., is applied to the surface of a 1.5-in. × 3-in. flat steel plate. The plate is drawn longitudinally across the O-ring over the area containing the flaw.

The leak rate tends to diminish at higher pressure with the grease present, as shown in Fig. 7. Release of the pressure usually allows the O-ring to return to its initial leaking condition.

V. Seal Surface Flaw Tests

Damaged sealing surface tests are performed to investigate this seal failure scenario. Pressure rise in the primary (P) to secondary (S) seal annulus is again used to calculate the volumetric flow rate of the seal flaw. The seal surface is scratched perpendicular to the centerline of the primary (P) O-ring. Us-

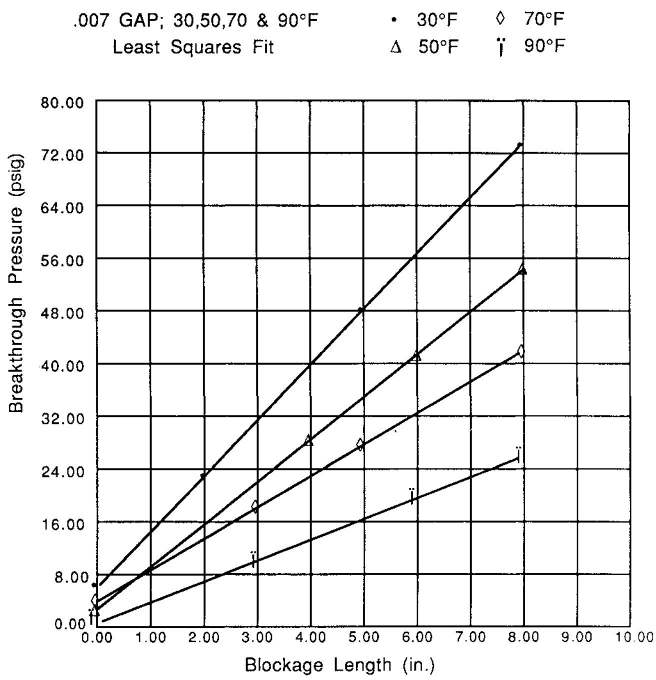

Fig. 4 Grease blockage test.

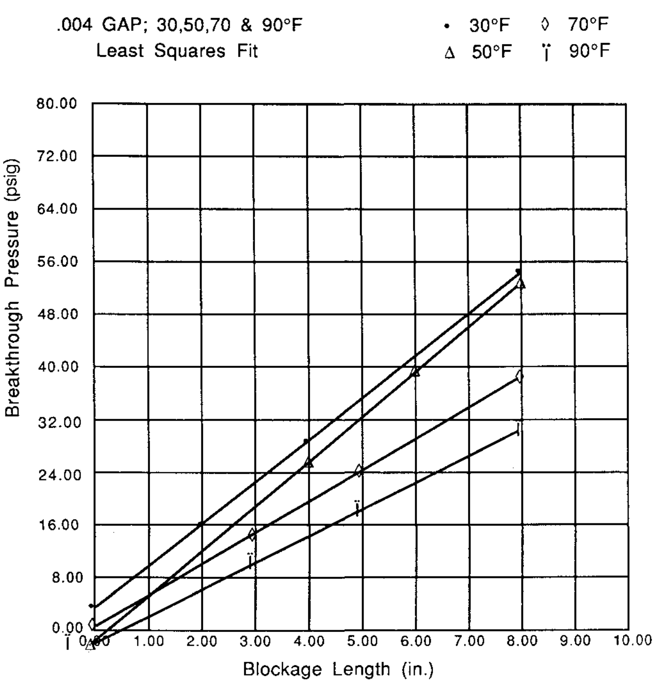

Fig. 3 Grease blockage test.

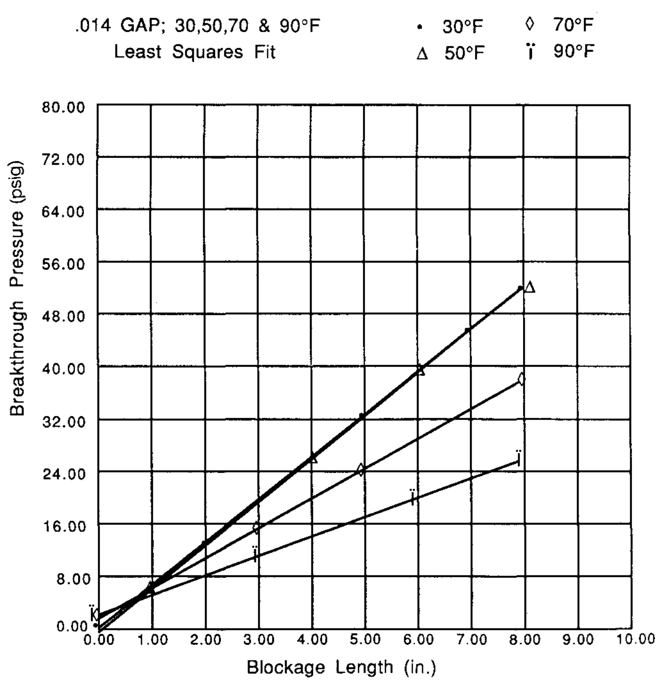

Fig. 5 Grease blockage test.

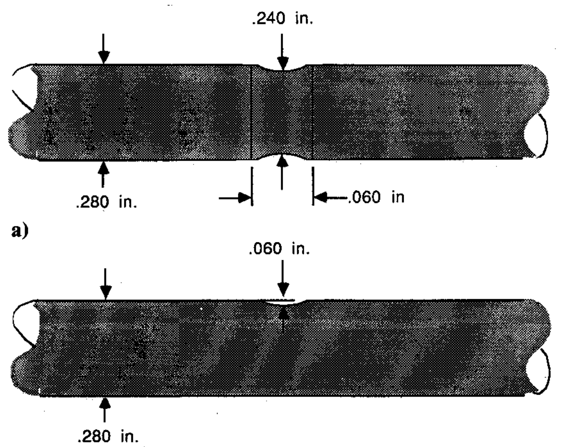

Fig. 6 Flawed O-ring configuration.

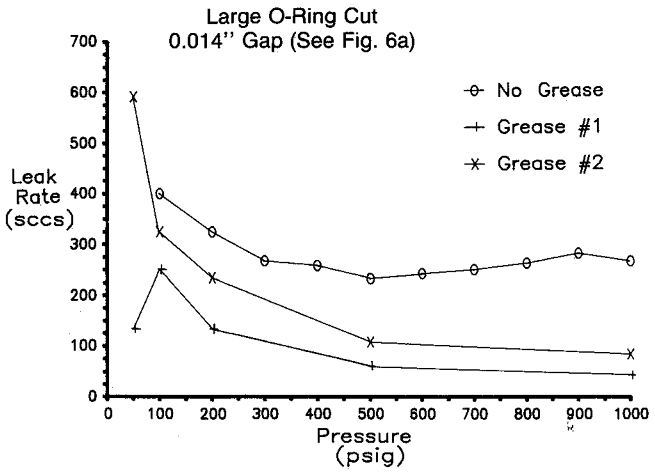

Fig. 7 Leak rates.

Table 1 Sealing surface flaw test sequence

Test number	Grease	O-ring position
1a	None	Out
1b	None	In
2a	B-P	In
2b	B-P	Out
3a	B-P	Out
3b	B-P	In
4a	P-S	Out
4b	P-S	In
5a	P-S	In
5b	P-S	Out
5c	P-S	In

B = Barrier seal. P = Primary seal. S = Secondary seal.

ing the primary (P) O-ring allows testing of both the barrier to primary and primary to secondary sealing surfaces.

A flaw is created on the top plate using a carbide tipped scribe. Characterization of the flaw is performed by making a reverse impression using dental plaster. The impression is then viewed and measured using an optical comparator with magnification capabilities up to 50 power.

After flaw characterization, the fixture is assembled, and the primary O-ring is tested using light oil as the lubricant. This process is repeated until a flaw which produces a leak in the order of 0.01 sccs is generated.

The flaws and the three O-ring configuration of the GET fixture used during this test program are graphically represented in Fig. 8. A pressure test of the primary O-ring is accomplished by applying pressure to the primary to secondary (P-S) annulus of the test fixture to move the primary (P) O-ring to the "outposition," opposite side of groove from the working pressure configuration. After O-ring equilibrium is obtained, a volumetric flow rate is determined. Flow rates are computed for pressures of 50, 100, 200, 500, and 1000 psig.

The pressure is then relieved and subsequently applied to the barrier to primary (B-P) annulus. This will move the primary O-ring to the "in-position," which will simulate launch conditions. After O-ring equilibrium is obtained, volumetric leak rates are again determined and compared with the previous leak rates.

The tests are performed with and without a grease bead applied to the primary O-ring. When grease is used, it is applied to either the barrier to primary (B-P) or primary to secondary (P-S) side of the primary O-ring for a given test. When grease is not used, the O-ring is lubricated with light oil. The sequence of testing is illustrated in Table 1 and results in Table 2.

The results are 1) sealing surface flaws can be oriented to seal in one pressure direction and leak in the opposite direction, and 2) grease beads located on either side of the primary O-ring can mask the presence of a sealing surface flaw known to cause a leak. Pressure direction reversals reveal flaws previously masked by grease. Therefore, sealing surface flaw detection is sensitive to pressure direction when grease is present.

VI. O-Ring Extrusion Tests

The test objective is to determine the potential for damage to an O-ring if elongated into the tank/clevis gap of the SRB during a pressure test.

During a field joint pressure integrity test of the Space Shuttle SRB, pressure applied between the tang and clevis increases the nominal extrusion gap and allows the O-ring to further elongate into the gap. As the test pressure is relieved, the extrusion gap returns to the original position. The dynamic action of the tang and clevis could potentially damage the O-ring and jeopardize the pressure integrity of the joint.

A preflight SRB pressure test is simulated by applying pressure to the GET test fixture and allowing the upper plate to move, increasing the nominal extrusion gap. After O-ring

Table 2 Sealing surface flaw leak test rates

Test number	Grease	O-ring position	Leak rate, sccs 50 psi	100 psi	200 psi	500 psi	1000 psi
1a	None	Out	2.75E−05	8.20E−05	8.02E−05	7.90E−05	5.29E−05
1b	None	In	4.05E−01	4.83E−01	5.63E−01	5.73E−01	6.00E−01
2a	B-P	In	5.06E−04	2.96E−04	2.01E−04	3.64E−05	3.66E−05
2b	B-P	Out	1.44E−03	4.86E−04	3.02E−04	2.34E−04	1.81E−04
3a	B-P	Out	5.32E−05	2.62E−05	2.60E−05	2.59E−05	1.00E−06
3b	B-P	In	4.57E−01	7.80E−01	1.10E+00	1.82E+00	2.53E+00
4a	P-S	Out	3.78E−04	2.20E−04	1.32E−04	7.84E−05	7.86E−05
4b	P-S	In	4.95E−01	7.63E−01	1.04E+00	1.46E+00	1.99E+00
5a	P-S	In	3.76E−05	3.73E−05	5.52E−05	3.60E−05	1.80E−05
5b	P-S	Out	N/A	N/A	N/A	N/A	N/A
5c	P-S	In	9.61E−01	1.35E+00	1.71E+00	2.32E+00	3.04E+00

B = Barrier seal. P = Primary seal. S = Secondary seal.

Table 3 Percentage squeeze for O-ring extrusion test

Extrusion gap, in.	Gland depth, in.	O-ring % squeeze
0.000	0.213	22.5
0.016	0.229	16.7
0.029	0.242	12.0
0.034	0.247	10.2

equilibrium is obtained, the pressure is relieved quickly. Pressure reduction causes the upper plate to return to its original position, potentially damaging the extruded O-ring.

The primary O-ring is tested at two dynamic gap conditions with annulus pressure applied to either side of the primary O-ring. The two dynamic gap conditions of 0.029–0.034 in. and 0.0–0.016 in. are tested to represent the maximum and minimum dynamic extrusion gap conditions anticipated on flight hardware.

The percentage of O-ring squeeze associated with the extrusion gap conditions range from 10.2% to 22.5% as shown in Table 3.

The following is a summary of results for all series of testing.

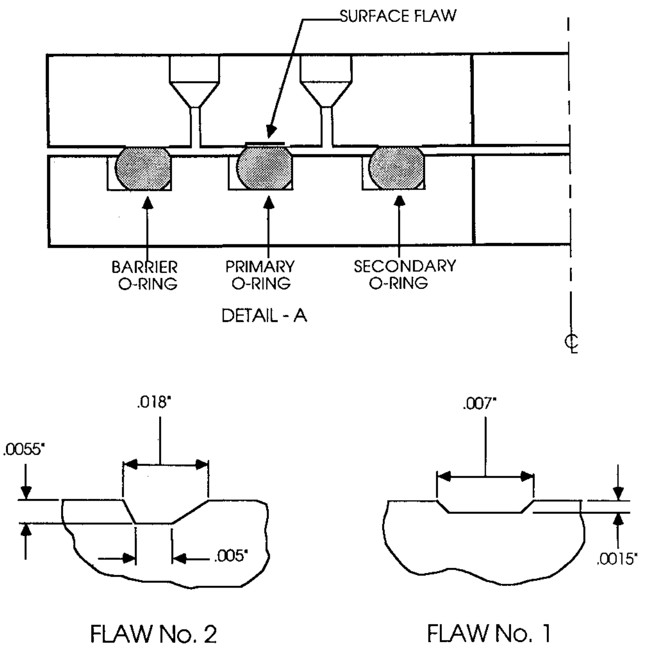

Fig. 8 Seal surface flaw contamination.

1) The primary O-ring elongates into the extrusion gap approximately 0.015 to 0.030 in. for a gap condition of 0.034 in. and a test pressure of 1200 psig. This occurs for either an "in-position" or "out-position" test using light oil as a lubricant.

2) No O-ring damage occurs for a dynamic gap condition of 0.029–0.034 in. in all test series, regardless of the primary O-ring position.

3) The O-ring cross-sectional ovality in the form of crease line occurs in all tests as a result of O-ring extrusion. This is typical O-ring behavior for the extrusion gaps studied.

4) The O-ring damage occurs at a dynamic gap condition of 0.000–0.016 in. on the third cycle of testing in both primary O-ring positions. The damage takes the form of 0.010- to 0.015-in. diameter craters located on the extrusion crease line.

5) The observed O-ring damage did not affect the O-ring sealability in subsequent tests.

VII. Seal Contamination

The objective of these experiments is to evaluate the ability to detect seal contamination with low- and high-pressure leak tests.

The test fixtures are functionally tested, without the presence of contaminants, to determine the baseline sealability. The GET fixture is assembled with a 0.004-in. gap and instrumented. The O-rings are installed with a thin coating of light oil. The isolated fixture is then monitored to determine the baseline "no leakage" condition. Leak rates in the range of 1×10^{-4} sccs for short duration tests and 1×10^{-5} sccs for longer duration tests are obtained consistently; leak rates of 1×10^{-4} sccs are defined as acceptable.

Seal contaminations investigated include hair, metal wire, and metal shavings. The contaminations are placed across the primary (P) seal prior to assembly of the GET fixture. The hair is approximately 0.004-in. diameter, the metal wire is 0.006-in. diameter, the metal debris is 0.010-in. diameter and 0.25-in. long. The specimens are tested with and without grease. For the hair contamination, five tests are conducted without grease and three with grease. For the wire contamination, two tests are conducted for both lubricated and nonlubricated conditions.

The results from the hair contamination tests show that as test pressure increases, the leak rate increases. Little difference is seen between lubricated and nonlubricated seals. Typical leak rates at 500 psi are 4×10^{-1} sccs.

Leakage resulting from wire debris shows a similar trend of increasing seal leak rates with increasing pressure with and without lubrication. Leak rates are approximately 1.2×10^{-1} sccs. Metal shaving contamination (see Fig. 9) dramatically shows that contaminated seals can hold pressure to as high as 200 psi then suddenly fail.

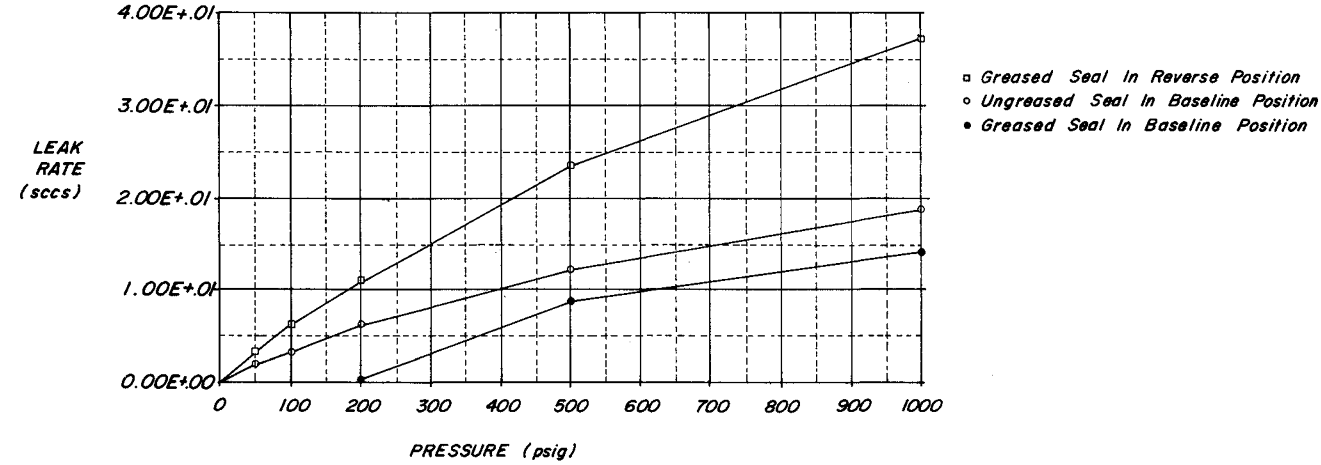

Fig. 9 Seal leak rates resulting from 0.004 in. diameter shaving contamination.

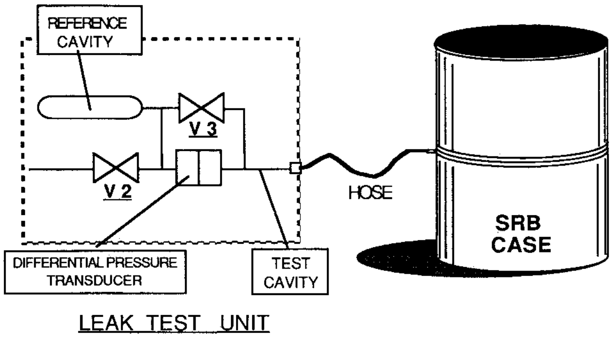

Fig. 10 Pressure decay leak detection system schematic.

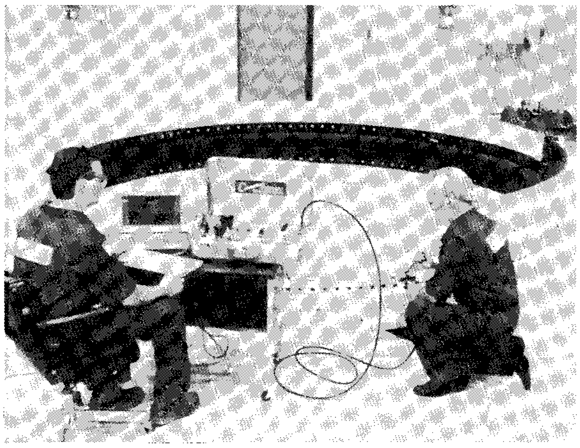

Fig. 11 Cameron Offshore Engineering flowmeter leak test system testing short stack SRB.

VIII. Short Stack Testing

Short stack SRB tests evaluate 1) grease buildup during the assembly-disassembly processes; 2) the qualitative observations regarding grease blockage on leak check testing; 3) the viability of the pressure decay and flowmeter leak check systems.

A short stack is a 3-ft-length segment of an SRB rocket motor factory joint. The sample was previously used in other testing resulting in localized seal surface damage to part of the segment. Addressing the damage required isolating the damaged part of the segment with a grease blockage and limiting the test pressure to 200 psi.

Several qualitative makeup and breakout tests are performed on a shortened SRB factory joint segment. Because of the reduced weight of the segment and because of the lack of factory equipment for the makeup process, only qualitative observations are made.

The observations from the makeup process verified the GET testing procedures. Specifically, during the makeup process, and depending upon the amount of grease available on the O-ring and sealing surfaces, grease can build up on the sliding surfaces of the O-ring.

IX. Leak Check Systems

Subsequent to the experimental investigations, efforts are directed towards the practical measurement of seal integrity for the SRB. The pressure decay method is selected in preference to the pressure rise method because of SRB configuration; later a flowmeter based system is developed. The pressure decay method demonstrates the ability to provide sufficient accuracy, portability, and reliability. The pressure decay method measures a change in pressure in the annulus between two seals which is then with gas laws converted to a change in volume over the test time interval.

Because of the sensitivity of seal integrity to different failure modes, pressure decay testing on the SRB is required at the pressure levels of 30, 100, and 1000 psi. A typical configuration is shown in Fig. 10. The system consists of the SRB joint, hose, and leak test unit. Within the leak test unit are a differential pressure transducer, a reference volume, and isolation valves. The differential pressure transducer is placed between the reference cavity and the joint being tested. Initially, the reference cavity and joint are at the same pressure. Changes in pressure between the test cavity of the joint and the reference volume is reflected as a differential pressure. An RTD is placed inside the reference cavity to measure gas temperature. Tests are conducted for different time periods depending upon test pressure.

As part of the required volume leak rate determination, the system volume is determined. The internal volumes of the SRM joints vary slightly between assemblies; therefore, the volume of the joint seal annulus must be measured. The measurement is made by releasing the pressurized contents of a control volume into the unknown joint volume and applying gas laws using the temperature and pressures of the system.

During a leak test, data are gathered and the average leak rate determined. Because the measurements are averaged over time, longer testing procedures tend to increase accuracy asymptotically.

Typical leak rate accuracy of 1×10^{-4} sccs is achievable with this approach. Results are highly reproducible and satisfy all seal acceptance criteria. The only significant disadvantage of the approach is the testing duration, which can become substantial.

Cameron Offshore Engineering-Aerospace Division began in-house development of a flowmeter leak test system (FLTS), which can meet accuracy, reliability, and usability requirements but can reduce testing times. The system comprises a data acquisition system (DAS) and a pneumatic panel. A view of a prototype is shown in Fig. 11. The panel includes pressure/flow circuits instrumented to measure gas pressure, temperature, and flow rates. The circuits are designed for either 100 or 1000 psig. (A single unit with multiple pressure level testing capability is available.) Depending upon the requirements, one to seven mass flowmeters are located in a panel. The software in the DAS automatically selects and displays only the active flowmeter(s) during a particular test. Multiple flowmeters are used to measure to the 100 psi and the 1000 psi circuits. Flowmeters can also be installed so that both leakage from the FLTS into the test annulus and out of the test annulus into the adjacent annulus is measured. The measurement of reverse flow into an adjacent annulus assists in the location of leaks.

The FLTS is constructed and exercised on both the GET fixture and short stack configurations. The equipment demonstrated ability to reduce testing time (approximately 50% reduction) and measure leak rates (0.2–0.0002 sccs).

X. Summary

The following summarizes the experimental and analytical efforts from the O-ring seal investigation.

1) A wide variety of parameters can affect a reliable seal performance pressure test. These include temperature, type and quantity of grease, test pressure, and seal direction. The most reliable performance pressure tests are at or above the working pressure of the seal with a minimum amount of lubricant, at highest expected working temperature, with the seal in its working configuration.

2) A wide variety of failure scenarios can produce seal failure including contamination, seal damage, and seal surface damage. Seal acceptance criteria must selectively screen failure mechanisms.

3) The seal material, lubricant, gland configuration, operational medium and pressure, assembly procedure, and seal verification procedure are a system of inter-related mechanisms.

4) Different types of potential seal failure mechanisms exist for contaminants, seal damage, and seal surface damage.

a) Generally, contaminations by wire, hair, and metal debris produce leaks which increase with increasing test pressure, similar to an orifice.

b) Although varying substantially because of flaw size and pressure direction, cut O-rings tend to reduce leak rates with increasing pressure, and may seal. However, a threshold pressure which produces total seal failure may exist.

c) Damaged seal surfaces act like wire contaminations and will increase leak rates with increasing test pressure.

References

[1]Moore, C. J., "Solid Rocket Joint Seal Analysis," NASA TM-86580, Jan. 1987.

[2]"Performance Evaluation of O-Rings to Substantiate New Criteria for Surface Defects, Surface Contaminations, and Compressure," Rept. SRC-19TM, Aeroject General LMSC Subcontract 17-10098.

[3]Parker O-Ring Handbook, March 1982.

[4]Molari, P. G., "Stress in O-Ring Gaskets," 6th International Conference on Fluid Sealing, Paper 82, Feb. 27–March 2, 1973.

[5]McArdle, J. G., "Leak Testing," *Nondestructive Inspection and Quality Control*, 8th ed., Vol. 2, American Society of Metals, pp. 260–269.