AECL Research

Fluid Sealing Technology Unit

HIGH PERFORMANCE SEALING - MEETING NUCLEAR AND AEROSPACE REQUIREMENTS

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by

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ABSTRACT

Although high performance sealing is required in many places, two industries lead all others in terms of their demands—nuclear and aerospace. The factors that govern the high reliability and integrity of seals, particularly elastomer seals, for both industries are discussed.

Aerospace requirements include low structural weight and a broad range of conditions, from the cold vacuum of space to the hot, high pressures of rocket motors. It is shown, by example, how a seal can be made an integral part of a structure in order to improve performance, rather than using a conventional handbook design. Typical processes are then described for selection, specification and procurement of suitable elastomers, functional and accelerated performance testing, data-base development and service-life prediction.

Methods for quality assurance of elastomer seals are summarized. Potentially catastrophic internal defects are a particular problem for conventional non-destructive inspection techniques. A new method of elastodynamic testing for these is described.

INTRODUCTION

Seals are basically devices for restricting or preventing leakage through a gap or joint between components or surfaces. Hundreds of different types of seal are in common use, ranging from the simple cork in a bottle or rolled edge on a can, to the complex labyrinth seals on a jet engine or cascade of rotary face seals in a nuclear main coolant pump.

More than 25 years ago a group of specialists was formed at AECL's Chalk River Laboratories to pursue seal research, product development and field application, resulting in a vast improvement in the performance, safety, reliability and maintainability of a wide variety of fluid seals (Ross-Ross and Metcalfe, 1980). This was necessary to resolve major shortcomings of commercial seals, which were evident in early CANDU® nuclear plants.

In an outgrowth of this technology, AECL contributed towards improving O-ring seals for Space Shuttle boosters in the aftermath of the Challenger accident (Wensel et al., 1988). Following the successful re-design of the case segment "field joints," AECL became prime contractor to Lockheed-Aerojet and NASA for seal design in the new generation of "advanced" boosters, employing numerous O-ring seals. This included extensive testing of various elastomer formulations to optimize the recipe for these applications and to ensure consistent quality. The technology resulting from these studies has become widely used throughout the sealing industry. Customized solutions implemented in numerous applications have paid for development costs many times over.

Taking high performance sealing applications from the aerospace and nuclear industries as examples, this paper describes factors governing high reliability and integrity of seals, and outlines methodologies critical to achieving optimum seal performance. The focus is on elastomer seals, but the approach applies widely to other types of seals.

ELASTOMER SEAL FUNDAMENTALS

Elastomers (i.e., rubber-like materials) are extensively used in sealing, particularly for static sealing at temperatures that are not too extreme. However, there is much more to elastomer sealing than simply squeezing a

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seal according to handbook guidelines, as was dramatically pointed out to the world when the Challenger exploded in January 1986 (Metcalfe et al., 1989).

The design of elastomer-sealed joints is always a compromise, but significant improvements are usually feasible if, from the outset, the seal design is integrated with the associated parts—not added as an afterthought, transcribed or scaled from another application. The priorities and trade-offs for optimum design decisions then require a good fundamental understanding of the sealing mechanism (Metcalfe and Wensel, 1994).

Taking an O-ring as an example, sealing is achieved when the leakage paths remaining when it is pressed against a counterface are small enough to prevent significant leakage. There must therefore be enough force to cause the relatively soft O-ring material to conform to the topography of the counterface (i.e., to in-fill the machining marks, scratches and other roughness). Initially, this depends on the amount by which the O-ring is squeezed from its original shape, which becomes flattened across each sealing "footprint," creating contact force (Kuran et al., 1994).

O-rings are able to transmit hydrostatic pressure independently of their deformation, since the hydrostatic component of stress on an O-ring creates no deformation (elastomers are essentially incompressible). Typical deformed shapes are usually the result of pressure variations of about 0.7 to 1.4 MPa (100 to 200 psi). In higher pressure applications, therefore, O-rings act almost as fluid-filled bags. This emphasizes their difference from conventional gaskets (e.g., spiral-wound), which rely on large clamping forces and require heavy flanges.

When hydraulic pressure is applied to the upstream side of an O-ring, this may either increase or reduce the contact force (contact pressure), depending on whether the arrangement promotes "pressure-assist" or not. This is a crucial consideration for soft seals in general. Too much pressure-assist can cause friction problems; for example, during sliding of piston-type seals. On the other hand, negative pressure-assist inevitably leads to leakage at higher pressures and is generally undesirable, unless the sealed pressure is significantly lower than the initial contact pressure.

The wedge-shaped seal in Figure 1 illustrates pressure-assisted behaviour. This will not seal well if installed as shown in Figure 1b, whereas when installed the opposite way, as in Figure 1a, the greater squeeze at the upstream end of the sealing footprint acts to reduce penetration of hydraulic pressure and thus increase the contact force and sealing effectiveness.

SPACE SHUTTLE BOOSTER O-RINGS

Elastomeric O-rings are suitable for most quasi-static joints at temperatures below about 150°C. They continue to be the most suitable option for Space Shuttle boosters (SRMs, Solid Rocket Motors), provided the hot gas inside is kept away from the joints!

The contrast between the field joints (those assembled at the launch site) of the "Re-designed" SRM (RSRM) and those of the next generation ("Advanced") ASRM, now in development, illustrates how much improvement a new, integrated approach can give over even the most thorough "afterthought" (Metcalfe and Wensel, 1994):

(1) The RSRM joint (Figure 2) required structural change—the addition of a "capture feature" to the upper half of the joint—to reduce the pre-Challenger gap opening problem during ignition transients. Many new case sections had to be manufactured to implement this.

(2) O-ring squeeze was increased for the RSRM by using a larger cross-section in the same depth, but wider, groove. This made the assembly procedures more problematic because of greater friction and the chance of cutting the O-rings, which then prompted a thorough revamping of the post-assembly leak-checking procedures and their efficacy.

(3) Various elastomers, manufacturing processes and lubricants were investigated for the RSRM in order to boost resilience and subjugate defects compared with the original SRM. However, the manufacturing process of splicing ground cord stock into finished O-rings presented such a restriction that only the defect detection and acceptance criteria were significantly changed. Heaters therefore became an RSRM requirement for cold launch conditions.

By comparison, there are fewer field joints in each ASRM, and they have been designed (Figure 2) with the following sealing considerations in mind:

(1) The ASRM case structure is designed for essentially zero gap opening at all the O-rings.
(2) High squeeze is used without creating assembly problems because of the face seal arrangement.
(3) The elastomer formulation is considerably improved and the O-rings are moulded at their full size (not spliced from smaller pieces).

Another ASRM joint where vast improvement over the "handbook" design was possible is the igniter-to-case joint, shown in Figure 3. This is a static application. Since the only significant movement is during assembly, it is desirable to create high contact forces in the sealing footprints, which should be as wide as possible. High squeeze and large O-ring cross-section are therefore two important design goals.

As in the field joints, the basic shape of this joint is essentially fixed by the structural requirement for zero gap opening. Positioning the seals in a conventional bore seal arrangement (Figure 3a) raises concerns for damage to a critical sealing surface or an O-ring during assembly. The sealing bore of the uppermost member could easily be scratched due to metal-to-metal contact as it slides across the upper lip of the lower member. This is unlikely to be noticed during assembly due to the large size and weight of the components. Such scratches in the cross-footprint direction could cause leakage. O-ring damage could also occur during assembly because of the sliding distance, particularly when passing a leak check port. High squeeze exacerbates this.

Considering the effects of machining tolerances, including out-of-roundness and eccentricity of these two large-diameter components, the squeeze range for the conventional bore seals will be about 15%. This means that if for assembly reasons 25% squeeze is not to be exceeded, then at the opposite extreme of tolerances the squeeze will only be 10%. This range is too wide for satisfactory performance.

In considering potential accident conditions, a conventional design would incorporate two identical seals having critical sealing surfaces on the same member, directly in line with one another. These are prime candidates for common-mode failure. For example, should a leak path be established by erosion of the first seal by a jet of high temperature gas, erosion of the second seal could be quick to follow.

Recognizing these problems of the bore seal design, and returning to the original goals of high squeeze and large footprint, it is clear that this conventional arrangement is marginal at best. Neither can the cross-sectional size of the O-rings simply be increased to improve the situation. Available axial space is already used up by:

(1) lead-in chamfers for assembly,
(2) groove width (to provide sufficient axial space to prevent overfill of the groove by the squeezed O-rings),
(3) the lip on the uppermost edge of the uppermost groove (to ensure that it will not be damaged by bending or breaking if bumped).

By moving the O-rings into the corners (Figure 3b), much more axial space becomes available for the seals—the lead-in chamfers become part of the seal cavities, the lip above the uppermost seal no longer exists and the axial lengths of the grooves become less (relative to the O-ring sectional diameter). Much larger seals can thus be accommodated in the given space—in fact, in addition to the 30% increase in seal size incorporated in the alternative design shown, the axial length and weight of the joint is reduced.

The corner seal arrangement allows much greater squeeze to be applied to the O-rings, since this comes from axial compression rather than radial interference. It is also much better controlled, being governed by short axial dimensions and tolerances rather than large diameters.

The potential for common-mode failure has been reduced by the alternative design, which avoids an "in-line" arrangement. Damage to the lower seal due to "jetting" of hot gases past a leak in the first seal is much less likely because of the tortuous path. The potential for assembly damage due to sliding, or to the leak check port, is eliminated.

From the perspective of transient response to sudden pressurization at SRM ignition, the corner seals have a number of additional advantages over the rectangular groove bore seal arrangement. The first is "diagonal sealing." The "inlet" to each seal cavity is diagonally opposite the "outlet." On sudden pressurization, then, there is a larger pressure force urging the O-ring to move towards, and thus seal, the outlet. With a bore seal arrangement, such "pressure-assistance" can be delayed, particularly when the O-ring is pre-set to the upstream edge of its groove (as is the case in this application because a high pressure leak check is conducted prior to flight). A further advantage is that once pressure is established, the contact force in the footprint region is magnified due to the acute angle, over that for rectangular grooves. High contact force means better in-filling of asperities and flaws, and better "bridging" of contaminants.

Other benefits of the alternative design are:

(1) It eliminates clearance at the lower of the two seals, thus minimizing any concerns over possible extrusion.
(2) Critical sealing surfaces are more accessible, both for initial machining and for refurbishment (ASRM components are intended for multiple use).
(3) Internal stresses in the O-ring are lessened; triangular confinement avoids the damaging stresses of high squeeze in an unconstrained rectangular groove.

Looked at as a whole, many benefits accrue from the corner seal design. However, parts must be carefully toleranced to avoid damage by exceeding 100% fill. As stated previously, elastomers are essentially incompressible; however, they may swell, and their thermal expansion is $\sim 2\times10^{-4}$ K^{-1} (i.e., an order of magnitude greater than most metals).

OPTIMUM ELASTOMER SELECTION

Elastomer Characteristics. Elastomer seal "compounds" are intermittently produced in relatively small batches, compared to most industrial products. They are made by adding a variety of ingredients to a base elastomer stock. The choice of ingredients and their proportions govern the physical, chemical, and functional properties of the finished product. Since there are many base elastomers and many additives, the variety of compounds having different properties is often overwhelming. Industry-wide standardization by formula does not exist, nor is it feasible.

Being organic, elastomers are subject to deterioration with time, temperature, fluid contact, and other environmental influences. To select the best elastomer compound for a particular set of service requirements, compound-specific testing is required, with careful choice of performance criteria and test methodology (Wensel, 1993).

Readily measured physical properties, like hardness and tensile strength, have traditionally been favoured in the selection process, rather than functional performance like (for seals) leak-tightness and extrusion resistance in actual service conditions. There is often little correlation.

Hence, functionally related testing procedures must be used if high performance is needed. They must be based on the particular conditions under which the O-ring will or could be required to serve. These "functional tests" must cover all relevant effects of the actual service conditions, including accelerated lifetime testing (Wensel, 1985). Each test should reproduce a type of failure encountered or expected in actual service.

Although functional tests must provide the basis of the methodology for selection of compounds for severe service, readily measured properties can then help to "fingerprint" the specific compound, once selected, to ensure that subsequent batches are the same.

Space Shuttle O-Ring Selection. As an example of an extremely comprehensive process to derive the best fluorocarbon compound for all O-rings of the ASRM, thirteen measurable, function-related properties and their corresponding test methods were devised that encompassed all the service requirements for these seals (see rows and columns of Figure 4). Next, weighting factors were estimated for each "box" of this matrix, based on the expected influences of each property on each sealing requirement. Trade-offs were appraised and quantified during this process.

The thirteen properties of sixteen different candidate compounds were then measured. Each formulation and manufacturing process was strictly controlled. The quantifiable results, analyzed to ensure statistical significance, were then used with the pre-established weighting factors to select the optimum compound for ASRM service. They also demonstrated that most of the sixteen compounds could be considered "qualified" for the intended service, but with reduced margins.

Next, this optimum compound was evaluated for variations, especially batch-to-batch, to establish rejection limits for quality assurance. Three functional properties (compression-recovery, hot jet resistance, high temperature extrusion resistance) and eight physical/chemical properties (specific gravity, tensile strength, elongation, modulus, hardness, compression set, rheometry, volumetric swell) were found sufficient for this purpose. Together, these properties and their respective rejection limits served to "fingerprint" the compound.

Nuclear O-Ring Selection. For nuclear applications, ethylene propylene (EPDM) is often the preferred basic elastomer class due to its resistance to hot water and aging. In its formulation, there are trade-offs such as extrusion resistance gained at the expense of thermal aging. Selecting the optimum commercially available compound requires both testing and application-specific prioritizing of performance requirements (Wensel et al., 1994).

Figure 5 illustrates the wide range of performance that occurs. In this case, three EPDMs are compared on the basis of thermal aging resistance when used as static seals in hot water. The range of failure times, particularly at the higher temperature condition, is striking: 37 weeks for the best and only 2 weeks for the worst. Similarly, extrusion resistance tests in hot water for loss of cooling in a typical nuclear plant (Figure 6) give a wide range of performance between EPDMs. One compound resists extrusion at gaps four to five times those of another, although in common industrial practice such materials are often regarded as equivalent. There is clearly a strong need to be compound-specific.

SPECIFICATIONS, INSPECTION AND DEFECTS

To ensure the correctly performing compound is received for critical applications, specifications must not unwittingly open the door to other compounds in the same class of elastomer. Otherwise, service may be unacceptable—low safety margins, unreliability and frequent replacement. If alternative compounds are needed as back-up, then each must be separately qualified. As a minimum, purchase specifications should require that each elastomer seal be traceable to the particular "batch" of ingredients mixed and processed together to form the unvulcanized stock from which the seal was made, and that a manufacturer's certificate of conformance be provided confirming the seal's size, compound identification, batch number, date of cure, hardness, specific gravity and tensile strength relative to the manufacturer's expected values.

In AECL-produced main coolant pump seal assemblies, for example, all elastomer seals are batch qualified by functional testing. In addition, the most critical elastomer seals in the assembly are individually serialized, and their moulds have cavities for simultaneous production of O-rings, which can then be functionally tested. This, and positive identification of the parts, serves to verify the moulding process in addition to verifying the batch of unvulcanized elastomer. Receiving inspectors at a plant, in this case, need only confirm the documentation.

Defects—Overall Nuclear Approach. An oft-neglected area of quality assurance that impacts heavily on seal integrity and reliability is inspection methodology and acceptance criteria for defects. This includes defects in the seal gland as well as in the elastomer seal, since machining marks and other irregularities in the gland surfaces can disrupt sealing just as much as isolated scratches, pits, abrasions, and cuts in the seal itself.

Although defect acceptance criteria for seals and seal glands are best established by application-specific functional testing, some general guidelines apply. Defects like scratches, machining marks ("chatter marks" in a lathe-turned part) or cuts that extend across the "footprint" of the seal are a prime concern. Whether these are acceptable depends largely on their steepness (i.e., their depth to width ratio). This applies equally to defects in the surfaces of the seal gland. The deeper and narrower the scratch or groove, the more difficult for the elastomer to deform into it. Limits can be assigned based on test data and analysis (Kuran et al., 1994).

For surface defects, examination by unaided eye is a satisfactory inspection method. This requires stretching of each region, since many defects, such as cuts and tears, are difficult to see in unstrained parts. Size can be compared to reference standards that simulate acceptance limits, and (if necessary) measured using optical and mechanical aids (e.g., calibrated magnifier, depth measuring microscope, stylus profilometer).

For detection of internal defects, such as inclusions, voids and regions of inhomogeneity in elastomer seals, a non-destructive tool called an Elastodynamic Tester has been found most useful. It measures reaction force resulting from an imposed deformation. Figure 7 shows an automated system for elastodynamic testing of O-rings—a 1994 R&D 100 Award winner (Anon, 1994). The reaction force on two pinch rollers is measured as the O-ring is driven and squeezed between them. Internal defects are signalled by spikes in reaction force. Any generally high or low force, or variation around the O-ring, signifies abnormal properties when compared with a known baseline.

Space Shuttle O-Ring Defects. The approach followed in developing rejection criteria and defect inspection methods for Space Shuttle O-rings was first to develop functional sealing tests that subjected the O-ring to simulated conditions exceeding "worst-case," and then to use these tests to evaluate intentional defects of all plausible and potentially dangerous types (Wensel et al., 1988). For each type of defect, the critical size for unacceptable leakage was generally found by bracketing a failure at one size with a pass at a smaller size.

Supplementary tests with transparent fixtures allowed defect behaviour to be observed under the simulated service conditions, both statically and during ignition transient simulations. O-rings were viewed and photographed to measure the shape and width of the footprint (region of contact) under a range of squeeze, pressure and gap opening conditions, thus establishing the size of each type of defect at which bridging of the footprint (i.e., leakage) occurs.

"Defect detection requirements" were established by applying a safety factor (i.e., a reduction of at least two in the largest defect that consistently passed the sealing tests and was also seen to be safe in the footprint observations). If the O-rings could consistently and economically be manufactured to a more stringent requirement, and detection method sensitivity was sufficiently reliable at these smaller defect sizes, then a higher safety factor than two was applied.

The detection capabilities of inspection techniques were assessed relative to the detection requirements. Rejection limits specific to each adopted detection technique were determined for each defect type. For visible, directly measurable surface defects (abrasions, grooves, voids, cuts), rejection limits were defined simply in terms of defect dimensions. For sub-surface defects (voids, inclusions, regions of inhomogeneity, sub-standard material where depth and orientation within the cross section were important factors), rejection limits were defined in terms of elastodynamic test results. This measured the effect of defects on the static and dynamic contact (sealing) force response, and was therefore most closely related to sealing ability.

In summary, inspection requirements and defect limits for severe service should be customized to functional, application-specific testing. This assures safe service without imposing overly stringent standards and wastefully high rejection rates.

ELASTOMER SEAL STORAGE AND USAGE

Elastomers are subject to deterioration with time, temperature, and other environmental influences. Ideal storage conditions are cool, dark, and free from contaminants (such as ozone, solvent vapors, etc.). Elastomer seals should be stored in a relaxed state, free from strain (i.e., not folded, twisted, or hanging on a rack). Under such conditions, most elastomer compounds will remain serviceable for many years. Measurement of critical sealing properties (e.g., compression set, extrusion resistance, hardness) of O-rings of certain ethylene propylene and nitrile compounds stored under such conditions by AECL has shown them to be essentially unchanged after more than twenty years. Not all elastomer compounds are this stable, however, particularly not all nitrile compounds.

Immediately prior to installation, after verifying that an elastomer seal taken from storage is of the required size and material, it should be thoroughly examined for defects that might previously have gone unnoticed, particularly for crazing or cracking that might have occurred during storage. All contacting surfaces of the seal gland should be examined for edge break at the corners of grooves, and smoothness of lead-in chamfers and countersurfaces over which the elastomer must slide during assembly.

Rolling or twisting of an O-ring in its groove with bore-type assemblies can be avoided by ensuring smooth surfaces and correct lubrication. Only a thin film is needed, and once applied, care is necessary to avoid introducing contaminants, particularly hairs and fibres, which readily create leak paths. However, excessive or inappropriate lubricant can cause failures (e.g., by causing swell or by restricting small flow passages or contaminating the rotary face seals in main coolant pumps).

SUMMARY

The Canadian nuclear industry had special needs to develop greater fundamental understanding, improved products and better practice in the field of fluid sealing. Various factors for high performance have been described. The key is a thorough understanding of principles, coupled with an open-minded, custom-design approach, and close attention to delivering consistent, well-qualified material.

The economic benefits to Canada of better sealing provided by AECL's seal improvement programs in the nuclear industry alone are in the hundreds of millions of dollars. In addition, there has been immeasurable spill-over, with many industries now using and benefitting from nuclear-developed sealing technology—and nuclear plants benefitting from the greater knowledge gained through Space Shuttle O-ring improvement programs.

ACKNOWLEDGEMENT

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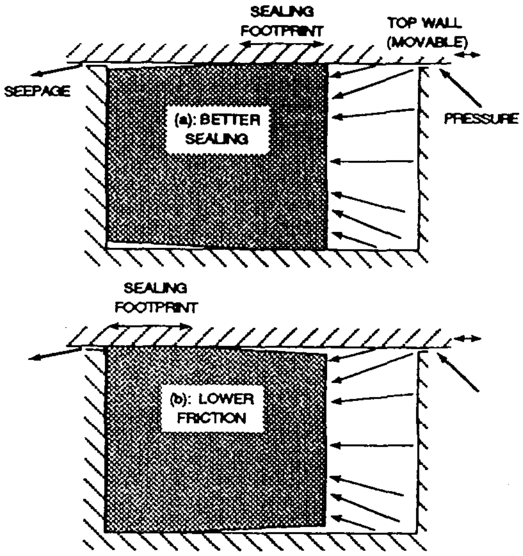
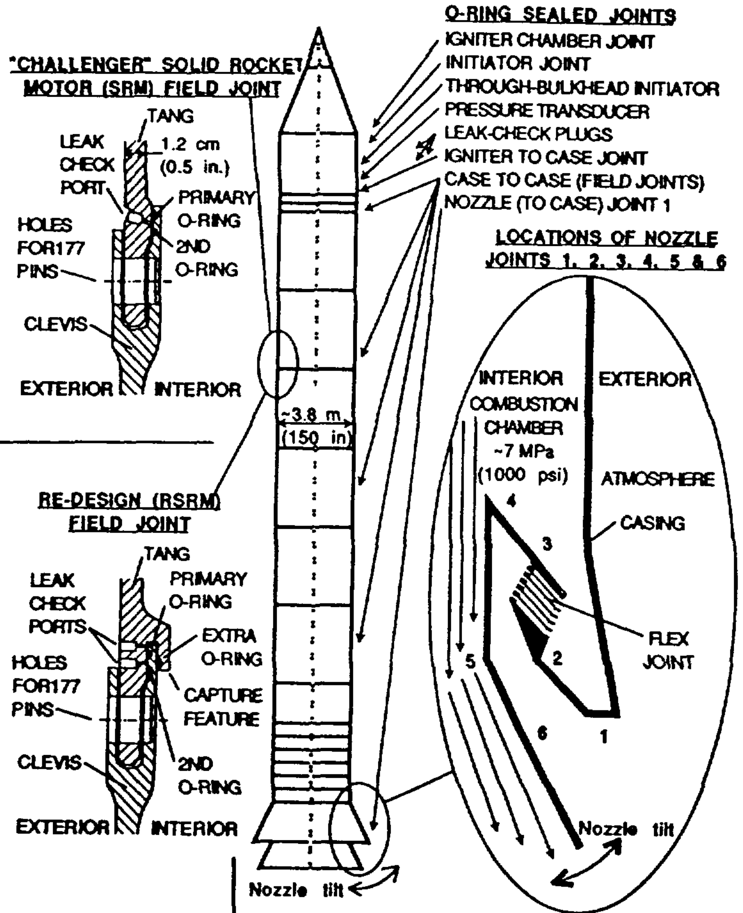
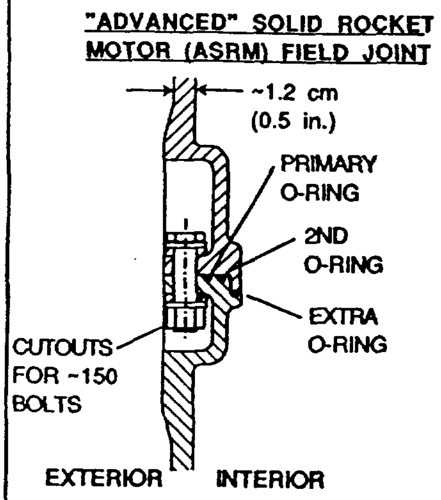


Figure 1. Wedge-Shaped Seal. Effects of forward vs. reverse pressure.

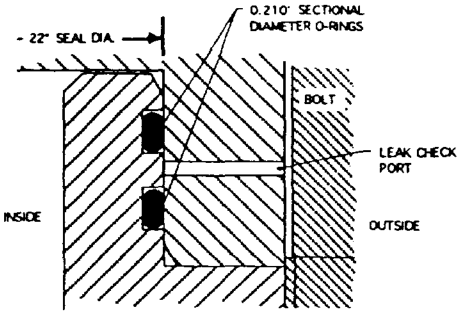


- **Initial gap still present**
- **Gap opening still present**
- **Axial movement still present**
- **Squeeze limited**
- **Assembly damage concerns**
- **Heaters necessary**

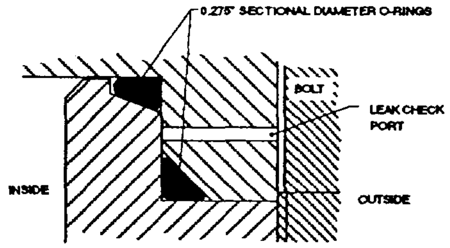


- **Zero gap opening**
- **High squeeze**
- **Potential for assembly damage greatly reduced**

Figure 2. Space Shuttle Boosters and their O-Ring Sealed Joints. There are numerous such joints in each booster. Failure of a "field" joint caused the 1986 Challenger accident. The "re-design" and "advanced" field joints are much more robust.



(a) Conventional Bore Seals



(b) Alternative Corner Seals

Figure 3. Comparison of Igniter-to-Case Conventional Bore Seals with Improved Corner Seals.

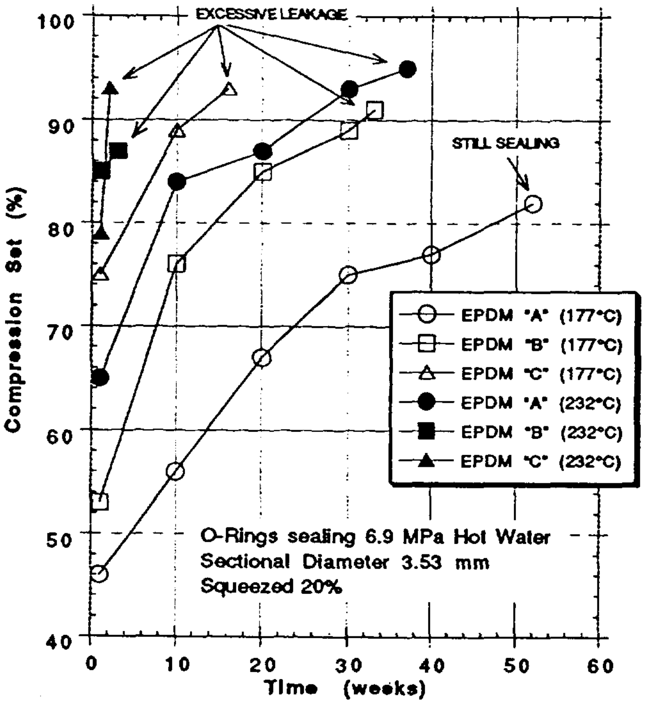


Figure 5. Thermal Aging Comparison of EPDM O-Rings. Mounted in flange-type gland, heated and pressurized, held to end of test or excessive leakage. Compression set measured every ten weeks.

MEASURABLE PROPERTIES	SEALING REQUIREMENTS							
	Cold (0.5°C) bounce back	Aged (5 y) bounce back	Seal without leakage	Resist heat	Resist damage	Seal against 1.6 μm Ra	Lubricant compat-ibility	TOTAL
Compression Recovery	3	2	3	0	1	0	0	9
Age Resistance	3	3	2	0	1	0	0	9
Extrusion Resistance	0	0	3	3	2	0	0	8
Hot Gas Jet Resistance	0	0	3	3	0	1	0	7
Tensile Strength	0	2	1	2	1	0	0	6
Surface Toughness	0	0	0	0	3	1	0	4
Sealing Ability	0	0	2	0	0	3	0	5
Permeability	0	0	1	0	0	0	0	1
Abrasive-Erosion	0	0	0	0	1	1	0	2
Modulus	1	0	1	0	1	2	0	5
Elongation	0	0	0	0	1	2	0	3
Hardness	1	0	1	0	1	3	0	6
Swell	1	3	0	0	0	0	3	7

LEGEND: 3 = High Relationship; 2 = Moderate; 1 = Low; 0 = No Relationship

Figure 4. Example of Matrix Relating Sealing Requirements to Measurable Properties.

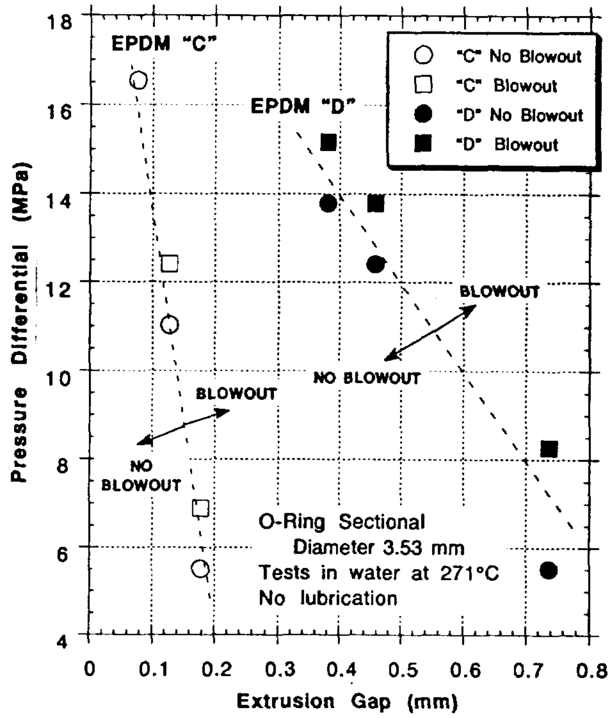


Figure 6. Extrusion Resistance Comparison of EPDM O-Rings.

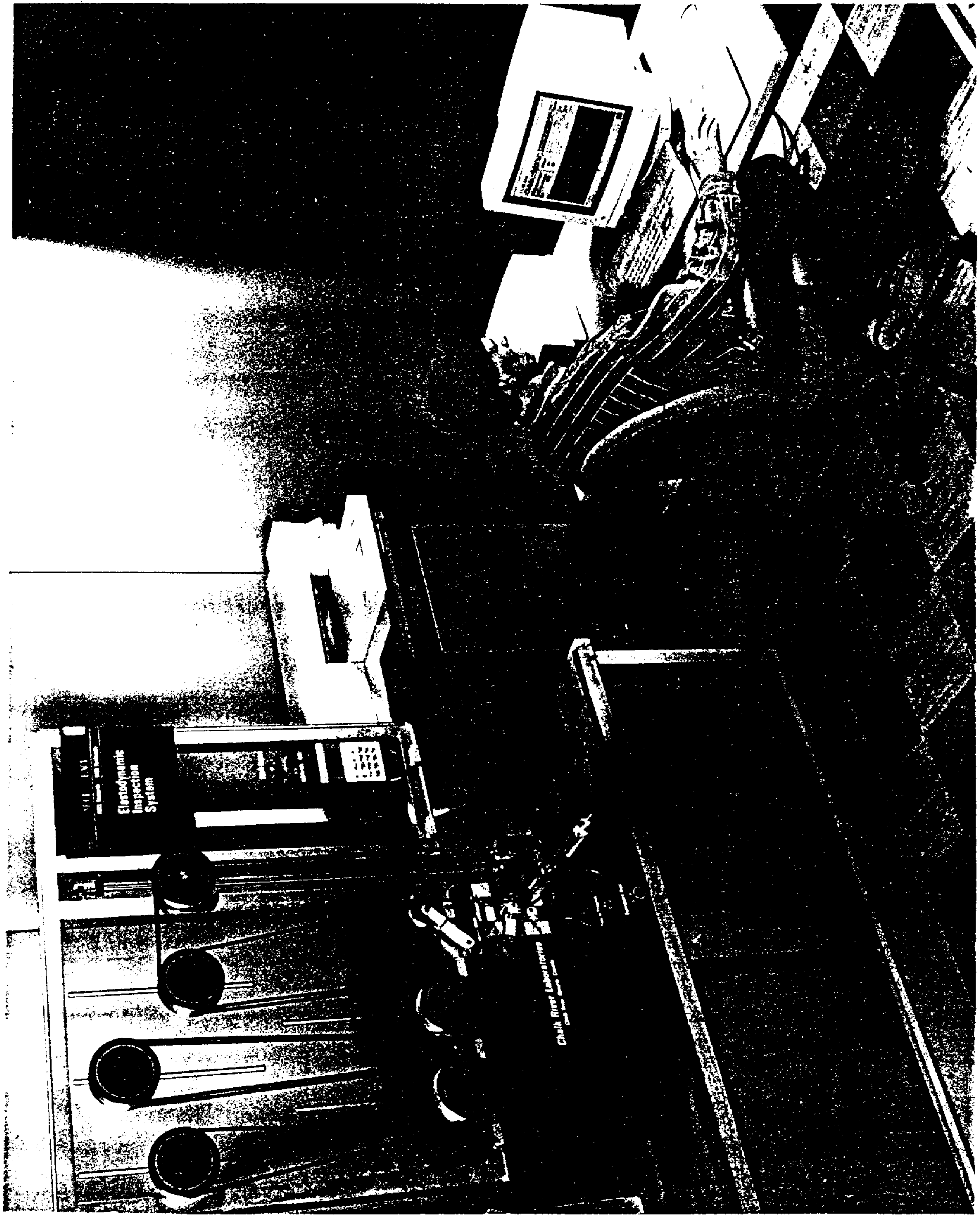


Figure 7. Elastodynamic Inspection System for O-Rings. A Space Shuttle booster O-ring is being inspected. Anomalies are compared with calibration signals for reference defects. Overall properties are compared with known baseline material.