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Upgrading Elastomer Seals for Nuclear Service

Amélioration des joints en élastomère pour utilisation dans les centrales nucléaires

K.C. Wittich, R. Wensel, R. LaRose, S. Kuran

Paper presented at the Society of Tribologists and Lubrication Engineers' Annual Meeting, 1995 May 14-19, in Chicago, Illinois

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UPGRADING ELASTOMER SEALS FOR NUCLEAR SERVICE*

by

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Résumé

Les pompes, la robinetterie et les instruments installés dans les centrales nucléaires ont toujours contenu dans le passé le type d'élastomère que chaque fournisseur de matériel utilisait traditionnellement pour des applications autres que nucléaires. La prolifération des composés à base d'élastomère, et leur fiabilité parfois douteuse, est en voie d'être restreinte grâce à l'amélioration et à la normalisation d'un plus petit nombre de composés dont on a vérifié pour chacun le haut degré de performances dans les conditions spécifiées pour leur catégorie d'utilisation. Le but de cette entreprise est d'améliorer de façon efficace et rentable la fiabilité et l'intégrité du matériel installé dans les centrales nucléaires de conception canadienne. Ces efforts portent essentiellement sur les joints en élastomère et englobent la maîtrise des principes fondamentaux relatifs aux joints d'étanchéité, la mise au point de données pertinentes en vue d'obtenir les meilleurs composés pour chaque application, et l'amélioration des méthodes d'assurance qualité, notamment des directives de manutention et de contrôle. En pratique, dans un premier temps, on examine soigneusement les problèmes avec le personnel de la centrale ainsi que les dossiers de la centrale. On donne deux exemples de service intense dans lesquels ces exigences ont été satisfaites par la démarche graduelle suivante : inspection et essais en laboratoire de joints ayant été utilisés dans la centrale, essais préliminaires et essais de qualification des améliorations apportées, remise en service, et surveillance des joints améliorés durant les périodes de remise en service graduelle. On a constaté des améliorations considérables au point de vue de la fiabilité et de la résistance, en situation simulée de service normal et en situation accidentelle, à la chaleur, aux rayonnements et à d'autres causes de détérioration. On prévoit également des économies importantes sur les frais d'entretien.

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Abstract

Pumps, valves and instruments in nuclear plants have historically contained whatever elastomer each equipment supplier traditionally used for corresponding non-nuclear service. The proliferation of elastomer compounds, and their sometimes uncertain reliability, is now being reduced by upgrading and standardizing on a handful of compounds that have each been verified to be high performers for their class of service conditions. The objective is to make cost-effective improvements in the reliability and integrity of equipment in Canadian-designed nuclear plants. The effort focuses on elastomer seals and includes: understanding sealing fundamentals, developing relevant data for superior compounds for each service, and improving quality assurance methods, including handling and inspection guidelines. In practice, discussions with plant personnel and review of plant records are the first step. Two severe-service examples are given where these needs have been met by the following progression of activities: inspecting and laboratory testing of seals removed from service, preliminary and qualification testing of improvements, introduction into service, and monitoring the upgraded seals during phase-in periods. Large gains in reliability and integrity have been demonstrated for simulated normal and accident service conditions of heat, radiation and other deteriorative influences. Significant savings in maintenance costs are also projected.

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TABLE OF CONTENTS

LIST OF FIGURES

UPGRADING ELASTOMER SEALS FOR NUCLEAR SERVICE

1. INTRODUCTION

In a nuclear plant, elastomer seals must function in many environments that do not exist or are uncommon in other industries. The best known of these is ionizing radiation, but nuclear seals often face high temperature water or high levels of ozone also. Performance requirements are unusually high because of the cost of breakdowns and maintenance in radiation fields, plus the need to keep the reactor safe at all times.

In equipment for nuclear plants, manufacturers usually supply elastomers (i.e., rubber-like materials) that are essentially identical to those they supply to other industries. Sales to nuclear plants are rarely large enough to warrant development of improved compounds, and data relevant to severe nuclear service rarely exist for commercially popular compounds. This sometimes results in equipment with seals of inferior or inappropriate elastomer compounds, or compounds of uncertain durability in service. It has also led to a proliferation of compounds being used, since each manufacturer has different favorites. Upgrading and standardizing on a handful of superior materials can greatly improve integrity, service life, and overall cost.

The need for equipment upgrading has been met in the Canadian nuclear industry by developing in-house expertise by the developer-architect-engineer for Canadian-designed pressurized heavy water reactors (PHWR). Improvements to elastomer seals have been ongoing since needs first surfaced in the sixties. Since then, the effort has developed into an integrated program with the objectives of upgrading elastomer performance, safety margin and service-life predictability in all operating and future PHWR plants. All aspects of elastomer seal optimization are being addressed.

2. OVERVIEW OF INTEGRATED APPROACH

The effort to upgrade elastomer seals falls into two categories: generic and service-specific. A key element in the generic work is identification of the fundamental properties that govern the mechanics of sealing. Also included is more applied work on:

- identifying and retrofitting improved elastomer compounds,
- developing and implementing new elastomer compound specifications and quality assurance procedures, and
- developing guidelines for installation, handling, and inspection of elastomeric components.

Service-specific effort often begins with identification of the need for an improved elastomer seal. This usually comes from discussions with plant personnel and review of maintenance and inspection reports and records of usage. The second stage of this effort encompasses:

- inspection and laboratory testing of seals removed from service,
- preliminary testing of possible improvements,
- qualification testing to demonstrate suitability of a selected improvement for service,
- introduction into service, and
- monitoring the "improved" seals during phase-in periods.

Sometimes, service-specific effort focuses on service-life prediction and environmental qualification. This uses "accelerated-aging" and simulated normal and accident service tests of elastomer seals and equipment under specific conditions of heat, radiation and other deteriorative influences.

3. ELASTOMER SEAL FUNDAMENTALS

An understanding of the mechanics of sealing with elastomers is required to upgrade them for severe-service, high-reliability applications in nuclear plants. Elastomers are extensively used for sealing at moderate temperatures because of their fundamental elasticity, resilience, conformability, toughness, etc. However, there is much more to sealing than simply squeezing an O-ring in accordance with handbook guidelines, as was dramatically pointed out to the world when the space shuttle, Challenger, exploded in January 1986 (1). This does not always appear to be recognized by equipment manufacturers.

Taking an O-ring as an example, sealing is achieved when the leakage paths 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 the sealing "footprint", creating contact force (2). This contact force decreases slowly over time, both through viscoelastic stress relaxation, which is reversible, and through compression set, which is permanent deterioration or "aging". Heat, ionizing radiation, ozone and other effects can accelerate the aging process.

When pressurized, an O-ring first deforms to seal potential leakage paths, then simply transmits any further pressure without further significant deformation, since the hydrostatic component of stress on an O-ring creates no deformation (elastomers are essentially incompressible). The deformed shapes of O-rings of typical hardness do not change significantly as pressure increases beyond 0.7 to 1.4 MPa (100 to 200 psi). In higher pressure applications, therefore, O-rings act almost as fluid-filled bags. The contact force and hence the sealing ability is generally "pressure-assisted" by the sealed fluid. This is different from conventional gaskets, which rely on large clamping forces and require heavy flanges.

4. ELASTOMER COMPOUND DATABASE

A database of relevant properties and behavior is key to elastomer selection and life prediction for severe service, such as in nuclear plants. This data must be compound-specific because within a given elastomer class (e.g., nitrile), the base polymer is compounded with varying amounts of fillers, vulcanizing agents, anti-oxidants, anti-ozonants, processing aids, plasticizers and accelerators from any number of suppliers. These variables, and the method and degree of mixing and curing, all profoundly affect functional properties of the end product—the elastomer seal. This is illustrated by the fact that two commonly used ethylene-propylenes, developed specifically for pressurized hot water, differ by a factor of over ten in their time-to-failure in this service.[†]

Properties alone are not enough for the database to be usable for severe service. It must also include *service*-specific behavior. Most rubber manufacturers' data can be misleading, because: (1) the effects of the fluid are neglected (e.g., air versus water versus other fluids), and (2) the measured damage parameters, that life predictions are based on, often have little bearing on how a seal actually fails in service. (Parameters are more often chosen for testing convenience and standardization.) For instance, maximum tensile elongation before failure, which is often quoted as the damage parameter for O-ring life prediction, does not play a significant role in the mechanics of forming a seal, nor does it correlate well with properties that do.

Besides choosing the most appropriate damage parameter(s), the level of damage considered to constitute a failure must also be chosen judiciously. Compression set may be correctly identified as the most likely failure mode for a particular application, but its magnitude for failure may be poorly estimated. For example, a compression set failure criterion appropriate for a piston seal will severely underestimate life for a bolted flanged joint. A high compression set criterion is appropriate for a flange seal since the O-ring is in a static, highly squeezed face seal arrangement, with no extrusion gap and no changes of squeeze. In contrast, a low compression set criterion is appropriate for a piston seal which is dynamic, lightly squeezed, and has parts with tolerance stack-ups that create significant eccentricity between the piston and bore.

Naturally, the amount of testing must always be balanced by the value of the results. Consider that accelerated thermal aging requires data at four temperatures for reasonable extrapolation, and at each temperature the duration of the test must be iterated to obtain the desired level of damage (see Figure 1). Consequently, developing a compound-specific database can become very expensive. This is another reason to rationalize the number of compounds used in the field to the fewest that adequately cover the required range of applications.

[†] These results were found by tests of O-rings sealing 6.9 MPa, 232°C (1000 psi, 450°F) water. One compound failed after five weeks; the other had not failed after 52 weeks.

5. ELASTOMER QUALITY ASSURANCE

5.1 Material Performance

To ensure that validity of the test data, the ingredients and processing variables for each chosen compound must be closely controlled for consistency, both in original qualification testing and in subsequent service. Manufacturing control can be verified by functional testing at appropriate intervals—more frequently for critical seals.

The most critical elastomer seals in main coolant pump seal assemblies supplied by the authors' company, for example, are produced in molds that have a cavity for simultaneous production of a test O-ring. By functionally testing this O-ring for set and extrusion resistance and comparing results with expectations, both the molding process and the quality of that batch of unvulcanized elastomer can be verified. Where possible, each critical seal is also individually serialized to ensure traceability. Receiving inspectors at a plant can then be supplied with full documentation to confirm the serviceability of that seal.

To ensure that the correct specific compound is received, purchasing specifications must not open the door to other compounds in the same class of elastomer. Otherwise, performance in service may be unacceptable (i.e., low safety margins, unreliability and frequent replacement). If alternative compounds are needed as back-up, each must be separately qualified. Purchase specifications, as a minimum, must 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. A certificate of conformance must be supplied specifying the compound, its batch number, date of cure and seal size, along with the hardness, specific gravity and tensile strength of samples from that batch, as compared with the manufacturer's expected values.

5.2 Defects

Inspection methods and rejection criteria for defects are often neglected in quality assurance programs for seals. This can impact heavily on seal integrity and reliability. Possible defects include ones 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 scratches, pits, abrasions, and cuts in the seal itself.

Although defect rejection criteria for critical seals and seal glands are best established by service-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 (2).

Surface defects can be inspected by unaided eye. This requires stretching each region, since many defects, such as cuts and tears, are difficult to see in unstretched parts. Size can be compared to reference standards that correspond to 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 localized dynamic squeeze. Figure 2 shows an automated system for elastodynamic testing of O-rings. The reaction force on two pinch rollers is measured while the O-ring is driven and squeezed between them. Localized 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.

6. ELASTOMER SEAL STORAGE AND INSTALLATION

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 vapor, etc.). Elastomer seals should be stored in a relaxed state, free from strain (i.e., not folded, twisted, or hanging on a rack). Their shelf life (expressed as expiry date) should be stated and be rationally based (e.g., if 90% of "as-new" lifetime for the particular service is deemed acceptable, and proper storage at the maximum allowable temperature is known to cause 1% loss per year, then shelf life is 10 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 proper conditions has shown them to be essentially unchanged after more than twenty years (for example, see Figure 3). Not all elastomer compounds are this stable, particularly not all nitrile compounds.

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 of lubricant 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).

7. CASE STUDIES

The following two cases of elastomer seal upgrades illustrate the potential for direct and immediate benefits to nuclear plant owners.

Early failures and frequent replacements of inflatable air-lock door seals in PHWR plants have consumed an inordinate amount of maintenance effort and money. A program to improve these is nearing completion. Bench-scale tests confirmed that in most plants the rate of seal retraction on depressurization was problematic after thermal and radiation exposure. Differences in this rate were found to be due to subtleties in seal cross-sectional geometry and elastomer materials. Material properties were inconsistent—the compounds were not well specified or controlled. Tests also showed how the type and orientation of reinforcing fabric affected performance.

A program of aging and functional testing was initiated to select a more radiation- and ozone-resistant material, in cooperation with manufacturers. Figures 4 and 5 illustrate the improvement in compression set resistance to heat and radiation. Three-fold gains in life were realized. From a design and material improvement effort of ten person-months, a total savings of several hundred thousand dollars annually is expected, with corresponding gains in reliability.

A second example of an elastomer upgrade resulting in large savings and improved reliability in PHWR plants is the retrofit of improved fuelling machine snout plug O-ring seals. The O-ring in this case is in a piston-seal arrangement in a groove on the outside diameter of the snout plug (Figure 6). To facilitate insertion and removal of the plug, the groove is extra deep to give zero or low interference. Once inserted, the O-ring is expanded radially against the cylinder wall by an axial force exerted through a spring-loaded squeezer (the O-ring is shown in the expanded position in Figure 6). For the 11 mm (0.43 inch) sectional diameter and 80 durometer O-ring used, this axial force (250-350 N per linear cm; 150-200 lbf per linear inch of O-ring) equates to the force for 20-30% squeeze of this O-ring (i.e., if squeezed between plates)—not an unusual amount. During each three-month period, the O-ring receives 10^5 grays (10^7 rad) of gamma radiation and is briefly exposed to 80°-180°C (175°-350°F) water approximately 200 times.

Previous O-rings were highly embrittled when routinely replaced after three months, often with chunks torn from them due to adhesion on the cylinder wall. Besides the leakage this caused, the chunks of rubber sometimes lodged themselves in components such as check valves in other parts of the fuel transfer equipment.

It was known from testing of the specific compound being used for these O-rings that the radiation dose had an insignificant effect on its compression set and hardness. Instead, thermal degradation, with adhesion to the wall and associated tearing stresses were the main problems to be overcome in selecting a better compound. From several well characterized candidates, the most likely compound was identified. A comprehensive program of service-specific qualification testing then confirmed its suitability. These O-rings now perform reliably in PHWR plants for four times as long.

There are many more examples of the high payback of elastomer seal upgrading. In addition to the direct payback in terms of increased service life and reliability, there are indirect benefits. The number of compounds becomes fewer. This simplifies the task of demonstrating service life and accident survivability, as is required in nuclear plants. It also reduces stores costs.

8. ACKNOWLEDGEMENTS

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(2) Kuran, S., Gracie, B.J., and Metcalfe, R., "*Low Pressure Sealing Integrity of O-Rings Based on Initial Squeeze and Counterface Finish*", Tribology Transactions, 38.2, 1995 April, (AECL Report AECL-11154).

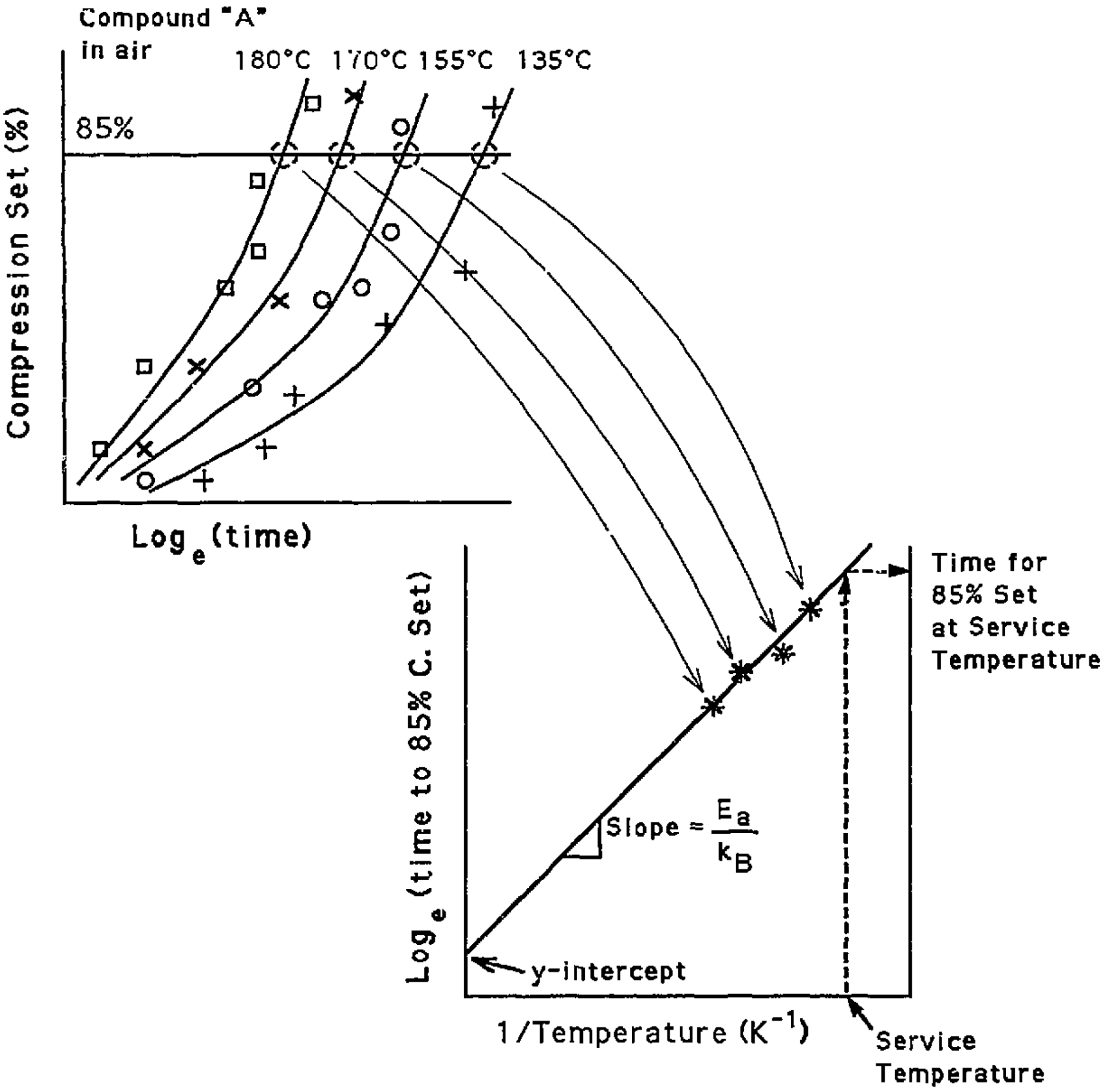

FIGURE 1: ARRHENIUS THERMAL AGING TESTS. THIS FIGURE ILLUSTRATES THE NUMBER OF DATA POINTS REQUIRED FOR A REASONABLE EXTRAPOLATION.

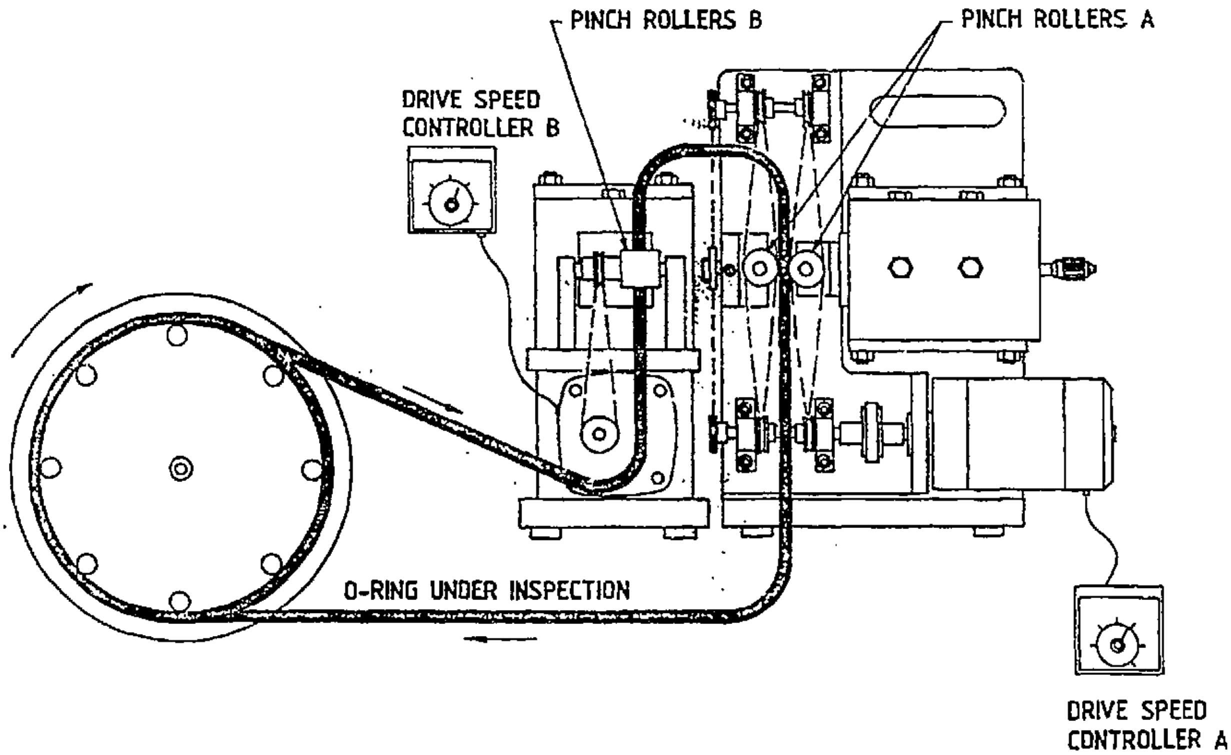

FIGURE 2: ELASTODYNAMIC TESTER FOR DETECTION OF INTERNAL DEFECTS IN O-RINGS

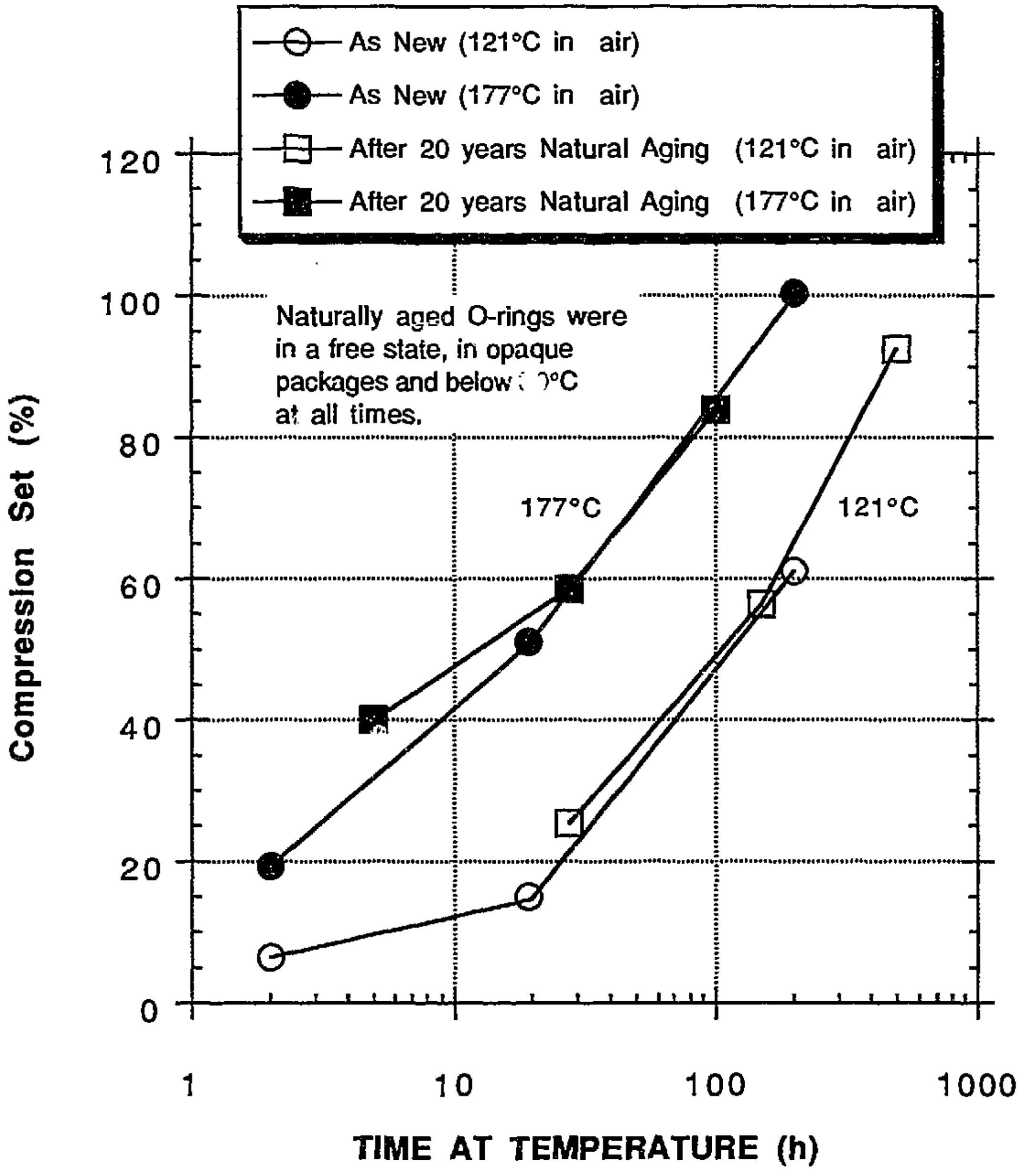

FIGURE 3: EFFECT OF TWENTY YEARS OF NATURAL SHELF AGING ON A SPECIFIC NITRILE O-RING COMPOUND

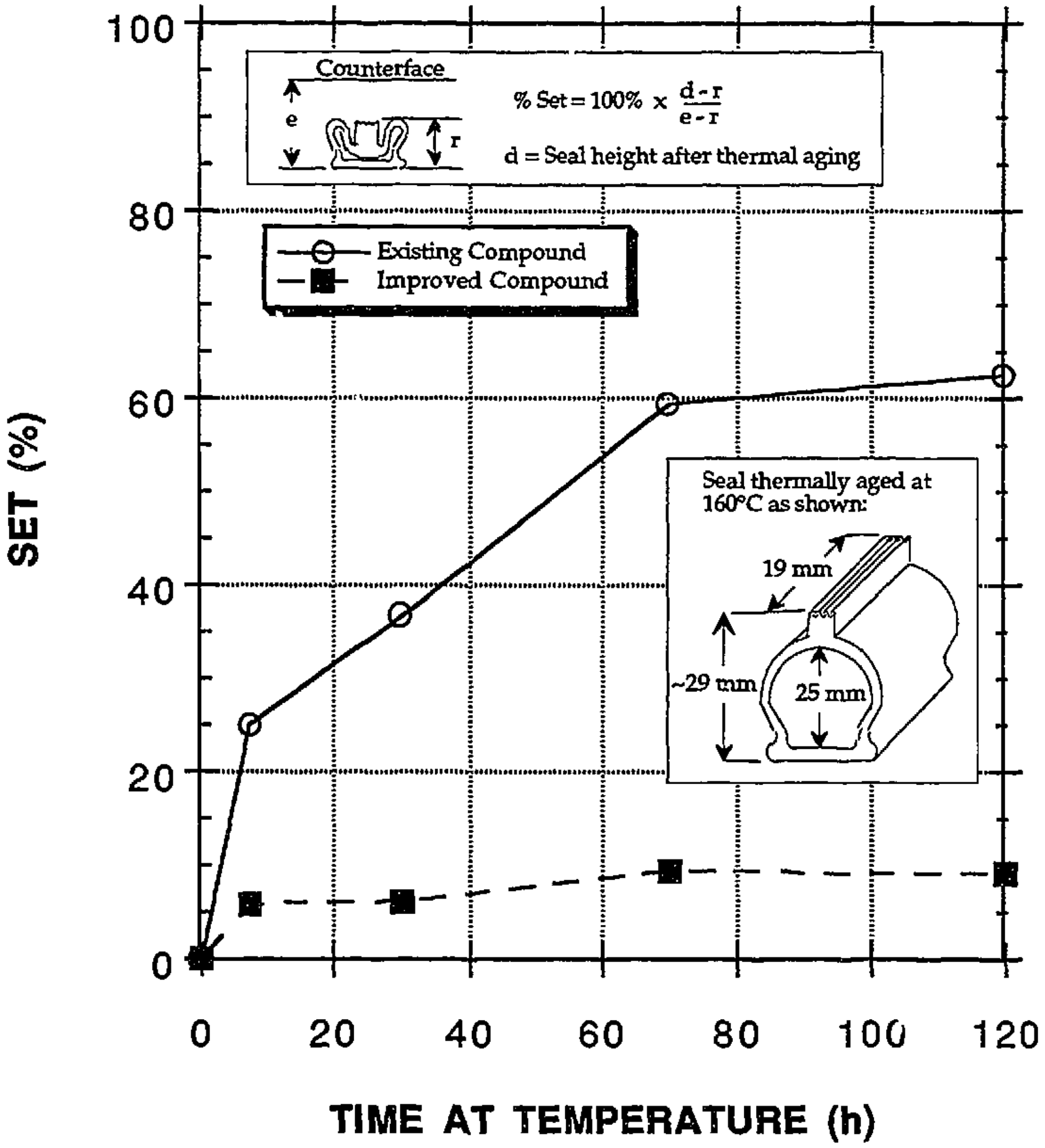

FIGURE 4: EFFECTS OF THERMAL AGING ON COMPRESSION SET OF INFLATABLE DOOR SEAL SEGMENTS

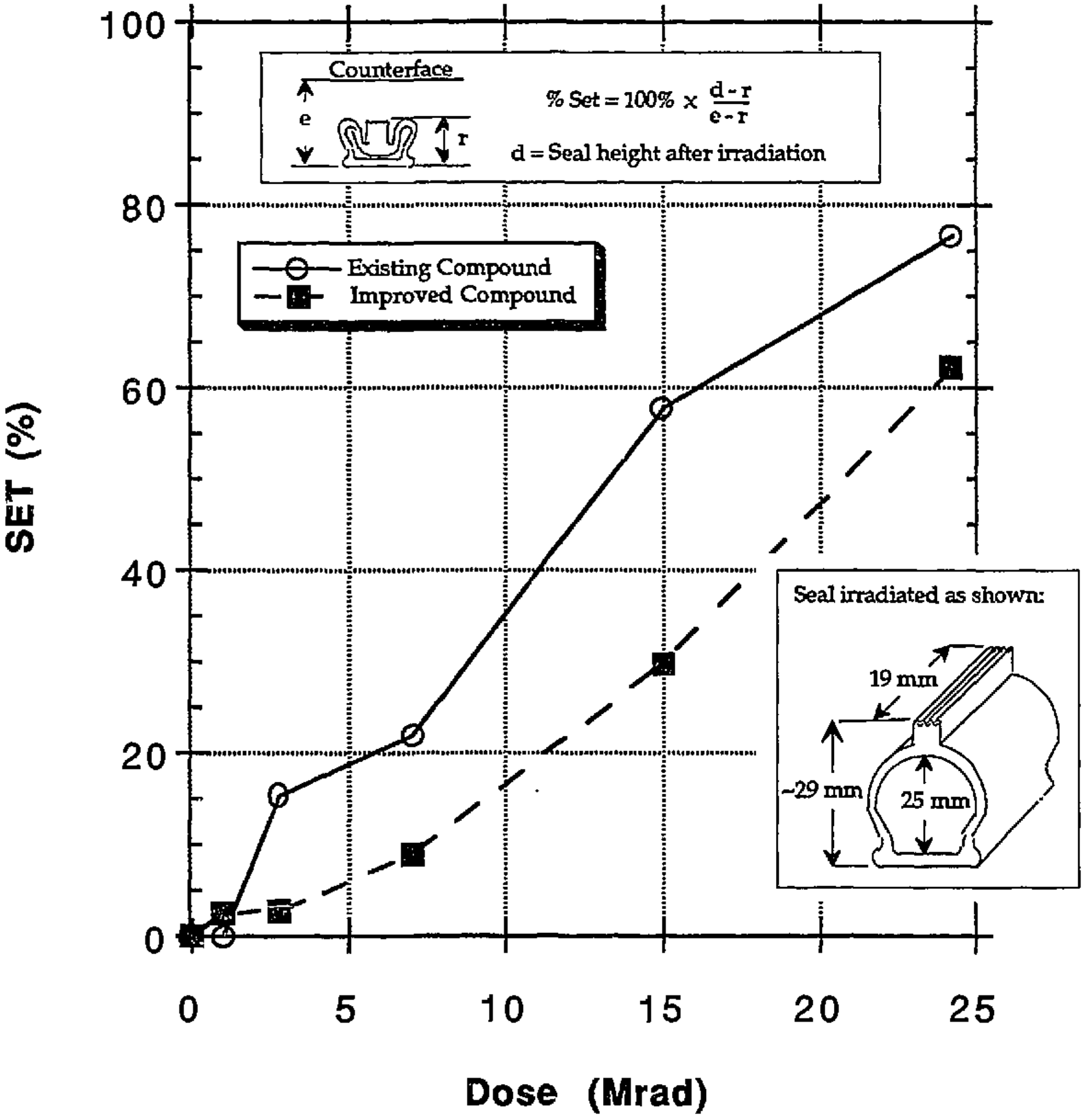

FIGURE 5: EFFECTS OF GAMMA RADIATION AGING ON COMPRESSION SET OF INFLATABLE DOOR SEAL SEGMENTS

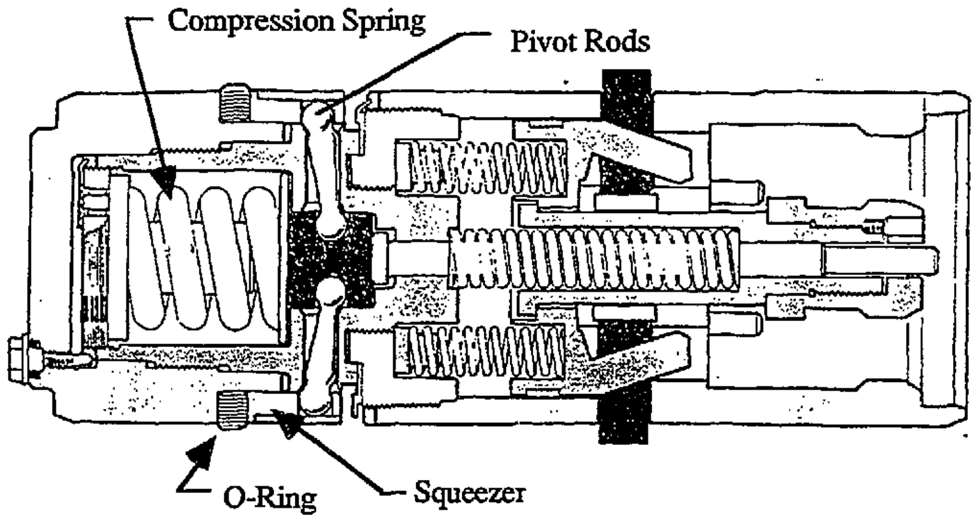

FIGURE 6: FUELLING MACHINE SNOUT SEAL SHOWING O-RING

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