# IMPROVED RELIABILITY, MAINTAINABILITY AND SAFETY THROUGH ELASTOMER UPGRADING*

by

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## ABSTRACT

Equipment in nuclear plants has historically contained whatever elastomer each component supplier traditionally used for corresponding non-nuclear service. The resulting proliferation of elastomer compounds, many of which are far from optimal for the service conditions (e.g., pressure, temperature, radiation, etc.), has multiplied the costs to provide station reliability, maintainability and safety.

Cost-effective improvements are being achieved in CANDU® plants by upgrading and standardizing on a handful of high performing elastomer compounds. These upgraded materials offer significant gains in service life over the materials they replace (often by factors of 2 or more).

This rationalization of elastomer compounds also facilitates the EQ† process for safety-related equipment. Detailed test data on aging is currently being generated for these specific elastomers, encompassing the conditions and media (air, water, oil) common in CANDU® service. Two key elements characterize this testing. First, each result is specific to the compound used in the test, and second, it is specific to the tested failure mode (e.g., compression set, extrusion, fracture, etc.).

Having fewer, but more thoroughly tested compounds, avoids the penalty (associated with poorly characterized materials) of having to replace parts prematurely because of conservatism, while maintaining safe, reliable service. This paper provides an overview of this approach covering:

- the benefits of compound rationalization
- the how and why of establishing relevant failure criteria
- appropriate quality assurance to maintain EQ
- procurement, storage and handling guidelines
- monitoring and predicting in-service degradation.

## 1. WHY UPGRADE?

The high costs of station downtime and of maintenance in a radiation environment, and the need to ensure and assure that the reactor is safe at all times make performance requirements for equipment in nuclear plants higher than in most other industries. Historically, equipment in nuclear plants has contained whatever elastomer each component supplier traditionally used for non-nuclear service. More than most plant operators realize, the resulting proliferation of elastomer compounds, many of which are far from optimal for the service conditions, has multiplied the costs to provide station reliability, maintainability and safety.

By standardizing on a handful of superior elastomer compounds (for seals, hoses, electrical insulation, etc.), service life can be extended, maintenance planning and safety can be improved, environmental qualification can be streamlined, and procurement and handling of replacement parts can be simplified. Extensive tests have identified high performing compounds for each class of CANDU® service. These upgraded materials offer gains in service life by factors of two or more over original materials. Moreover, the aging characteristics of the new materials are much better understood than those of the original materials, many of which are only known by generic type. Detailed data on aging is now being generated, specifically focused on strengthening and simplifying the process of EQ of safety-related equip-

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† Environmental Qualification, i.e., a technical process of assessment of safety-critical equipment in a nuclear plant, providing assurance that it will perform reliably should it be exposed to the harsh conditions of design basis accidents at any time in its installed life, taking into account the deterioration that normally occurs in its service.

ment relying on elastomers. Past practice in EQ has often been insufficiently compound- and application-specific. (The consequence has been over-conservatism in replacement schedules and, in some cases failure to satisfy regulators.) With retrofit to a short-list of well-characterized new materials the entire process of ensuring safety can be put on a more defensible footing.

## 2. CANDU® ELASTOMER PROGRAM

The objective of AECL's elastomer program is to make cost-effective improvements in the reliability and integrity of equipment in Canadian-designed (CANDU®) nuclear plants. The program includes selection and, where necessary, development of superior compounds for each type of CANDU® service, improved quality assurance methods, handling and inspection guidelines, and transfer of all relevant technology to operators, maintainers and designers of CANDU® plants.

Program effort falls into two categories: generic and service-specific. A key element in the generic work is identification of the fundamental properties that govern elastomers. The generic work encompasses:

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

Service-specific effort focuses on the need for specific improved elastomeric components (e.g., inflatable door seals, conduit seals, valve actuator diaphragms). Discussions with plant personnel, review of maintenance and inspection reports and other such activities form the first stages of such activities. Subsequent activities include:

- inspection and simple bench-scale testing of parts removed from service
- preliminary (scoping) testing of possible improvements
- qualification testing to demonstrate suitability of a selected improvement for service
- introduction into service
- monitoring the "improved" parts during phase-in periods.

Other service-specific effort focuses on service-life prediction and environmental qualification. This is based on "accelerated-aging" and simulated normal and accident service tests of elastomeric parts and equipment under specific conditions of heat, radiation and other deteriorative influences.

The remainder of this paper highlights key stumbling blocks in the use of elastomers and gives an overview of how they are being addressed in AECL's program.

## 3. RELEVANT AGING CRITERIA

Deterioration of equipment in a nuclear plant is often due to "aging" of elastomeric parts such as seals, diaphragms, gaskets, cable insulation and hoses. These degrade much faster than metallic parts when exposed to radiation, high temperature, pressure, humidity, and mechanical stress. Knowledge of elastomer service life is needed under both normal and accident conditions since safety demands that certain components be capable of functioning through accidents that could occur after long periods of aging under normal plant conditions.

To establish the life of any elastomeric component, the type and magnitude of deterioration that causes a failure in service must be known, as well as the deterioration rate. There are many possible types of failure, e.g., extrusion, chemical attack, wear-out, tensile cracking, load relaxation and compression set. They are all influenced by a combination of material characteristics and service conditions. Commonly reported material properties alone cannot quantify extrusion resistance, chemical resistance, wear resistance, etc. Some properties are closely related to common failure modes (e.g., tensile strength to tensile cracking failure) but other commonly quoted properties such as hardness, ultimate elongation, permeability and thermal expansion are only tenuously associated.

A primary challenge, then, in assessing an elastomeric component for a particular service, is to determine when and how it might fail in service. Relevant and comprehensive failure criteria based on functional properties are necessary for meaningful life prediction. These need to be based on a fundamental understanding of the performance needs for the particular application.

## 4. COMPOUND- AND SERVICE-SPECIFIC AGING DATABASE

A database of relevant properties and behavior is key to elastomer selection and life prediction. 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 elastomer product. For example, AECL's studies have shown that two ethylene-propylenes, developed specifically for pressurized hot water seals, one in common use in CANDU® plants and the other recommended for retrofit, differ by a factor of over ten in their time-to-failure in this service.†

As discussed above, properties alone are not enough for the database to be usable for severe service. It must also include *service*-specific behavior. Most of the published data on elastomers is 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 part actually fails in service. Parameters are more often chosen for testing convenience and standardization

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 seal 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 for low friction and wear, 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.

## 5. "BATCH" APPROACH TO QUALITY ASSURANCE

To ensure relevance of elastomer 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. 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 of a particular compound, traceable to the particular "batch" of ingredients, mixed and processed together to form the unvulcanized stock from which the part was made. A certificate of conformance should be supplied specifying the compound, its batch number, and date of cure, along with the hardness, specific gravity and tensile strength of samples from that batch, as compared with the manufacturer's expected values. In this manner the elastomer compound can effectively be "fingerprinted".

## 6. DEFECTS IN ELASTOMERS

Inspection methods and rejection criteria for defects are often neglected in quality assurance programs for elastomeric parts. This can impact heavily on integrity and reliability. Surface defects in most parts can be detected by unaided eye. In the case of elastomeric parts this is most effective when the elastomer is strained appropriately (i.e., by bending, pulling, pressurizing, etc.), 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 (inclusions, voids, discontinuities in reinforcing materials, etc.), as well as for monitoring state of aging (on the shelf or in service) a non-destructive technique called elastodynamics has been found most useful. A tool has been developed, employing this technique for inspection of O-ring seals. Basically the tool measures reaction force on two pinch rollers while the seal is driven and squeezed between them. Localized defects are sig-

† 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.

naled by spikes in reaction force. Any generally low or high force, or variation around the seal, signifies abnormal properties when compared with a known baseline. A version of this tool, developed for monitoring the condition of elastomeric parts of all types is described in Section 7.

## 7. STORAGE AND HANDLING

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 parts 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). Many elastomers are very stable under store-room conditions. Measurement of critical functional properties (e.g., compression set, extrusion resistance, hardness) of elastomers 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 2). Unfortunately, not all elastomer compounds are this stable.

Many elastomers are incompatible with common solvents. Ethylene-propylene elastomers are notable for their lack of resistance to petroleum-based products. Some elastomers have very poor resistance to cutting and tear propagation. To cover the many facets of proper use and handling of elastomeric parts a one day on-site training course for mechanical maintainers has been developed. This has been very well received by station personnel, having been presented nine times to date.

## 8. MONITORING IN-SERVICE DEGRADATION

Nuclear plants contain many examples of vaguely defined elastomer compounds that make accurate prediction of service lifetime impossible (yet many of these parts are accessible for interim inspection). Even in applications where well-defined compounds are used, the service conditions may not be well known. There are also cases where station personnel would like to assess the state-of-aging of elastomeric components held in inventory for long times.

In applications such as these a recently developed tool called an elastodynamic spot tester promises to be very helpful. If there is sufficient data to show how a particular elastomeric compound's properties change qualitatively with time in the service environment, and if the starting quantities and minimum required quantities for these properties are known, then making an interim measurement of these quantities using the elastodynamic spot tester gives a non-destructive method to pinpoint the current "effective age" of the part in terms of the percentage of service lifetime expended. For example, most elastomers age-harden. If hardening is the failure mode and functionality of the part requires hardness less than say 80 durometer*, with new parts being 70 durometer, then an interim measurement of hardness of 75 durometer suggests that half the service life remains (50% effective age) if the degradation rate is linear with time. However, aging data may also show that hardening accelerates and that the part's age is therefore already say 90%.

The advantage of elastodynamic spot testing is that it measures much more than hardness. It also measures stress relaxation and recovery, and can measure these as a function of mechanical stress level in order to discern the onset of permanent damage. Essentially, the stiffness, damping and strength are quantified. It then only remains to relate these to age, in the same way that measurements of weight, running speed and subsequent pulse rate, for example, might pinpoint the effective age of an individual in a population of genetically and environmentally similar humans. Note that aging of elastomers does not always reduce functional performance, at least not in early life, due in part to curing being incomplete. The elastodynamic spot tester is further described in a separate paper being presented at this conference.

## 9. A VISION

### Where Could We Go From Here?

Researchers should not only be expected to explore and develop, but also to paint a vision of how things could be. The preceding sections have essentially provided an overview of a program aimed at improving CANDU® plants through improved elastomers, and more knowledgeable use of elastomers. Although the emphasis has been on retrofits (upgrades) in existing stations, it should be clear that

* "Durometer" is a measure of rubber hardness, as determined by indentation depth of a stylus under a given load after a given period of time.

the new elastomer materials and knowledge offer benefits to CANDU®'s of the future.

Imagine for a moment an entire plant with all elastomeric parts made from one of a handful (8 to 10) of high-performance, formula-controlled, well-characterized elastomers. The potential savings in EQ costs alone are staggering. Can it be done? Yes, the materials and technology to achieve it are with us today!

Should it be done? Yes, but only to an optimum level of standardization determined by a cost-benefit study encompassing plant construction, licensing and lifetime operating costs.

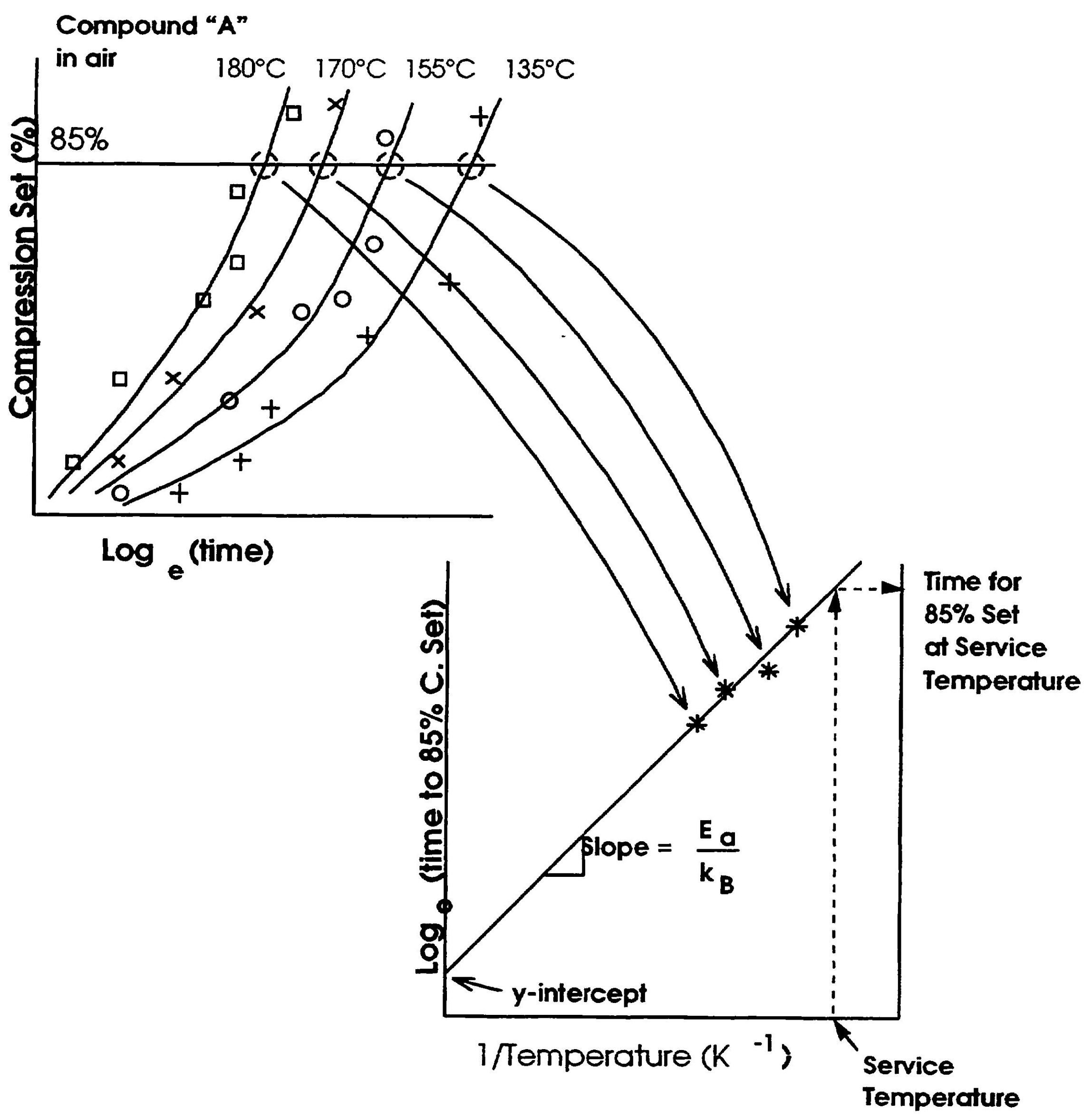


Figure 1: **Arrhenius Thermal Aging Tests.** This figure illustrates the number of points required for a reasonable extrapolation.

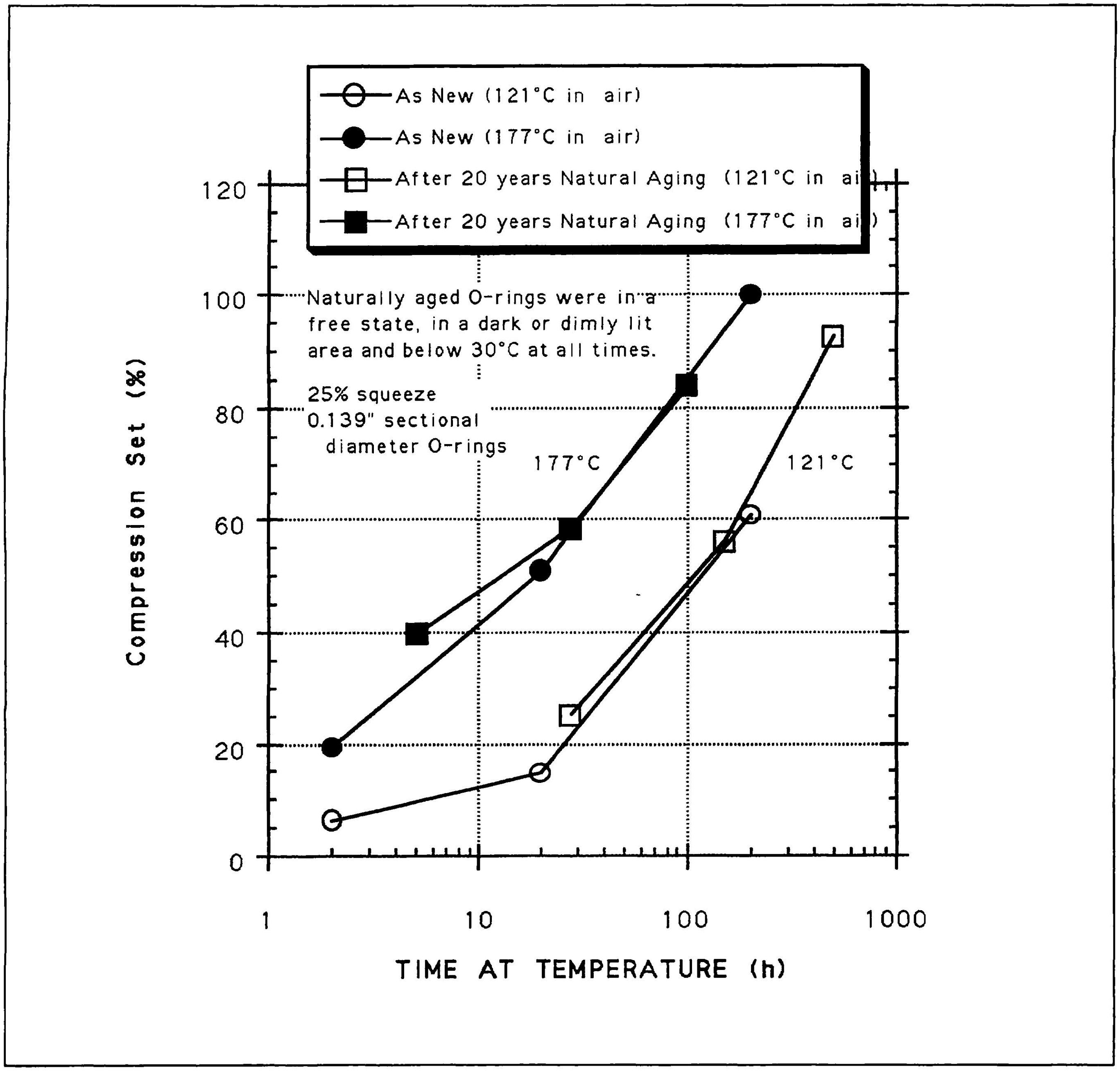


Figure 2: **Effect of Twenty Years of Natural Shelf Aging on a Specific Nitrile O'Ring Compound.**