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Response of Ethylene Propylene Diene Monomer Rubber (EPDM) to Simulant Hanford Tank Waste

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RESPONSE OF ETHYLENE PROPYLENE DIENE MONOMER RUBBER (EPDM) TO SIMULANT HANFORD TANK WASTE

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Abstract

This report presents the findings of the Chemical Compatibility Program developed to evaluate plastic packaging components that may be incorporated in packaging mixed-waste forms for transportation. Consistent with the methodology outlined in this report, we performed the second phase of this experimental program to determine the effects of simulant Hanford tank mixed wastes on packaging seal materials. That effort involved the comprehensive testing of five plastic liner materials in an aqueous mixed-waste simulant. The testing protocol involved exposing the materials to ~143, 286, 571, and 3,670 krad of gamma radiation and was followed by 7-, 14-, 28-, 180-day exposures to the waste simulant at 18, 50, and 60°C. Ethylene propylene diene monomer (EPDM) rubber samples subjected to the same protocol were then evaluated by measuring seven material properties: specific gravity, dimensional changes, mass changes, hardness, compression set, vapor transport rates, and tensile properties. We have determined that EPDM rubber has excellent resistance to radiation, this simulant, and a combination of these factors. These results suggest that EPDM is an excellent seal material to withstand aqueous mixed wastes having similar composition to the one used in this study.

ACKNOWLEDGMENTS

The support of our sponsor, the U.S. Department of Energy, Office of Transportation (EM-24), is gratefully appreciated. Specifically, the encouragement provided by Arnie Justice and Mona Williams in the DOE National Transportation Program Office is acknowledged. The technical assistance provided by Tatianna G. Dickens was responsible for the timely completion of this work.

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INTRODUCTION

Hazardous and radioactive materials packaging is designed to facilitate the transport and storing of materials without posing a threat to the health or property of the general public. U.S. regulations establish general design requirements for such packagings. While no regulations have been written specifically for mixed waste packaging, regulations for the constituents of mixed wastes, that is, hazardous and radioactive substances, have been codified by the U.S. Department of Transportation (U.S. DOT, 49 CFR 173) and the U.S. Nuclear Regulatory Commission (NRC, 10 CFR 71). The packaging materials and contents must be chemically compatible. Furthermore, Type A [49 CFR 173.412 (g)] and Type B (10 CFR 71.43) packaging design requirements stipulate that there be no significant chemical, galvanic, or other reaction between the materials and contents of the package.

Based on the federal requirements, a Chemical Compatibility Testing Program was developed in the Transportation Technology Department at Sandia National Laboratories/New Mexico (SNL/NM). The program attempts to assure any regulatory body that the issue of certain packaging material compatibility towards hazardous and radioactive materials has been addressed. This program was detailed in a 1993 milestone report[1] submitted to the Department of Energy (DOE). The results of this program were reported to the DOE in various unpublished milestone documents and in a number of externally published papers.[2-6]

The milestone report *Chemical Compatibility Test Plan and Procedure Report* (CCTP&PR) describes a program to evaluate plastic transportation packaging components that may be used in transporting mixed waste forms. Consistent with the methodology in the CCTP&PR, the first phase of this experimental program has been completed. This effort involved screening ten plastic materials in four simulant mixed waste types.[7] All materials that include "rubber" in their names are used as seals; the others are used as liners. These plastics were as follows:

Seals

- butadiene-acrylonitrile copolymer rubber (Nitrile),
- epichlorohydrin rubber (EPI)
- isobutylene-isoprene copolymer rubber (Butyl),
- ethylene-propylene rubber (EPDM),
- fluorocarbon (FKM) rubber, and
- styrene-butadiene (SBR) rubber

Liners

- cross-linked polyethylene (XLPE),
- high-density polyethylene (HDPE),
- fluorocarbon (Kel-F™)
- polytetrafluoroethylene (Generically PTFE or Teflon®),
- polypropylene (PP).

The selected simulant mixed wastes were

(1) an aqueous alkaline mixture of sodium nitrate and sodium nitrite;
(2) a chlorinated hydrocarbon mixture;
(3) a simulant liquid scintillation fluid; and
(4) a mixture of ketones.

The first phase of testing protocol involved exposing the materials to 286,000 rad (290 Krad) of gamma radiation followed by 14-day exposures to the waste types at 60 °C. After radiation and chemical exposure, the seal materials or rubbers were tested using Vapor Transport Rate (VTR) measurements, while the liner materials were tested using specific gravity. For these tests, screening criteria of about 1 g/hr/m^2 for VTR and a specific gravity change of 10% were used. Materials that failed to meet these criteria for all four waste types were judged to have failed the screening tests and were excluded in the next phase of this experimental program. Based on this work, it was concluded that while all seal materials passed exposure to the aqueous simulant mixed waste, EPDM and SBR had the lowest VTRs. In the chlorinated hydrocarbon simulant mixed waste, only VITON® passed the screening tests. This means that only FKM rubber would be selected for further testing in the chlorinated hydrocarbon simulant. In both the simulant scintillation fluid mixed waste and the ketone mixture simulant mixed waste, none of the seal materials met the screening criteria. For specific gravity testing of liner materials, the data showed that while all materials passed the screening criteria in the aqueous simulant, Kel-F™, HDPE, and XLPE were found to offer the greatest resistance to the combination of radiation and chemicals.

Following the completion of these screening tests, the next phase of this program (i.e., the comprehensive testing of liner materials in the aqueous simulant mixed waste) began. Since screening tests showed that all liner materials met the screening criteria when exposed to the aqueous simulant mixed waste, the five liner materials were subjected to comprehensive testing. The five materials evaluated consisted of HDPE, XLPE, PP, Kel-F™, and Teflon®. The testing

protocol involved exposing the respective materials to approximately 143, 286, 571, and 3,670 krad of gamma radiation followed by 7-, 14-, 28-, 180-day exposures, respectively to the waste simulant at 18, 50, and 60 °C. The radiation exposure values were calculated based on γ-ray dose rate data available to us for the components of a pump submerged in a specific storage tank at Westinghouse Hanford Company. These data indicate a maximum γ-ray dose rate in the range of 750 to 850 R/hour. The maximum dose rate of 850 rad/hour was used in calculating the dose that container materials will receive from a ^{60}Co source at SNL/NM. Using this dose rate, the four doses described above were calculated for 7-, 14-, 28-, 180-day exposures, respectively. From the data analyses, the fluorocarbon Kel-F™ was identified as having the greatest chemical durability after exposure to gamma radiation followed by exposure to the Hanford Tank simulant mixed waste. The most striking observation was the extremely poor performance of PTFE when exposed to the higher radiation doses. Even at lower radiation exposures, PTFE exhibited significant losses in performance. These results were reported as a Sandia Report[8] to the DOE. A synopsis of these test results were published in the proceedings of the Fourth Biennial Mixed Waste Symposium.[9]

In this report, we present another part of the second-phase testing. Since all seal materials passed the screening tests in the aqueous simulant mixed waste, all seal materials would be subjected to comprehensive testing. While earlier studies investigated the response of butyl rubber, this second-phase study involved the comprehensive testing of EPDM rubber. The results of comprehensive testing of EPDM and butyl rubber have been reported to the DOE. A synopsis of the comprehensive test results for EPDM and butyl rubber was presented at the Fourth Biennial Mixed Waste Symposium[9] and at PATRAM '98.[10] The comprehensive testing protocol involved exposing EPDM rubber to a matrix of four gamma radiation doses (~143, 286, 571, and 3,670 Krad), three temperatures (18, 50, and 60 °C), four exposure times (7, 14, 28, and 180 days), and the aqueous Hanford Tank simulant. It should be mentioned that while some EPDM samples were exposed to only the simulant, other samples were only irradiated, and still others were irradiated and then exposed to the simulant to mimic the action of mixed wastes. Following exposure to these conditions, the EPDM rubber samples were evaluated by measuring seven material properties. These properties included specific gravity, dimensional changes, mass changes, hardness, compression set, VTR, and tensile properties.

TEST DESCRIPTION

In this section, we describe the experimental aspects of the comprehensive phase of this testing program for elastomeric materials.

Materials

The selected material, EPDM rubber, is an elastomer with known chemical resistance to a wide variety of chemicals. Appendix A provides additional information on this material.

Simulant Preparation

The simulant mixed waste form used in this testing phase was an aqueous alkaline simulant Hanford Tank waste developed locally based on more complex formulations used by researchers at the Hanford Site. It was prepared by dissolving 179 g (2.10 moles) of sodium nitrate and 50 g (0.73 mole) of sodium nitrite in de-ionized water (600 mL) using a 4-L beaker. After these salts had completely dissolved, 82 g (2.05 moles) of sodium hydroxide was stirred in under slight heating using a magnetic hotplate (Corning, Model PC-320). To this hot (~70 °C) stirred solution, 17 g (0.107 mole) of cesium chloride and 16 g (0.0952) of strontium chloride were added. Finally, 32 g (0.301 moles) of sodium carbonate were added to the solution, resulting in the formation of a copious amount of white precipitate. Due to its insolubility, this precipitate was believed to be strontium carbonate. To the resulting mixture, another 400 mL of de-ionized water was added to bring the total volume of water used to 1 L. After cooling to near ambient temperature, the stirred mixture was stored in amber glass bottles (Fisher Scientific, #03-327-6). The procedure described above was scaled up threefold to give 3-L batches of the simulant. The mixture had the following chemical concentrations:

2.1 Molar (M) Sodium Nitrate
0.7 M Sodium Nitrite
2.1 M Sodium Hydroxide
0.3 M Sodium Carbonate
0.1 M Cesium Chloride
0.1 M Strontium Chloride.

Sample Preparation

Standardized test methods were used to cut, condition, and test the materials. The geometry of the material samples was specified by the test method. The samples were cut using an expulsion press (Part #22-16-00) and dies manufactured by Testing Machines, Inc., Amityville, NY. For example, the rectangular (1″ × 2″ × 0.125″, 2.5 cm × 5.0 cm × 0.318 cm) samples required for specific gravity and hardness measurements were cut in the expulsion press fitted with an Expulsion Straight Edge Die (Part #23-10-06). Rectangular (1″ × 3″ × 0.125″, 2.5 cm × 7.6 cm × 0.318 cm) samples required for dimensional and mass measurements were cut in the expulsion press fitted with an Expulsion Straight Edge Die (Part #23-10-07). Circular (0.5″ diameter × 0.125″ thick, 1.3 cm diameter × 0.318 cm thick) discs required for compression set measurements were cut in the expulsion press fitted with a custom circular cutter from CCS Instruments, Akron, OH. Larger circular (2.69″ diameter × 0.125″ thick, 6.83 cm diameter × 0.318 cm thick) discs required for VTR measurements were cut in the expulsion press fitted with an expulsion die (Part #23-00-00) specifically designed for American Society for Testing and Materials ASTM D 814[11] testing. Similarly, the Type C tensile samples required for tensile testing were cut in the expulsion press fitted with an Expulsion Die (Part #23-14-08) specifically designed for use in the ASTM Standard Test Method D 412-Method A.[12]

The use of a press and dies permitted the cutting of multiple samples having uniform dimensions. An identification code was developed for samples to uniquely indicate the test type, sample number, and testing conditions. The black EPDM rubber samples were individually labeled using indelible ink marking pens. As recommended by ASTM D 1349,[13] the plastics were conditioned at a standard temperature of 73.4 °F (23 °C) and relative humidity of 50% for at least 24 hours prior to the testing process. This was done by storing the cut samples in a desiccator filled with magnesium nitrate hexahydrate (500 g) saturated with water. A humidity/temperature sensor was used to monitor the conditions in the desiccator. Procedures for generating this constant relative humidity environment are described in ASTM E 104.[14] During conditioning, the samples were stacked atop each other and separated from each other using ~1/16-in.- (~0.16 cm) thick metal pins. The required number of samples for each test were bundled together using plastic cable ties by procedures described in a subsequent section.

Sample Quantities

Some EPDM samples were exposed to gamma radiation alone, to the simulant (chemicals) alone, or to a combination of radiation followed by exposure to the simulant. Since radiation was expected to have the greatest effect on the compression set and tensile properties of EPDM, we prepared specific samples for radiation exposure alone. These samples were referred to as *Rad Only* samples. The purpose of exposing certain samples to only gamma radiation, while other samples received exposure to both radiation and chemicals, was to differentiate the effects of radiation alone from those when the combination of the two environmental conditions (radiation and simulant) were applied.

For *Rad Only* compression set measurements, 48 samples (two specimens per test) were cut for the matrix of four radiation doses, four exposure times, and three exposure temperatures for a total of 96 samples. The exposure times for *Rad Only* samples represent the time periods (7-, 14-, 28-, and 180-days) that the samples were held at the respective temperatures. Tensile property measurements (five specimens per test) for Rad Only samples required the preparation of 240 samples. For these two measurements, 336 samples were needed. In view of the perceived effect of radiation on compression set and tensile property measurements, the material properties of EPDM were measured prior to exposure to either radiation and temperature. These measurements required the preparation of an additional 7 samples.

Simulant Only samples, referred to as 0K samples in subsequent discussions, were required for each of the seven measurements. For specific gravity and hardness measurements, 12 samples were required. Dimensional and mass measurements (three per test) required the preparation of 9 samples. For VTR measurements (three per test), 9 samples were needed. Compression set measurements required 24 samples. Finally, tensile property measurements required 60 samples. Thus, 114 samples were required for all 7 *Simulant Only* tests. These samples were exposed to the aqueous simulant for the four time periods at the three temperatures.

We now turn to the samples required for exposure to the combination of radiation and chemicals. For specific gravity and hardness measurements, 48 samples were cut out for the combination of three temperatures, four radiation doses, and four time periods. For dimensional and mass measurements, 36 samples were prepared. Compression set measurements involved 96 samples. VTR measurements involved 36 samples and tensile testing involved 240 samples. Thus, for all seven measurements, 456 samples were prepared

for exposure to the three temperatures and four radiation doses. For nondestructive tests such as specific gravity, dimensional, mass, hardness, and VTR measurements, the same samples were re-used for the other exposure times (i.e., one sample set was used for 7-, 14-, 28-, and 180-day exposures at each temperature and for each radiation dose).

A total of 913 EPDM samples were used to perform the various measurements.

Sample Irradiation

The elastomer samples were irradiated by an underwater ^{60}Co gamma source at SL/NM. These samples were loaded into a metal basket in the same configuration as was used to condition the samples (i.e., the samples were stacked atop each other and separated by a metal spiral or by metal pins). The basket was then inserted into a water-tight stainless steel canister (volume ~4 L). The canister was sealed and lowered into the pool to a depth of 6 feet, purged with a slow, steady flow (~ 30 mL/min) of dry air and allowed to come to thermal equilibrium at either ambient (~32), 50, or 60 °C.[15] Once thermal equilibrium was attained within the canister immersed in the pool of water, the canister was lowered into its irradiation location in the pool, and exposure was begun to obtain the desired radiation dosage. The highest dose rate currently available at the Low Intensity Cobalt Array (LICA) Facility is ~730 Krad/hr. The array used for irradiating these samples had dose rates of ~95 Krad/hr. Thus, for irradiation where a gamma-ray dose of 143 Krad was required, the samples were exposed for approximately 1.5 hours. For doses of 286, 571, and 3,670 Krad (3.67 Mrad), the corresponding longer exposure times were needed. After the samples received the calculated radiation dosage, the canister was removed from the pool, and the samples were again placed in the conditioning chambers. No more than 24 hours typically elapsed between the time that the samples had been exposed to radiation and when they were exposed to the simulant waste or the test temperatures.

Sample Exposure to Simulant

The general exposure protocol for specific gravity samples involved placing four specimens of the EPDM rubber into a container and exposing them to the aqueous simulant at three temperatures and four time periods. The four specimens were bundled together using 7.5-in. (19 cm) nylon cable ties. Within each bundle, the specimens were separated through the use of ~ $1/16$-in. (0.16 cm) metal pins as spacers. This allowed for the ready access of the waste simulant to all surfaces of each specimen. A 2-L glass bottle or 2-L plastic container was

loaded with the four bundled test specimens and then filled with 1,600 mL of the test solution. Care was taken to ensure that sufficient simulant waste was present to expose the entire surface area of all the samples. After adding the liquid simulant waste, the plastic lid was attached to the jar and tightened. The jars were placed in respective environmental chambers maintained at 18, 50, and 60 °C. The jars were kept in these environmental chambers for 7, 14, 28, and 180 days. Similar procedures were followed for each of the other four testing procedures (dimensional testing, hardness testing, compression set tests, and tensile tests). In the case of VTR measurements, each of three 1/2 pint (~236 mL) Mason Jars (Kerr Group, Inc., Los Angeles, CA, Part #70610-3) was filled with approximately 200 mL of the test solution. The EPDM rubber discs were loosely attached to the jars with metal bands. The jars were placed in an upright configuration (EPDM rubber and band facing up) into the respective environmental chambers. The jars were held at the respective test temperatures for one hour to equilibrate. After sealing and weighing, the jars were placed in the chambers again in an inverted position and held at the specific test temperature for the required time.

Experimental Approach

The material properties that should be evaluated to assess the suitability of potential plastic materials in mixed waste packaging designs are density changes (involving mass and dimensional changes), hardness, compression set, VTR, tensile property changes (tensile strength, modulus of elasticity, elongation at yield, and elongation at break). Since the measurement of *all* these material properties was expected to be costly and time consuming, screening tests with relatively severe exposure conditions such as high temperatures and high radiation levels were implemented to quickly reduce the number of possible materials for full evaluation. The results of these screening studies have been previously reported in a milestone document,[16] at several technical conferences,[2,6] and in a SAND Report.[7] From the screening study[7], it was found that all of the selected seal materials had passed the screening criteria in the aqueous simulant mixed waste. This necessitated testing six materials by exposure to a matrix of four radiation doses, three temperatures, and four exposure times in the simulant waste. In view of the extensive number of materials and exposure conditions, this second phase of the program was referred to as the Comprehensive Testing Phase.

Because of budget constraints imposed on this program, the testing was further subdivided into comprehensive testing on liner materials and seal materials. Further funding constraints required an additional subdivision of the testing activity such that individual elastomers were

evaluated. The order of testing for these individual elastomers was established by the degree of response in the aqueous simulant. In other words, the best elastomer was evaluated first while the worst elastomer would be evaluated last. From the data given in a previously submitted milestone document,[16] the best-to-worst materials in the aqueous simulant were determined to be EPDM, butyl, SBR, nitrile, Viton®, and EPI rubber. Accordingly, the first material to be evaluated was EPDM rubber.

The evaluation parameters used in this comprehensive testing phase consisted of measuring the specific gravity, dimensions, mass, hardness, compression set, VTR, and tensile properties in the seal materials including tensile strength, ultimate elongation yield, and tensile stress. These parameters were evaluated using standardized test methods such as those developed by the ASTM. For specific gravity measurements, ASTM D 792[17] was used. In measuring dimensions and mass, ASTM D 543[18] was used. For hardness measurements, ASTM D 2240[19] was used. In evaluating compression set, ASTM D 395 - Method B[20] was used. However, in using ASTM D 395, two samples of 0.125-in. (3.17 mm) thickness were held at ambient temperature with a spacer bar with a thickness of 4.5 mm. For VTR measurements, ASTM D 814 was used. Finally, for evaluating tensile properties, ASTM D412 - Method A was used.

Before describing the results of this study, we will discuss the comprehensive testing strategy used for EPDM rubber. This strategy is shown in a flow diagram in Figure 1. The rubber was subjected to four different protocols (Paths A-D). To determine the intrinsic properties of the materials, baseline property measurements (Path A) were made in each of the seven tests. These properties were measured at ambient conditions. To differentiate the effects on the materials by radiation and chemicals, one series of samples was exposed to the simulant alone (Path B), while the other series of samples was exposed to both radiation and the simulant (Path C). The first series of these samples is referred to as "Simulant Only" in the flow diagram. It should be noted that both series of samples were exposed for the four time periods (7, 14, 28, and 180 days) at three different temperatures (18, 50, and 60 °C). For two testing protocols, tensile testing (Tensile) and compression set (Set), where the effects of radiation and temperature alone could have significant impact on these properties, a series of samples described as "Rad Only" are shown in the flow diagram (Path D). These samples were irradiated at three temperatures (18, 50, and 60°), respectively, and then exposed for four time periods (7,14,28, and 180 days) at the three respective temperatures. What may not appear obvious from the flow diagram is the large number of samples being tested in this

comprehensive testing phase of the program. A total of 1,738 measurements on 913 samples were analyzed (Appendices B through J).

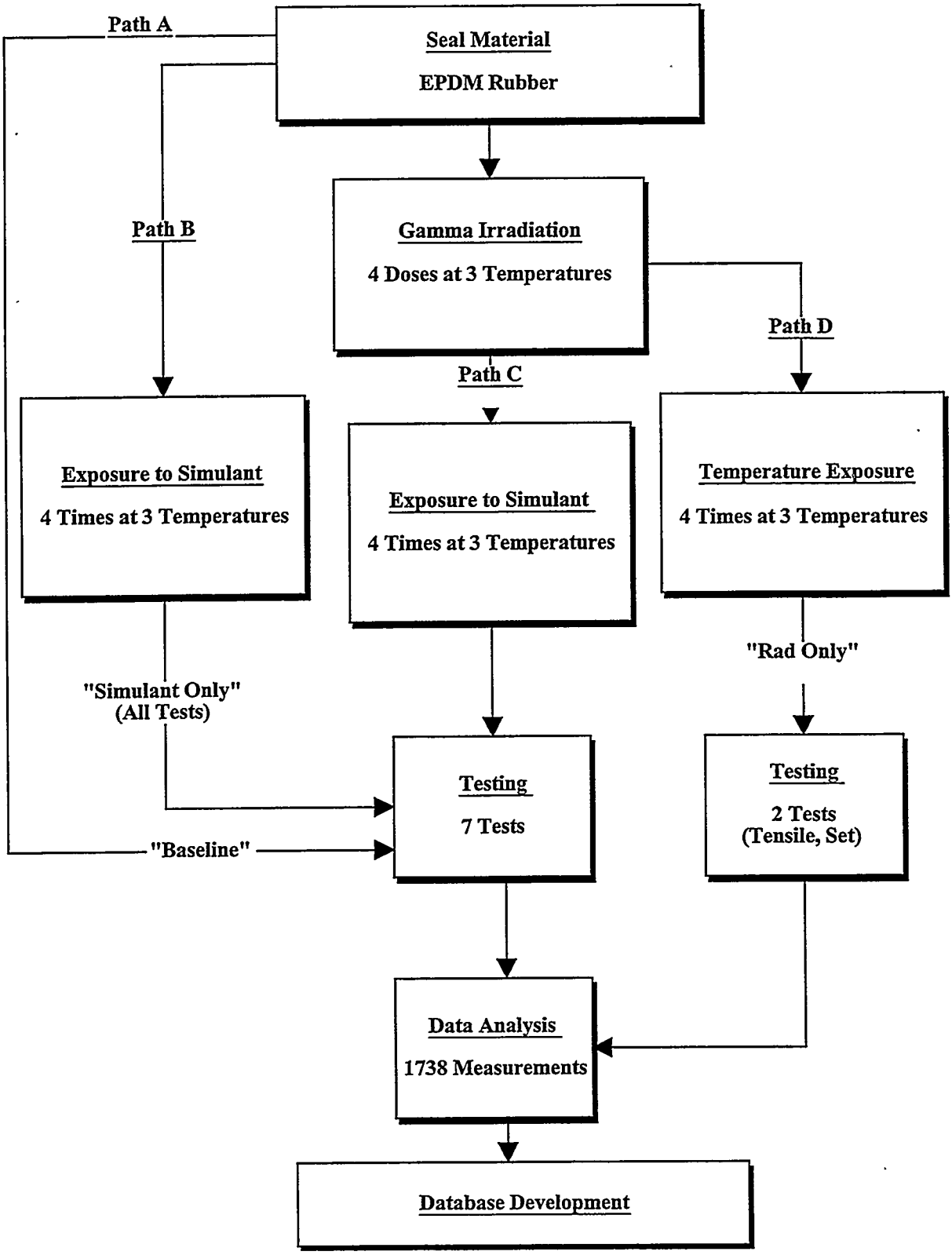


Figure 1. Comprehensive Seal Testing Strategy

RESULTS

Specific Gravity

Specific gravity measurements, also known as relative density measurements, measure the densities of materials under different conditions. A decrease in density of the material can indicate leaching or swelling. Swelling can lead to increases in permeability. Such indications of increases in permeability in the material will also be confirmed by VTR measurements. Increases in density are caused by absorption of the test liquid, indicating higher permeability to the test liquid.

In Figure 2, the effects of exposure time, gamma radiation dose, and exposure temperature of the aqueous simulant on EPDM are shown.

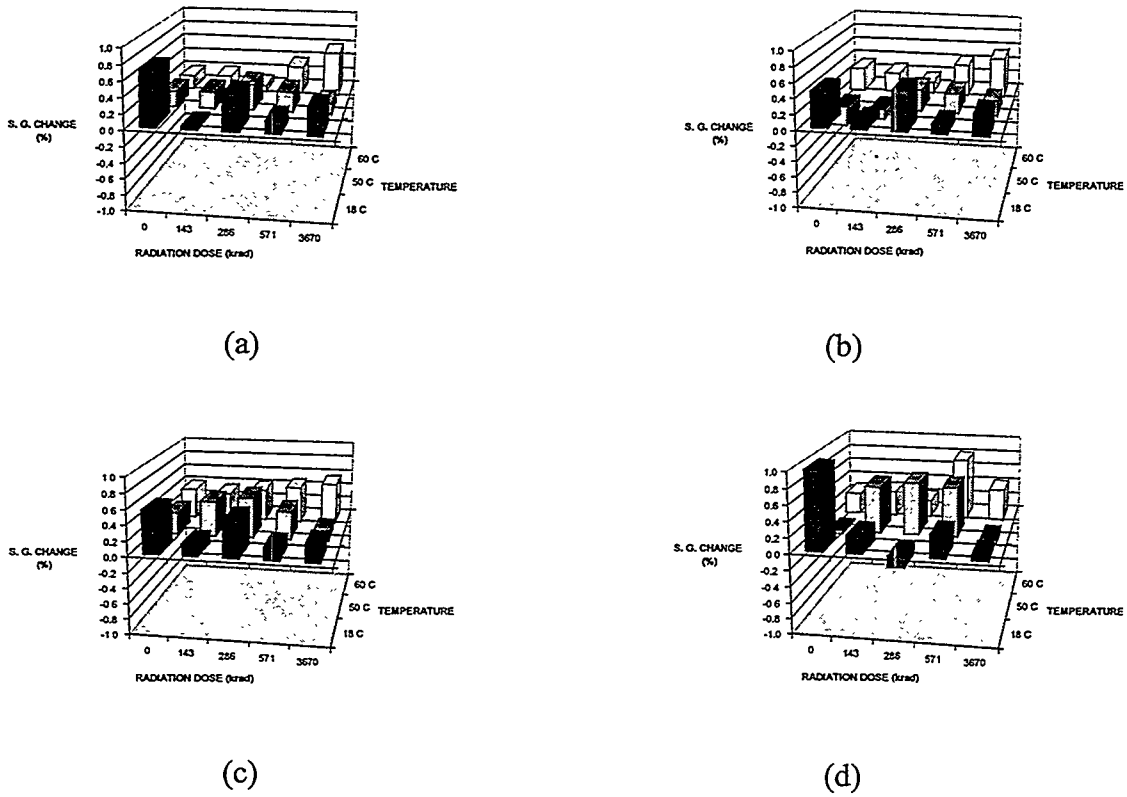


Figure 2. Specific gravity (S.G.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

These three-dimensional bar graphs provide a plot of radiation dose, exposure temperature, and the average percent specific gravity change in the x, y, z directions, respectively. When

the radiation dose is indicated as 0, the samples received no gamma radiation and were only exposed to the simulant (i.e., these samples are the "Simulant Only" samples discussed earlier). It should be noted that the scale for these specific changes is rather small (e.g., from 0 to 1%) and either positive or negative. In Figure 2 and all subsequent figures, negative changes can be recognized by the dark bar tops in the x-y plane. These bars project into the negative portion of the graph. The sign of the specific gravity indicates whether specific gravity has increased or decreased when compared to that of the virgin material (i.e., the specific gravity of EPDM at ambient conditions). Therefore, changes in the magnitude and the sign of specific gravity values indicate changes in this property. The greater the absolute values of the changes, the more the materials are affected by the specific set of environmental conditions. Since properly engineered packaging components are not expected to be affected by contents of the package, such as aqueous mixed wastes, elastomers exhibiting the smallest change in specific gravity should be selected as packaging components.

From an overall perspective, the data in Figure 2 show that neither temperature of the simulant, the radiation dose, nor the exposure time has any dramatic effect on the specific gravity of EPDM because changes in excess of 1% are not observed. These results are consistent with the known chemical resistance of this elastomer and demonstrate that EPDM is a suitable elastomer for use under these conditions if specific gravity is the determining package design criterion. As shown in Figure 2, EPDM that had not been irradiated, exhibited the greatest change at the lowest exposure temperature. However, since the changes involved are at the 0.5% levels, these experimental results are of little practical consequence. While the exact specific gravity values are not obvious from the data in the previous figure, their precise values can be found in Appendix B.

In the following section, we present the results of the effects of the simulant waste, and the results for a combination of radiation and simulant on the dimensional properties of EPDM.

Dimensional Properties

Similar to specific gravity measurements, dimensional property measurements can provide important information about the effects of different environmental conditions on materials. Specifically, the swelling of the material or leaching of components of the material will be manifested by increases or decreases in the dimensions of the material. The dimensional properties measured and reported in this section include changes in length, width, and thickness of the materials. Since the standard test method ASTM D 543 used to measure

dimensional properties includes the determination of mass as part of the test, this property was also measured. Dimensional changes are described by evaluating the product of these changes, that is, volume (length × width × thickness). The technical justification for using this approach is that while length and width changes have generally been much smaller than thickness changes, the product of these changes encompasses individual components into one general dimensional property, the volume of the materials. The effects of the different environmental conditions on the mass changes are presented first.

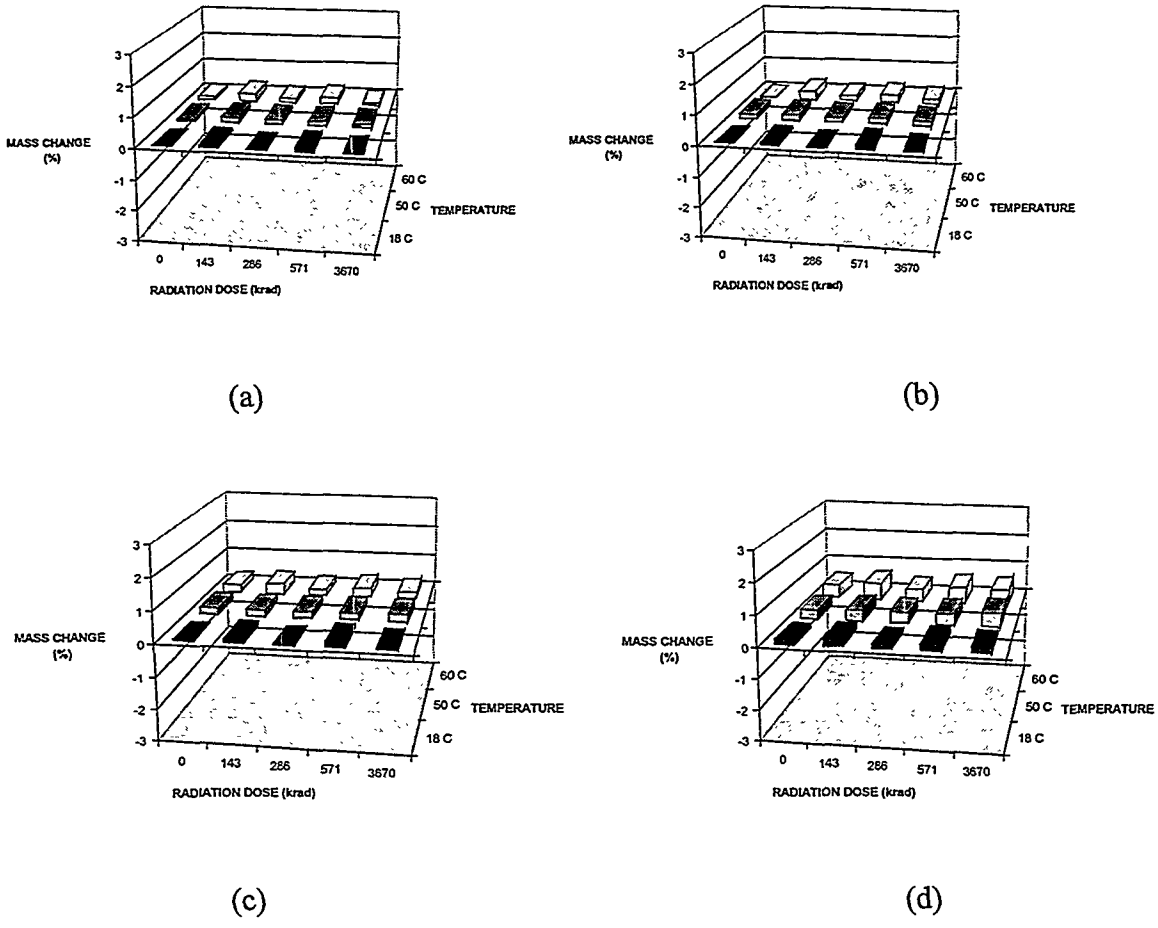


Figure 3. Mass changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on EPDM, the mass of the samples was measured before and after exposure to only the surrogate waste. The results are given in Figure 3 (a-d) above in the 0 data field. Similar to data shown in the previous section, the scale for average percentage of weight (mass) change

is very small (e.g., from 0% to 3%). The sign of the mass changes, i.e., whether positive or negative, indicates whether the mass of the material has increased or decreased when compared to that of the pristine materials (i.e., the material's mass under ambient conditions). Therefore, changes in the magnitude and the sign of percentage of mass change values varies for this property. The greater the absolute values of the changes, the more the material is affected by this set of environmental conditions. Since properly engineered packaging components are not expected to be affected by contents of the package (i.e., the mixed wastes), materials exhibiting the smallest change in mass should be selected as packaging components. Overall, the data in Figure 3 show that neither temperature of the simulant nor exposure time has any dramatic effect on the changes in mass of the material because changes in excess of ~0.6% are not observed. As can be seen from the data, an increase in temperature and exposure times results in slight increases in mass. The greater the temperature increase, the larger the mass changes. While the exact mass values are not obvious from the data in Figure 3, their precise values are given in Appendix C.

In Figure 4 (a-d), the average percentage of volume changes of EPDM exposed to the four gamma radiation doses followed by exposure to the aqueous simulant waste at 18, 50, and 60 °C for 7, 14, 28, and 180 days is given. EPDM had volume changes of less than approximately ± 0.5% under these conditions. With increased exposure time and exposure temperature, there is a very slight decrease in the sample volume (i.e., EPDM appears to contract when exposed to these environmental conditions). A general trend suggests that most EPDM samples contracted with increasing exposure time. The greatest volume changes can be seen in Figure 4b, where EPDM exhibited the greatest changes in volume at 18 °C. It should be noted, however, that these changes are at the 0.5% level. These results are counter-intuitive, since the largest changes in volume would be expected at the highest temperatures and longest exposure time. While the exact volume values are not obvious from the data in the previous figure, their precise values are given in Appendix D.

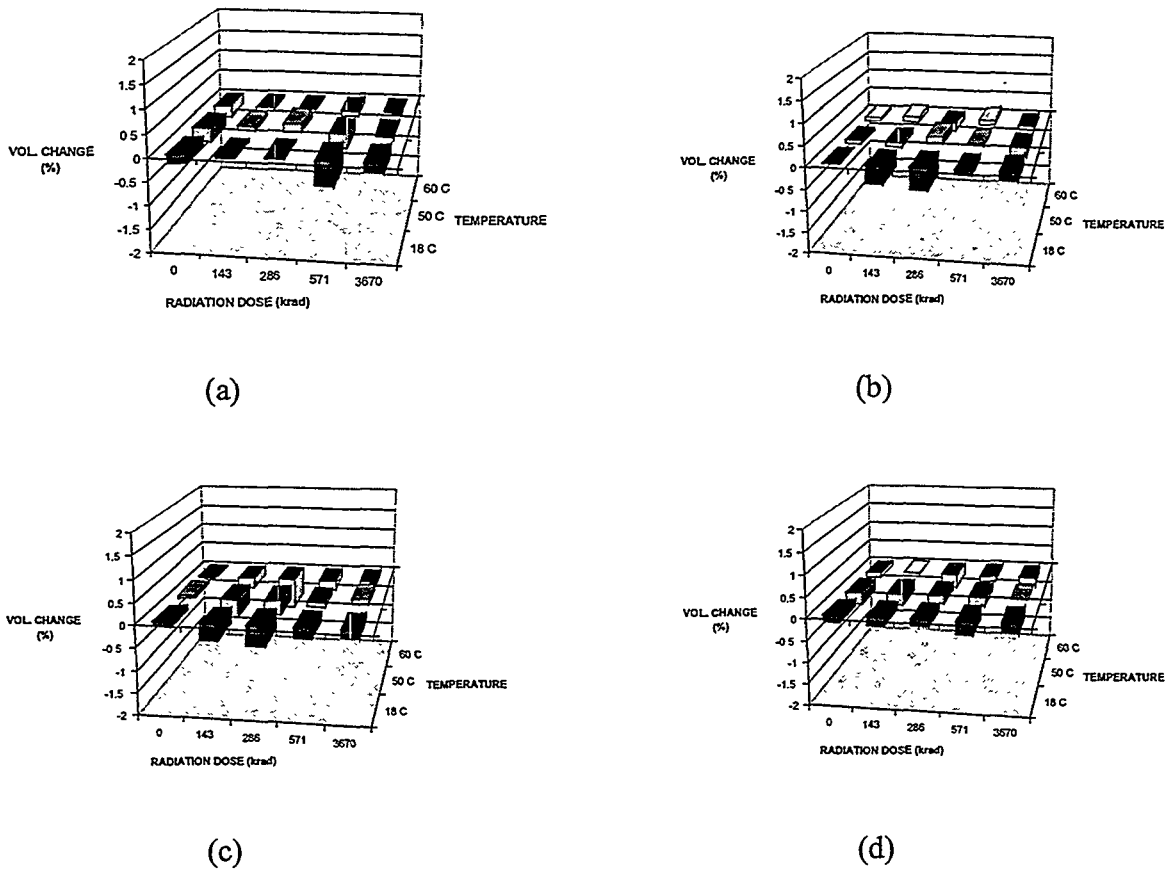


Figure 4. Volume (Vol.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

Hardness Properties

The measurement of changes in the hardness of materials can provide important clues to the effects of environmental conditions on the material. If the hardness of the material decreased, the material may have swelled. Alternatively, the polymeric constituents of the elastomer may have substantially degraded. Conversely, if the hardness of the material increased, additional cross-linking of the polymer may have resulted. The results of these measurements, in addition to providing important data by themselves, may complement other measurements such as specific gravity and dimensional and tensile properties.

The measurement of hardness involves the use of a standard instrument manufactured by Shore Instrument Company known as a Shore Durometer. The hardness of the plastic material will dictate the type of durometer used. For elastomers, which in relative terms tend

to be rather soft, a Type A Durometer is used. Similar to the approach used for the previously described property measurements, the initial hardness values were determined for pristine samples (i.e., samples not exposed to anything). Using these initial hardness values, the percentage of hardness changes was measured for samples exposed to the simulant alone [see 0 krad data set in Figure 5 (a-d)] at the three temperatures and four exposure times, and to a combination of radiation and simulant at these temperatures and exposure times. The results of these measurements are provided below.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on EPDM, hardness testing was performed on the materials exposed to the surrogate waste alone at the three temperatures and four time periods. The results of these measurements are given in Figure 5 (a-d) under 0 krad radiation dose. The sign of the hardness changes indicates whether the hardness of the material has increased or decreased when compared to that of the pristine material. Decreasing hardness indicates that the material has become softer as a consequence of the exposure conditions. As was previously mentioned, properly engineered plastic packaging components are not expected to be affected by the packaging contents. An elastomer exhibiting the smallest changes in hardness should be considered a good candidate as a packaging component. An inspection of the results shown in Figures 5 (a-d) shows that in general, the hardness of EPDM decreases with increasing time and temperature of exposure to the simulant. However, the decrease in hardness was never more than 1.3%. At a relatively short exposure time of seven days, a number of samples had slight increases in hardness. These calculated increases were within the experimental error of the measurements. At the longest exposure times of 180 days (Figure 5d), a close inspection of the data revealed that all samples became softer. There is some indication that as the radiation doses increase, EPDM does not become softer to the same degree, even at higher temperatures. These results suggest that in some instances, radiation causes hardness increases in EPDM. At the longest exposure times, highest radiation dose, and highest temperature, EPDM has a comparable, but 1 point lower, hardness compared to that of the pristine material. These results suggest that exposure to either the simulant or the combination of radiation and simulant results in plasticization of EPDM. Since decreases in volume at these temperature (Figure 4a - d) was observed, this plasticization appears not to be due to the swelling in the material. While the actual hardness values are not obvious from the data in Figure 5, their precise values are given in Appendix E.

Compression Set

Compression set tests measure the ability of elastomers to retain elastic properties after prolonged action of compressive stresses. Compression set, also referred to as "set" hereafter, is usually determined in air and reported as the percent of deflection by which the elastomer fails to recover after a fixed time period under a specified compression and temperature. In these experiments, the time period of compression was 22 hours at ~23 °C. A complete return by the elastomer to its original thickness after the compressive stresses are removed results in a calculated set of 0%. For a situation where the elastomer does not return to its original thickness but remains at the thickness under compression (4.5 mm), a set of 100% is calculated. The practical aspect of such a situation is that the elastomer just contacts the matting surface of the device that contains the elastomer. In the case of O-ring seals, this situation could lead to seal failure because the elastomeric seal makes minimum contact with the sealing surface. It should be obvious from the previous discussions that materials having a low set value are desirable. To measure set, we have used the standardized test method, ASTM D 395. Using this method, the EPDM samples were held in the compression set device at room temperature (~23 °C).

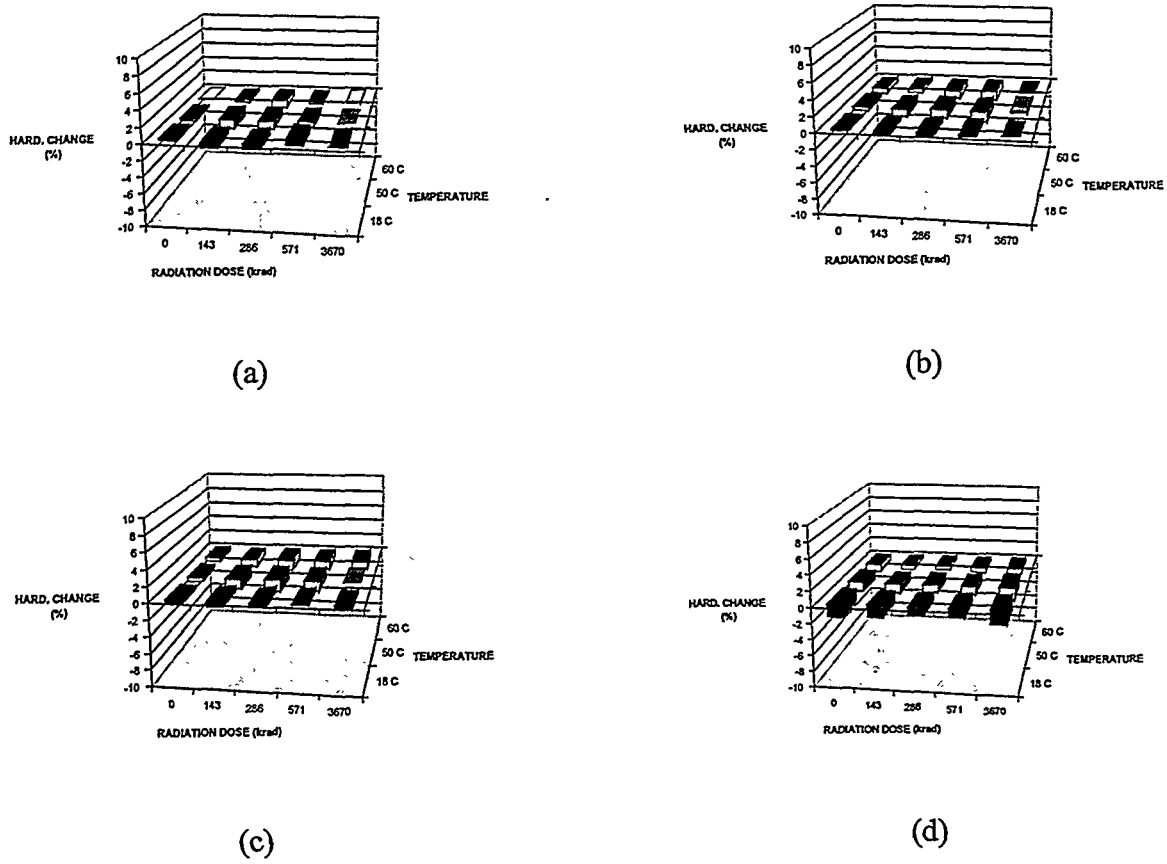
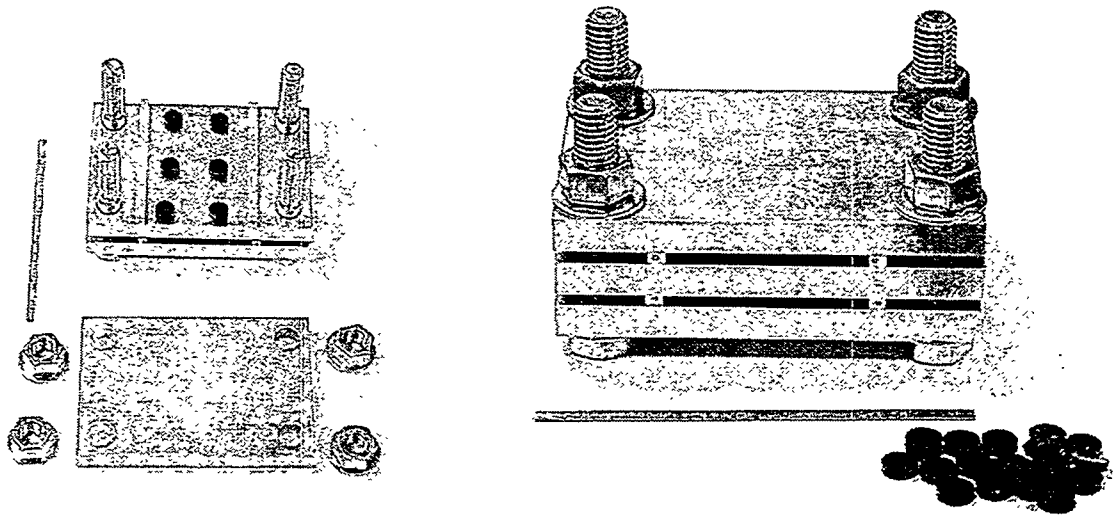


Figure 5. Hardness changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

Figure 6 shows an example of the experimental configuration used for the compression set tests.



(a) (b)

Figure 6. Compression set fixture: (a) a partly assembled fixture with the 4.5 mm spacer bars and EPDM samples and (b) an assembled fixture with EPDM samples.

In order to understand effects of radiation alone on set values, some EPDM samples were exposed to only the four radiation doses (i.e., no chemical exposure), the three temperatures, and the four exposure times. Similarly, the effects of the simulant alone were studied under these conditions. Finally, samples exposed to a combination of radiation and simulant were studied as discussed below. It is important to mention that the results given in Figures 7 and 8 plot changes in compression set versus radiation dose and temperature. These changes represent the difference in the set observed under the specific environmental conditions and the set of pristine EPDM samples. Because set values are expressed in percent, the change in set is also expressed as a percentage value.

In Figure 7 (a-d), the set changes for EPDM samples exposed to four gamma ray doses followed by 7-, 14-, 28-, and 180-day exposures at the three temperatures are provided. The important point to keep in mind is that the set was measured after being held for 22 hours at ambient temperature and *not* at the three temperatures. Another way to express this important experimental detail is that only the samples themselves saw the different radiation doses, exposure times, and exposure temperature. The compression set measurements were performed at one time and one temperature. The results show that while most samples exhibited an increase in set of ~1%, some samples had decreases in set of ~ 1% - 3%. More changes were observed in samples exposed for 180 days. However, no systematic trend was observed in samples exposed to increasing radiation doses, exposure time, and exposure

temperatures. The results suggest that the set changes were within the experimental error of the tests.

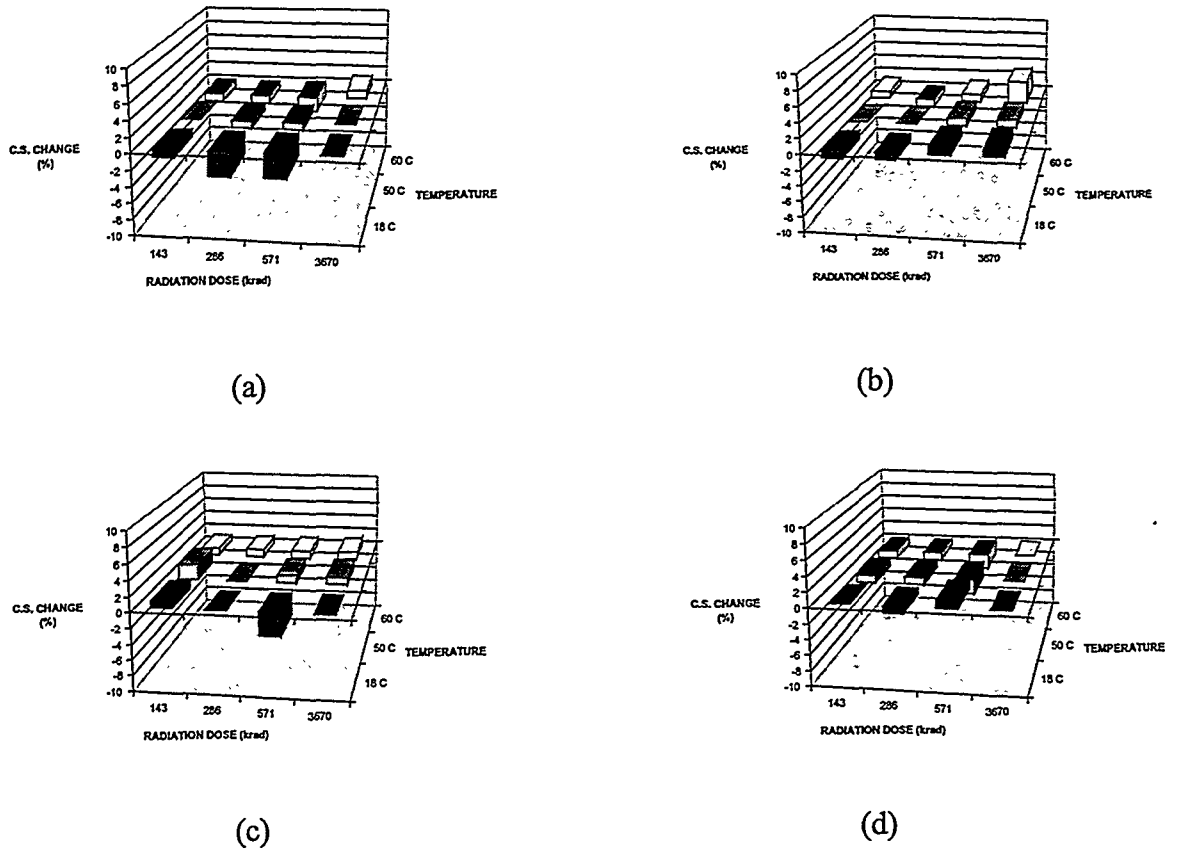


Figure 7. Compression set (C.S.) changes in EPDM after exposure to ~ 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60 °C.

Figure 8 (a-d) shows the set changes for EPDM samples exposed to a combination of the four gamma ray doses followed by 7-, 14-, 28-, and 180-day exposures to the aqueous simulant at the three temperatures. Similar to the samples exposed to gamma radiation alone, the set exhibited by samples exposed to a combination of radiation and the aqueous simulant was similar (i.e., 1% - 3%). The set in EPDM samples exposed to only the simulant (0 krad data field) generally increases with increased temperature and increased exposure time. In fact, the combination of radiation followed by exposure to the simulant has a "beneficial" effect by resulting in lower compression sets. A close inspection of the data further suggests that under certain exposure conditions, a minimum set is observed. For example, in Figure 8 (c) minimum compression set values appear in EPDM samples exposed to ~286 krad of gamma radiation and 28-day exposures to the simulant at all three temperatures. For longer exposure times, these minimum set values seem to shift to lower radiation doses.

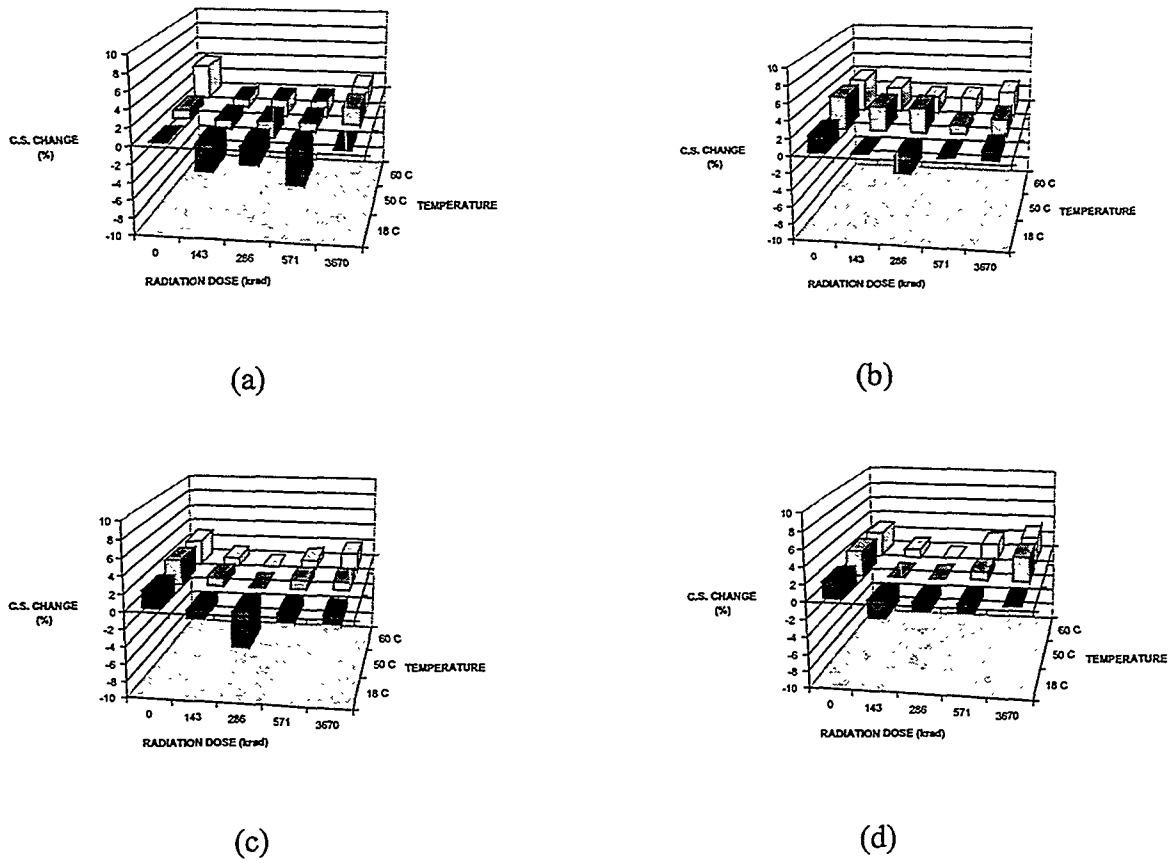


Figure 8. Compression set (C.S.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C, respectively.

To summarize the compression set results, EPDM is not affected greatly by radiation, the simulant, or a combination of these two environmental conditions. While the precise set values are not clear from the data in the Figure 8, their specific values are provided in Appendix F.

Vapor Transport Rates

Vapor Transport Rate (VTR) measurements provide a measure of the permeability of various chemical agents into elastomers. The rate of transmission of a liquid through an elastomer that acts as a barrier is important in elastomer seal performance. This transmission is referred to as vapor transmission, since the liquid diffuses through the elastomer in a molecular sense and escapes into the surrounding atmosphere in vapor form. This type of testing provides a steady-state measure of the rate of vapor and liquid transmission through relatively thin

elastomers. While the calculated values of VTR cannot be directly converted to traditional permeability values, the VTR values can be used to provide an indication of permeability.

The VTR measurements were performed at three temperatures and four exposure times. In these experiments, one set of EPDM samples was exposed to only the simulant aqueous waste while the remaining samples were exposed to a combination of radiation and the simulant. To measure VTR, we have used the standardized test method, ASTM D 814. Using this method, the EPDM samples were sealed to a ground-glass surface using a metal screw band. It should be noted that VTR experiments by this method with EPDM samples exposed to *only* gamma radiation are not possible because the testing method requires the presence of a chemical agent. Figure 9 shows a set of cells used in VTR experiments.

Figure 9. Vapor Transmission Rate Cells

VTR changes cannot be determined because it is not possible to determine VTR on "pristine" EPDM. The pristine property value of the material was used to calculate changes in that property. For example, in the previous section the compression set value of EPDM that had not been exposed to radiation, the simulant, or the combination of radiation and simulant was used to define the compression set of "pristine" EPDM. In VTR measurements, however, a similar VTR value for pristine EPDM is not possible, since its determination will require exposure to a simulant.

Figure 10 (a-d) shows VTR for EPDM samples exposed to a combination of the four gamma ray doses followed by 7-, 14-, 28-, and 180-day exposures to the aqueous simulant at the three temperatures. The data shown in the 0 krad data field represent samples exposed only to the simulant for the four exposure times and temperatures. All materials exhibited VTR values below 1 g/hr/m^2. In fact, most of the VTRs are below 0.1 g/hr/m^2. These results are consistent with the results previously observed in the screening tests where EPDM had the lowest VTR in aqueous simulant Hanford Tank wastes. The VTR for EPDM samples generally increased with increased temperature and decreased with

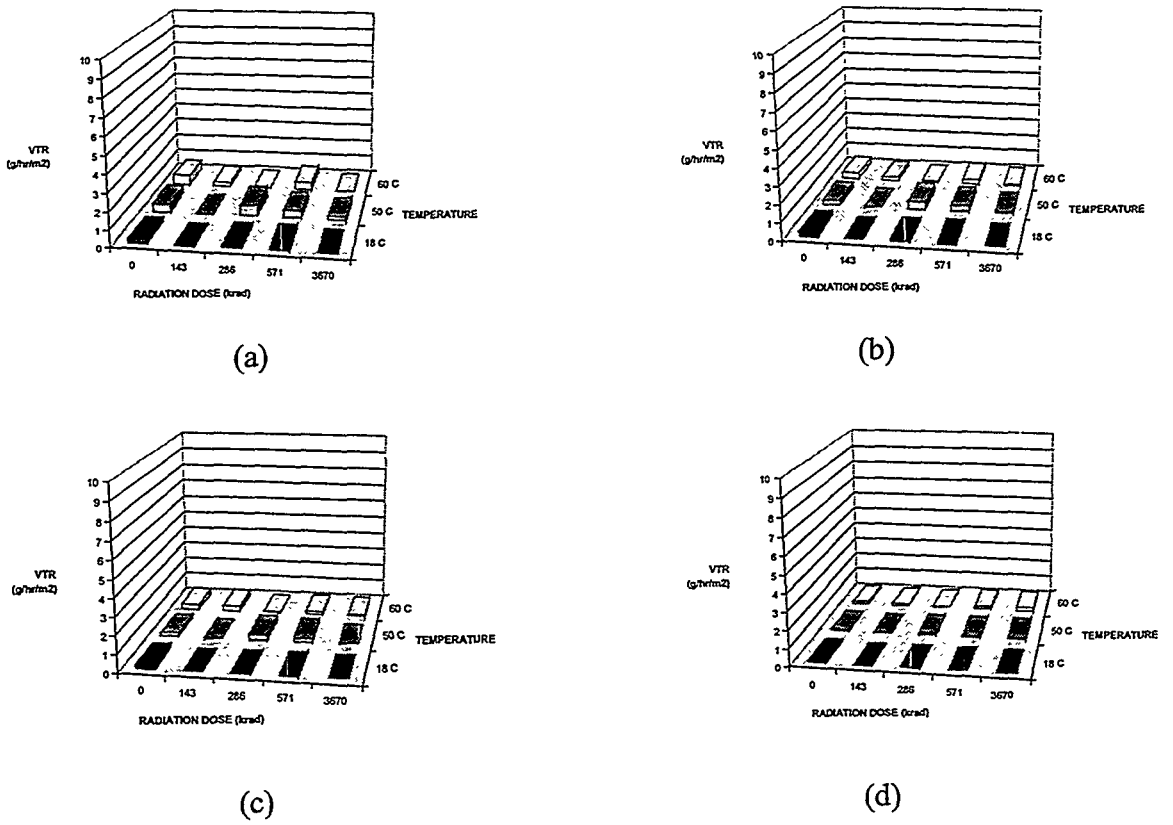


Figure 10. VTR in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C, respectively.

increasing exposure time. While the exact VTR values are not obvious from the data in Figure 10, their precise values are presented in Appendix G.

Tensile Properties

Tensile properties, also known as mechanical properties, are the properties associated with a materials response to mechanical forces. A quantity more useful than force is the

engineering stress (σ), which is the ratio of the magnitude of a force to the magnitude of the originally undeformed area of the body upon which it is acting. True stress is therefore defined as $\sigma = F/A$, where A is the cross-sectional area when the Force (F) is applied. The most common engineering units of stress are pounds force per square inch (lb/in^2 or psi). These units may be converted to the corresponding SI unit, the Pascal (Newton/meter) by multiplying the psi value by 6,895. However, since we always calculate the percentage of changes in properties, the units are irrelevant. The specific values in Mega Pascal (MPa) are reported in Appendix H.

Another important tensile property to consider is strain. A stressed material undergoes deformation or *strain* (ε), defined quantitatively as either the incremental deformation divided by the initial dimension or the percent of the original dimension. Since strain is a dimensionless quantity, the precise choice of units is not important. In this study, a 1-inch gage length was used, and the units of strain are therefore in/in. Two fundamentally different types of strain are observed. The first type is *elastic strain* or elastic deformation where strain is recoverable upon the release of stress. In other words, when a causal stress is removed, the resultant strain vanishes and the original dimensions of the body are recovered. A practical example of this type of strain is the stretching of a rubber band. Since EPDM is a specific type of rubber, this material exhibits this type of strain. The second type of strain is *plastic strain.* This occurs when stress is increased, and a value is eventually reached where permanent deformation of the body has occurred. An example of this property is the bending of wire with the fingers. Note that the term "plastic strain" does not necessarily mean that the deformed material is a plastic.

For many plastic materials that might be suitable as packaging components such as seals and liners, high strengths and high strains are expected from the material. The strains exhibited should also be elastic in nature. In certain instances, however, other specific tensile properties are desirable, that is, high strength and low strain. This study determined the tensile properties of the pristine material and then determine the effects of radiation alone, the simulant alone, and a combination of these environmental conditions on the tensile properties of EPDM.

Tensile Strength

The *tensile or ultimate strength* of a material is calculated by dividing the observed maximum load placed on the material during the tensile test by the original cross-sectional area of the material. While many polymeric materials exhibit stress-strain curves having an initial maximum followed by lower stresses, this is not the case for elastomers. The maximum load value in elastomers is typically observed at the break point of the material.

The measurement of tensile properties involves the use of tensile testing equipment that can apply controlled tensile loads to test specimens. The equipment is capable of varying the speed of load (stress) and accurately measuring the forces (strains) and elongation applied to the specimens. In this study, an Applied Test System, Inc., Universal Testing Machine, Series 1400, was used. This computer-controlled testing equipment was able to perform the required tests with user-developed testing methods. These methods prescribe the strain rates and breaking points along with many other experimentally important variables. The selection of these experimental variables was based on the standard test method ASTM D412. For the determination of the tensile strength of elastomers, the use of a high elongation extensometer and high rates of grip separation (50 mm/min, 20″/min) were used. The acquired data were analyzed with software developed by this manufacturer. The software calculates numerous tensile properties. The data discussed in this subsection require a determination of tensile strength. This can be calculated as described previously, using peak loads and cross-sectional area. In addition, the software also calculates ultimate elongation and tensile stress values. In this subsection, tensile strength values are of interest.

Since an understanding of the effect of mixed waste environments is not possible without understanding the effects of radiation and simulant alone, the latter experimental conditions were also investigated. The results of tensile strength changes in the materials exposed to gamma radiation at the three temperatures and four exposure times is provided in Figure 11. In Figure 11 (a-d), the average percentage for tensile strength changes of EPDM exposed to gamma radiation alone at 18, 50, and 60 °C for 7, 14, 28, and 180 days is shown. Similar to previous property measurements, these percentage changes were determined by measuring the change in tensile strength from that of the pristine materials. When the change in tensile strength (expressed as a percentage) is a positive value, the material tensile strength has increased under the specific exposure conditions. Negative values indicate decreases in tensile strength.

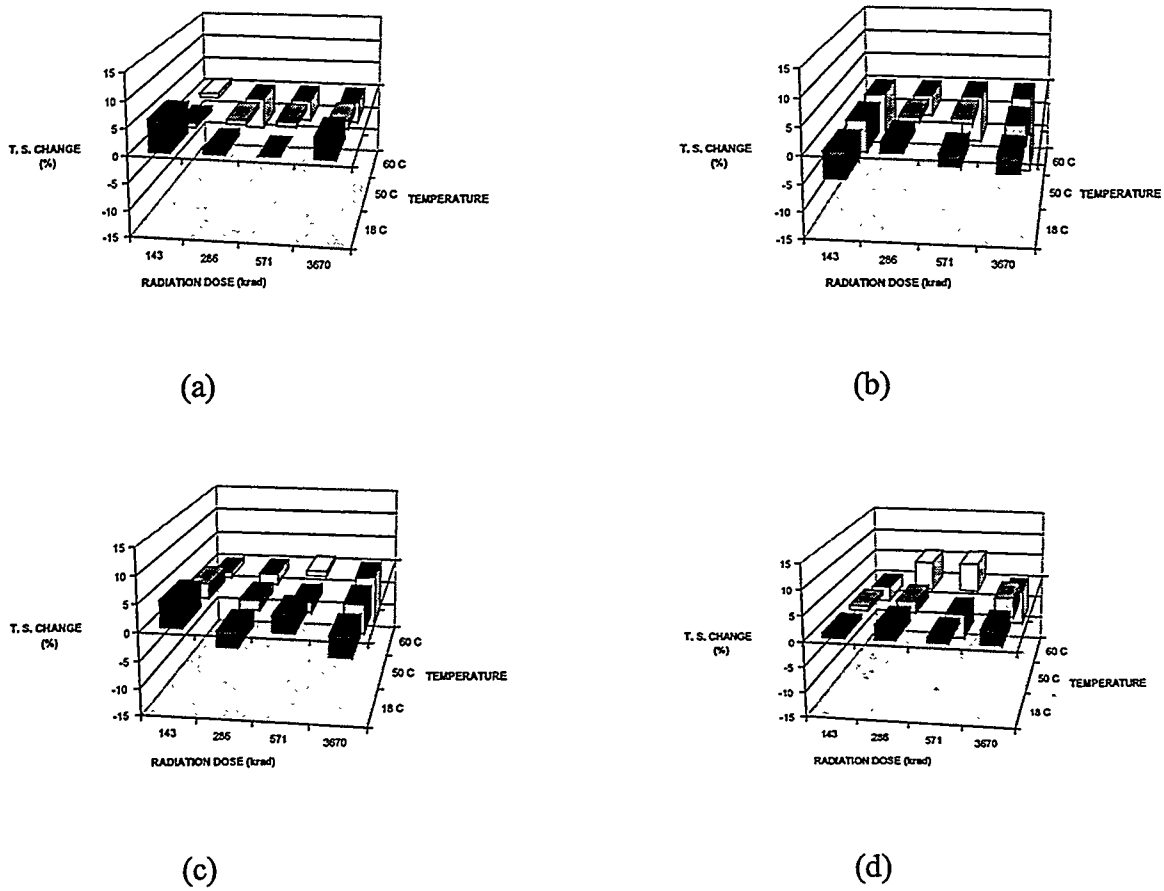


Figure 11. Tensile strength (T. S.) changes in EPDM after exposure to ~ 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60 °C.

From a general perspective, Figure 11 shows no significant effect on tensile strength for all radiation doses, exposure times, and exposure temperatures tested. Under these conditions, the changes in tensile strength for most of the samples were less than 10%. Many of these changes appear to be in the range of ± 1% - 4%. At the longest exposure time (180 days), tensile strength of EPDM appears to have increased slightly. It should be noted that the changes in tensile strength appear to be rather small.

Figure 12 shows the average values of percentage of tensile strength of EPDM exposed to four gamma radiation doses followed by exposure to the aqueous simulant waste at 18, 50, and 60 °C for 7, 14, 28, and 180 days. EPDM samples that were only exposed to the simulant (0K) waste show a decrease in tensile strength up to 28-day exposures. After a 180-day exposure, the tensile strength for these samples appears to increase slightly. A similar trend appears to be followed by samples exposed to both radiation and the simulant. These

changes indicate that EPDM exposed to radiation doses below 3,670 krad appear more affected by the simulant than by the radiation. At the highest radiation dose, a reversal of this process appears to have occurred. This could be caused by cross-linking of the ethylene-propylene constituents in the elastomer, which leads to relatively higher tensile strength. However, since most of the tensile strength changes are below 5%, the combination of radiation and simulant have no pronounced effects on the tensile strength of EPDM. At the longest exposure time, EPDM may be somewhat stronger but less elastic.

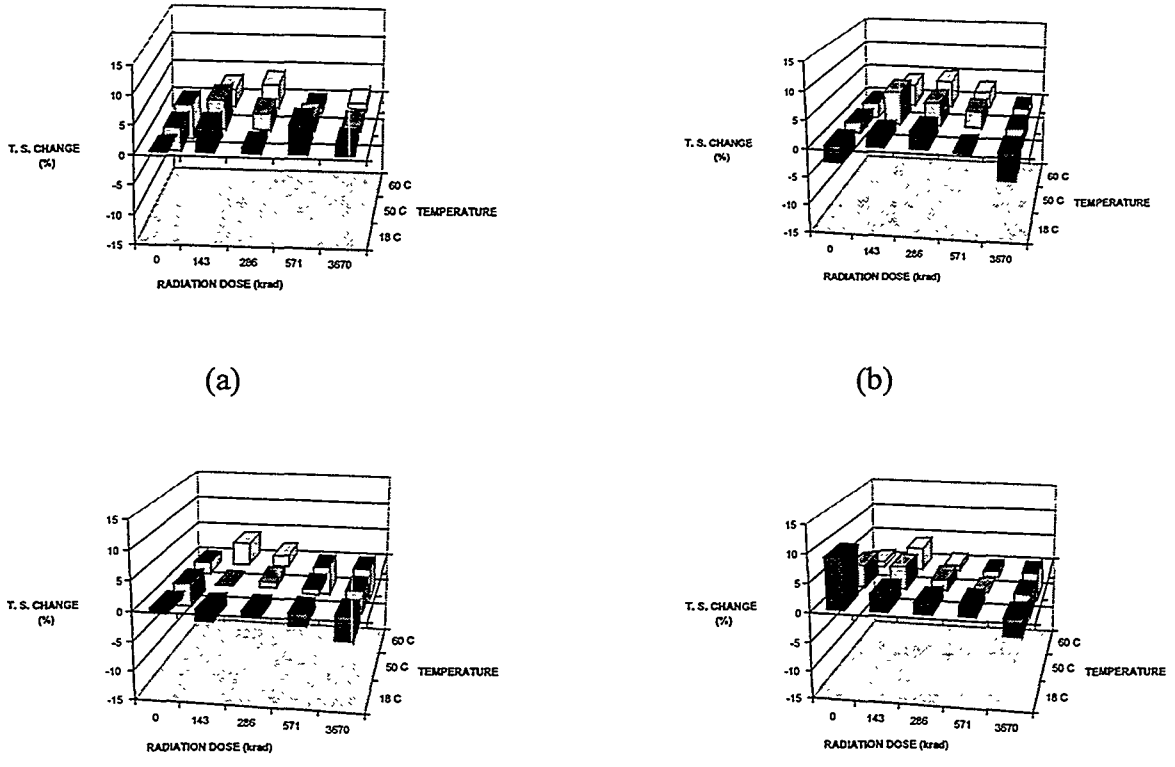


Figure 12. Tensile strength (T. S.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

Elongation at Break or Ultimate Elongation

As discussed previously, the stress-strain diagrams of linear polymers exhibit an initial maximum stress value. This maximum stress value occurs at the yield point of the material. At this point, deformation starts to localize in the material, forming a "neck," and the material is said to undergo "necking". However, since elastomers are extremely elastic,

necking is not observed in these materials. The determination of elongation at yield in elastomeric materials, as opposed to that of thermoplastic materials, is not possible. In elastomers, the maximum stress value occurs at the break point of the material. The amount of elongation that the material exhibits at this point is known as the elongation at break. For elastomers, the term "Ultimate Elongation" is used rather than elongation at break. The ultimate elongation of an elastomer is defined by Eq. 1 as

$$\text{Ultimate Elongation} = [(L_f - L_o)/L_o] \times 100, \qquad \text{Eq. 1}$$

where L_o is the initial gage length (1″ in this study) and L_f is the gage length at the break point. These ultimate elongation values are expressed as a percent. It should be clear that increasing values of ultimate elongation equate to increasing elasticity in the material, while decreasing values represent decreasing elasticity. The data presented in the following sections describe the change in elongation. These values were obtained by subtracting the ultimate elongation of the pristine material (164%) from the ultimate elongation observed in the material at the specific environmental conditions. As in previous measurements, positive and negative values for changes in ultimate elongation are possible. The ultimate elongation values are provided in Appendix I.

In Figure 13 (a-d), the average changes in ultimate elongation of EPDM exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60 °C for 7, 14, 28, and 180 days are given. It should be mentioned that the scale for ultimate elongation changes is considerably larger than shown in previous figures. In this section, the scale ranges from -50% to 50%. While the scale is larger than in previous measurements, it is still less than

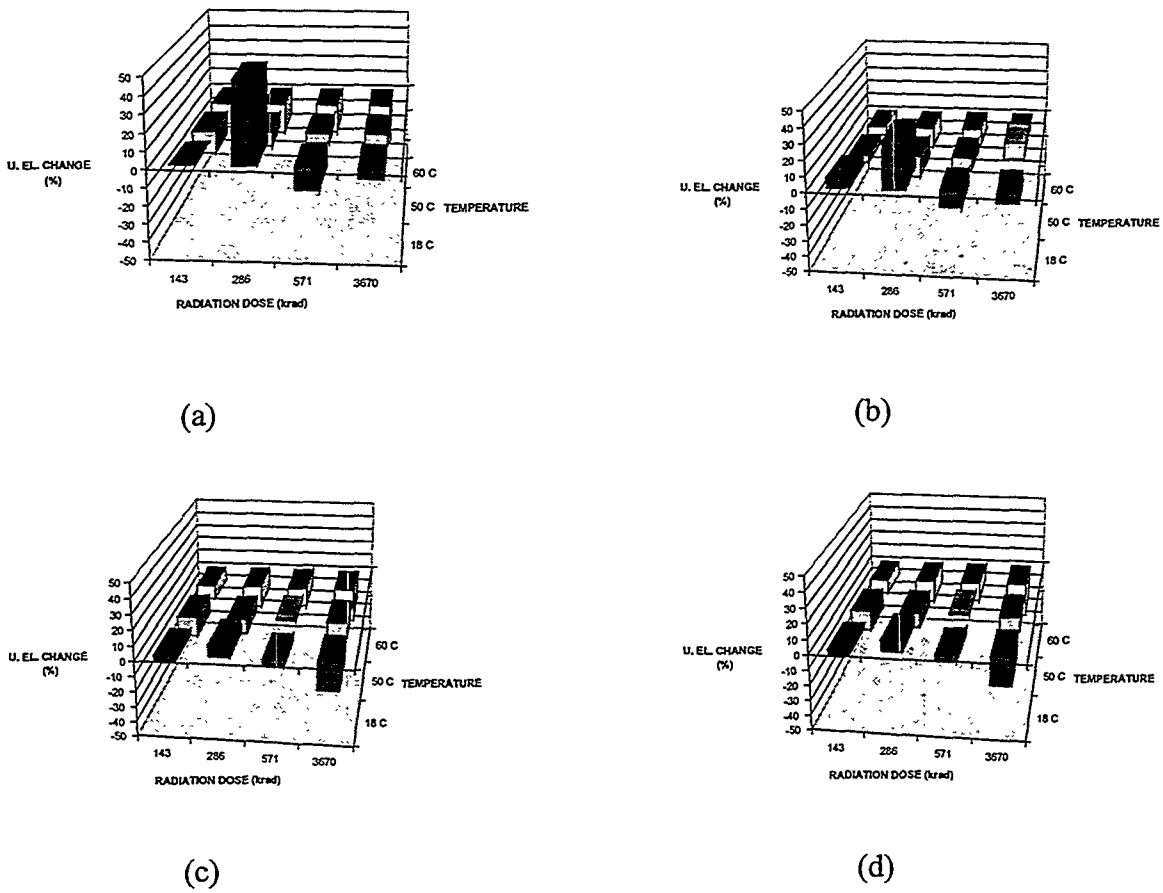


Figure 13. Ultimate Elongation changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60 °C.

observed[8] for thermoplastics. For the latter materials, the scales ranged from -600% to 1000%. These results suggest that the "necking" observed in thermoplastics play an important role for accommodating deformation.

The data generally show a decrease (10%) in ultimate elongation with increasing exposure time. This was especially true at the longest exposure time of 180 days. For this exposure time, decreases in ultimate elongation as large as 24% were observed. No general trends can be detected from the data for EPDM exposed to radiation alone. These results indicate that the elasticity of EPDM exposed to radiation alone is reduced.

Figure 14 shows the average changes in ultimate elongation for EPDM exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60 °C for 7, 14, 28, and 180 days to the aqueous simulant waste. Similar to the EPDM exposed only to gamma radiation, there

is a general decrease in ultimate elongation with increased exposure time. The decreases in ultimate elongation are in the 5% to 20% range. The EPDM samples exposed to only the aqueous simulant (0K data) also follow this trend but to a lesser degree. These results suggest that the simulant alone does not result in a strong decrease in ultimate elongation in EPDM. For certain EPDM samples exposed to a combination of radiation and the simulant, relatively large increases (~ 25% - 35%) in ultimate elongation were noted. No explanation for these anomalously large increases can be made. At the highest gamma radiation dose, most of the materials had negative changes in ultimate elongation; that is, their elasticity was below that of the pristine material. With 3,670 krad of gamma radiation and 28-day exposure (Figure 14c) to the aqueous simulant, the ultimate elongation had decreased by more than 30%. However, this trend of decreasing elasticity is not observed for 180-day exposures. While the ultimate elongation still had decreased, it decreased to just slightly over 15%. The specific ultimate elongation values are provided in Appendix I.

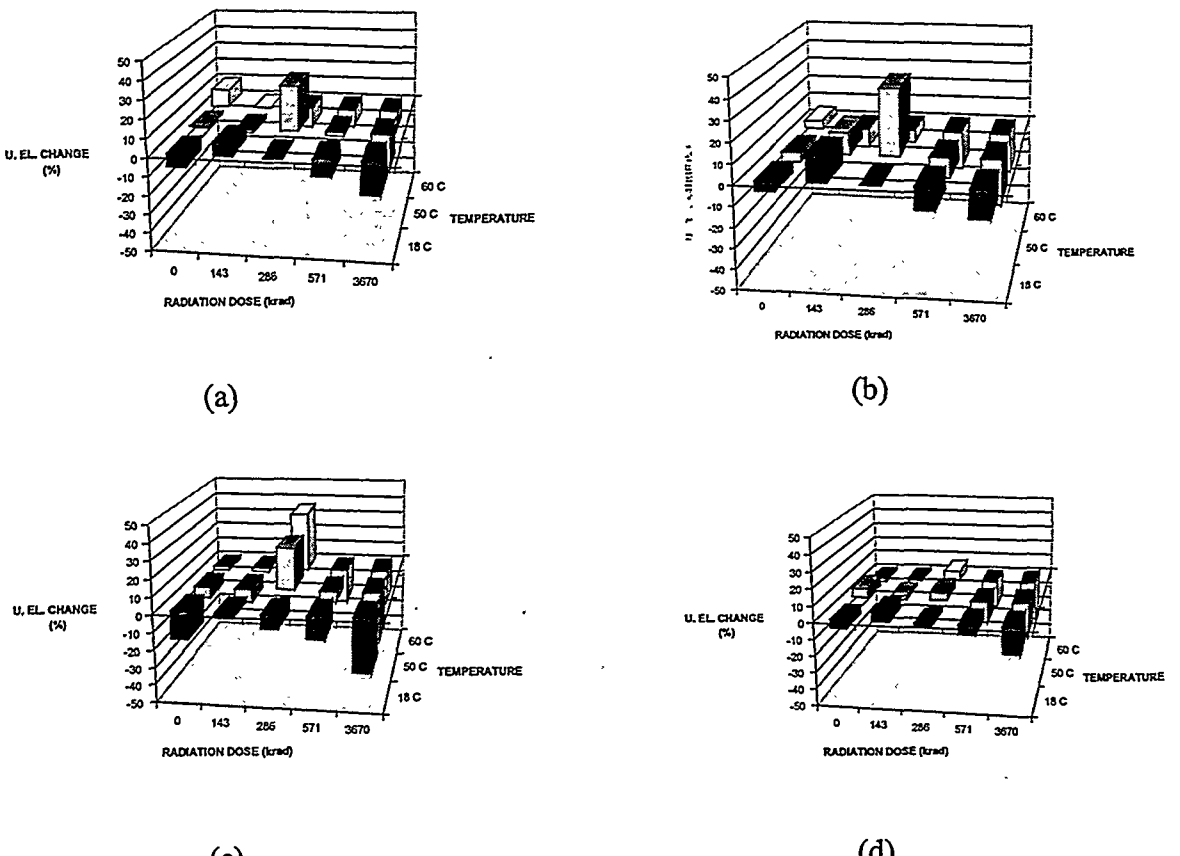


Figure 14. Ultimate elongation (U. El.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

Tensile Stress or 100% Modulus

For most materials, the initial portion of a stress-strain diagram is linear. This implies that strain is proportional to stress. The proportionality constant (slope of this linear region) is called the *modulus of elasticity*. The modulus of elasticity, or *Young's modulus*, is a property of the stressed material. In fact, the magnitude of the modulus can be related to the nature of the chemical bonds existing in the material. Therefore, the modulus provides a measure of the bonding strength in the material being investigated. High values of modulus indicate that strong bonding is present in the material.

As one might surmise from the previous discussion, materials having strong covalent bonding have the highest modulus values. Thus, the larger the value for modulus, the stronger the bonding expected in the material. Modulus has the same units as stress (psi or MPa). The rubber industry also refers to the modulus of a compound. They give it a specific designation such as 100% modulus or 300% modulus because the value generated is not an engineering modulus, but is rather the stress required to obtain a given strain. Therefore, the "100% modulus" is simply the stress (σ) required to elongate the elastomer to twice its reference gage length. Rather than representing the slope of a region in a stress-strain curve, the 100% modulus represents a single data point on the curve. The 100% modulus or tensile stress of an elastomer has identical units as the engineering modulus. Since we are interested in measuring changes in the tensile stress of the exposed material from that of unexposed or pristine material, we will discuss the percentage of change in tensile stress of the materials. This is calculated from the relationship given in Eq. 2

$$\% \text{ Change in Tensile Stress} = (\sigma_f - \sigma_o)/\sigma_o \times 100, \qquad \text{Eq. 2}$$

where σ_f is the measured tensile stress under the specific environmental conditions at 100% elongation and σ_o is the tensile stress of the pristine material at 100% elongation. The 100% modulus changes can be a positive or negative in value, depending on the magnitude of either σ_f or σ_o. Positive changes in percentage of tensile stress indicate that the material of interest required greater application of stress to elongate the elastomer 100% than was required for pristine material. Negative values indicate that the material of interest required less application of stress than in the pristine material. Appendix J provides the actual tensile stress values of EPDM under the different environmental conditions along with the percentage of change.

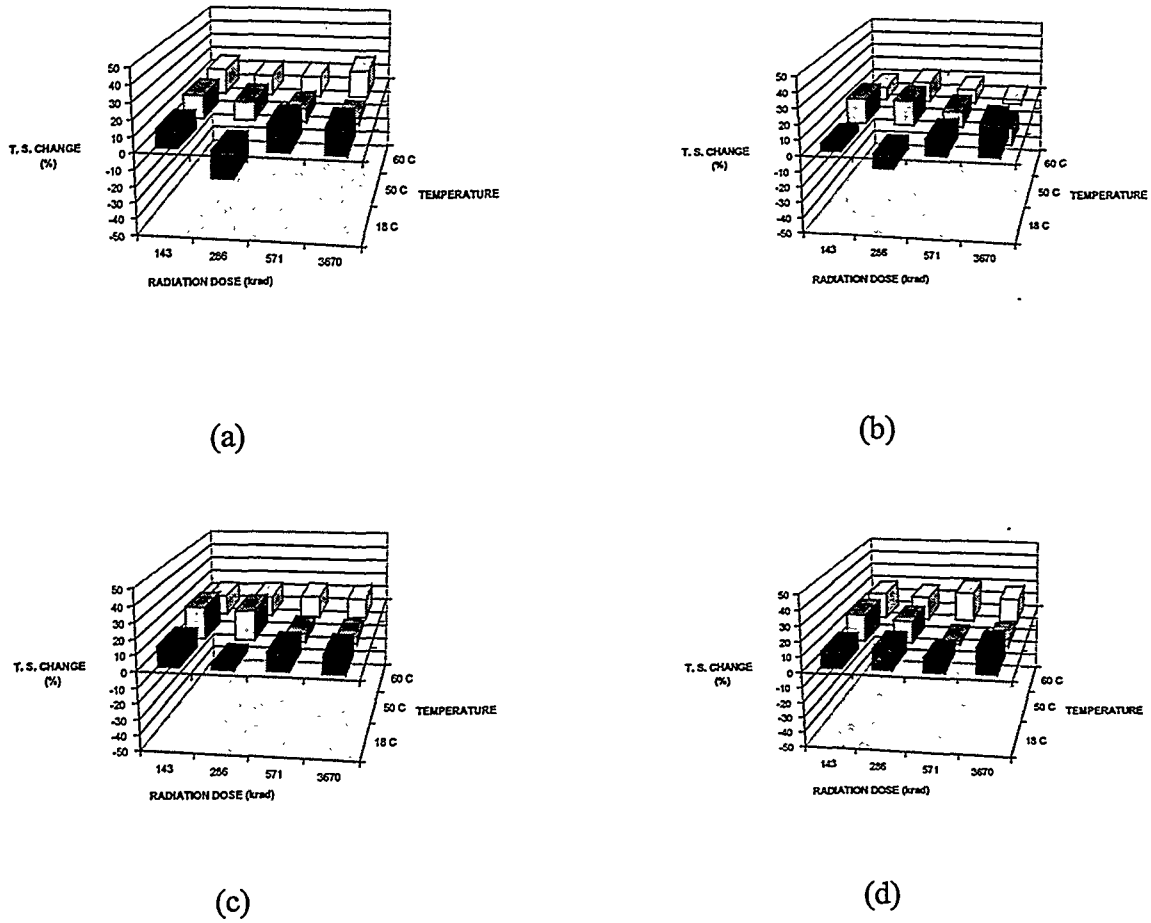


Figure 15. Tensile stress (T. S.) changes in EPDM after exposure to ~ 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60 °C.

Figure 15 (a-d) gives the average percentage of change in tensile stress of EPDM exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60 °C for 7, 14, 28, and 180 days. Increased gamma radiation doses do not result in large increases in tensile stress. Similarly increased exposure temperatures have no dramatic effect on the tensile stress of EPDM. The changes ranged from -16% to just over 20%. Even though some samples exhibited a decrease in tensile stress, the majority had increases in tensile stress. At higher radiation doses and temperatures, there is a general trend toward increased tensile stress. These trends are generally consistent with increased bonding (i.e., crosslinking of polymer chains). This observation is in agreement with an increasing brittleness in the material that has been confirmed by increases in tensile strength (Figure 12) and decreasing ultimate elongation (Figure 13).

Figure 16 (a-d) shows the average percentage of change in tensile stress of EPDM exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60 °C for 7, 14, 28, and 180 days to the aqueous simulant waste. As with the "Rad Only" data, there are no large

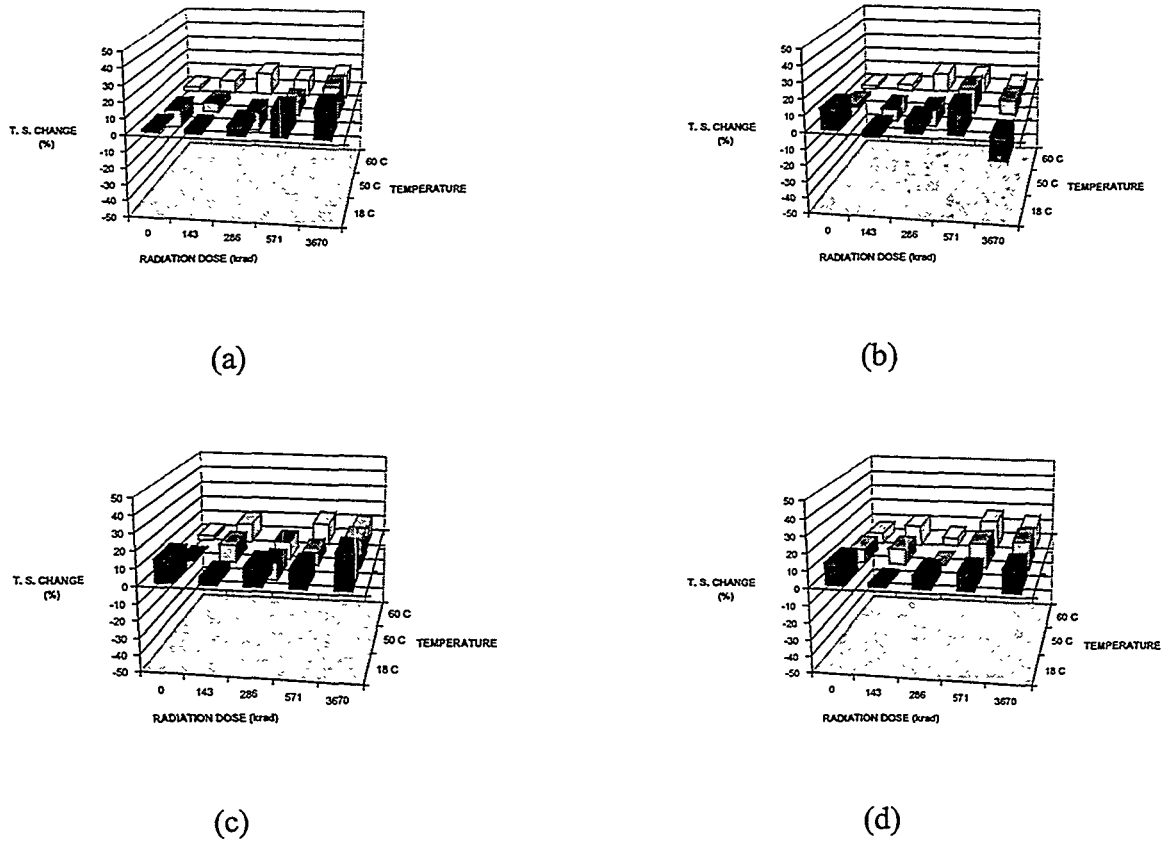


Figure 16. Tensile stress (T. S.) changes in EPDM after exposure to ~ 0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60 °C.

changes in tensile stress. The largest of these are on the order of ~ 16%. Comparing the results of Figures 15 and 16, EPDM exposed to both radiation and the simulant waste had slightly lower tensile stress values. These results suggest that simulant has counteracted the embrittling action of radiation; that is, the simulant acts as a plasticizer in EPDM. These effects are most pronounced when one compares the 0 krad values with the 3,670 krad values, that is, EPDM samples exposed to only the simulant and those samples exposed to the highest radiation dose. For virtually all the exposure times, the tensile stress changes were lower for EPDM exposed to only the simulant than for those samples having been exposed to both environmental conditions. The results in Figure 16 also show that increased exposure time and exposure temperatures lead to generally slight increases in tensile stress. However,

since these changes are not easily discernible and consistent, EPDM appears to be remarkably resistant to the effects of radiation, the simulant, and the environmental conditions.

DISCUSSION

The Chemical Interaction Program, previously referred to as the Chemical Compatibility Program, provides a scientifically defensible methodology for measuring the chemical interactions of polymeric liner and seal materials with hazardous wastes. These polymeric materials are those that may be used in current and future container designs for the transportation of hazardous and mixed wastes throughout the DOE complex. The approach used in this testing program was to assess the state of chemical compatibility testing technology and to direct the thinking of all those concerned toward routes that might lead to satisfactory, comprehensive, and reliable chemical compatibility data on plastics for use by the DOE Office of Environmental Management.

Since the completion of the screening phase of the program several years ago, the comprehensive phase of this program has been in progress. Since all seal and liner materials passed the screening tests when exposed to the aqueous simulant Hanford tank waste, 10 materials needed to be subjected to the test matrix, resulting in an extremely large sample set. In view of manpower and budget constraints, the comprehensive testing phase of the program was further subdivided into the testing of liner materials and seal materials. The results of liner testing have been the subject of a SAND Report.[8] Because of further funding constraints, the comprehensive testing of seal materials was subdivided into the testing of individual elastomers. In this report, we discuss the results of testing of the first elastomeric seal material, EPDM. Subsequent reports will discuss the testing results for the remaining elastomers (FKM, butyl, and SBR rubber exposed to simulant Hanford Tank Waste).

Overall, the data show that temperature of the simulant, the radiation dose, and the exposure time had no dramatic effect on the specific gravity of EPDM because changes in excess of 1% were not observed. These results are consistent with the known chemical resistance of this elastomer and demonstrate that EPDM is a suitable elastomer for use under these conditions if specific gravity is the determining package design criterion for selection of packaging components. Increasing exposure times and exposure temperatures generally caused slight increases in specific gravity while increasing radiation doses led to slightly decreasing specific gravity in EPDM. The EPDM samples that were not irradiated sometimes displayed larger increases in specific gravity than samples exposed to both

radiation and the simulant. These results indicated that radiation has a beneficial effect in minimizing changes in specific gravity. A similar effect has previously been noted in the thermoplastic liner materials. However, the small magnitude of these specific gravity changes could equally well represent experimental error in the measurements.

The mass of EPDM did not increase substantially after exposure to the simulant or the combination of radiation and simulant. at increasing exposure times and exposure temperatures. For these conditions, mass increases of more than 0.6% were not observed. The largest increases in mass were observed after 180-day exposures. Since mass increases are not very substantial, the slight increases in specific gravity noted earlier must be due to changes in dimensions. Specifically, the volume in EPDM must decrease for a net increase in specific gravity. In fact, this was observed. For most sample volumes, a slight decrease was observed. These combined results point to a shrinking of the material. It should, however, be kept in mind that this shrinkage is minimal (~0.5%). Furthermore, it should be recalled that volume changes were calculated from changes in the length, width, and thickness of the sample. Since these property changes are not isotropic in the rectangular geometry of the samples, large changes in one of the sample dimensions may dominate changes in volume. In actual packaging, seals are in the form of O-rings. O-rings with their circular geometry may exhibit more isotropic behavior. Thus, the relatively small anisotropic changes in dimension may be even smaller in O-rings, where isotropic behavior is expected. The practical implication of these results is that EPDM O-rings, even when directly exposed to a Hanford Tank waste under similar conditions as used in this study, are not expected to shrink significantly.

As was previously discussed for dimensional property changes, the hardness of EPDM changes very little when exposed to the simulant and exposure to both radiation and simulant. The material does become softer with increased exposure time. Additionally, radiation appears to exert a beneficial effect on the retention of hardness by EPDM. This was found to be especially true for the case where EPDM was exposed at the highest radiation dose, highest exposure temperature, and longest exposure time. Since EPDM shrinks under these conditions, the observed softening of the material cannot be ascribed to a swelling phenomenon. However, softening in the absence of swelling could be from chain scission in the polymer. Confirmation of this process will require additional tests. The observation that radiation may have a beneficial effect on hardness suggests that the cross-linking and chain rupture processes are occurring simultaneously. Possibly, the combination of processes leads

to a polymeric structure having generally shorter polymer segments that are slightly crosslinked.

Compression set measures the retention of elastic properties of material after exposure to compressive stresses. When EPDM samples were exposed to only gamma radiation, most exhibited set changes of ± 1%. For samples exposed to both radiation and the simulant, similar results were observed. A rather curious observation was noted for the later samples. In these experiments, a specific radiation dose at each exposure time resulted in minimum compression sets. At a radiation dose of 286 krad, a minimum compression set was observed. The significance of this observation is not clear. As previously discussed, perhaps the competition between cross-linking and chain scission reactions could offer an explanation. However, other factors such as the interaction of the other constituents of elastomers (oils, vulcanizing aids, fillers, etc.) with these environmental parameters need to be considered.

The VTR of EPDM similar to the previously discussed properties changes very little for radiation and simulant exposure. Most of the VTR for EPDM samples were less than 0.1 g/hr/m^2. These results are not unexpected, since the permeation of water molecules through this polymeric network is expected to be slow. That this process is temperature dependent is confirmed by the results. As temperature is increased, VTR also increases. The interesting aspect of the results is that VTR appears to decrease with increased exposure time. A possible explanation is that the presence of inorganic salts, especially the precipitate found in the simulant, may clog pores in EPDM to reduce the transport of water vapor.

The tensile strength of EPDM also exhibits minimal changes when exposed to radiation, the simulant, and both radiation and simulant. Many of the samples changed less than 5% in tensile strength. Since no systematic change in tensile strength could be detected for all the environmental conditions, it appears that EPDM retains its tensile strength. At the longest exposure times, the strength of EPDM was observed to have increased slightly for all samples except those that received radiation doses of 3.67 Mrad. These results suggest that cross-linking of the polymeric elastomer constituents leads to higher strength. At the highest radiation dose, the rupture of polymeric chains may dominate as the determining process that leads to lower strength. Thus, while the materials strength may be increasing, its elasticity may be decreasing.

The elastic property of materials can be measured by evaluating their degree of ultimate elongation. For EPDM samples exposed to just gamma radiation, a general decrease in elongation was observed with increasing exposure time. These results indicate that the material is becoming less elastic. However, because most EPDM samples were still elastic, stretching more than ~150% , a change of ~10% still results in rather elastic material. For EPDM exposed to both radiation and simulant, while there is a general decrease in elongation, the material still retained more of its elasticity than samples exposed to just the radiation. These results again point to the plasticizing effects of the simulant.

Finally, the tensile stress properties of EPDM will be discussed. Tensile stress or 100% modulus measurements provide a measure of the toughness of the elastomer. A greater tensile stress value indicates that the elastomer is more likely to recover from localized forces and thereby resist extrusion. The effect of radiation on the tensile stress values of EPDM was not greater than 20% (i.e., tensile stress increases of 20% were observed). The effects of radiation on EPDM resulted in slightly tougher material. For samples exposed to only the simulant or to a combination of both radiation and simulant, slightly lower values (16%) were observed. These results suggest that the simulant has somewhat counteracted the effect of radiation to reduce the toughness. As previously observed, the simulant appears to act as a plasticizing agent.

In summary, the measurement of changes in specific gravity, mass, volume, hardness, compression set, vapor transmission rates, tensile strength, ultimate elongation, and tensile stress has indicated that EPDM is remarkably resistant to the effects of radiation and the aqueous simulant at the temperatures and exposure times tested. The beneficial effect of both radiation and the simulant in helping to reduce the changes in material properties were noted. These results suggest that the type of aqueous mixed wastes used in this study has minimal effects on EPDM rubber.

CONCLUSIONS

Sandia has developed a program for studying the chemical interactions of plastic packaging components that may be used in packaging for transporting mixed waste forms. Consistent with the methodology outlined in this report, the second phase of this experimental program was performed to determine the effects of simulant Hanford Tank mixed wastes on a packaging seal material, EPDM rubber. This effort involved the comprehensive testing of EPDM with an aqueous mixed waste simulant. The testing protocol involved exposing the respective materials to ~ 143, 286, 571, and 3,670 krad of gamma radiation followed by 7-,

14-, 28-, 180-day exposures to the waste simulant at 18, 50, and 60 °C. From the analyses performed, we determined that EPDM rubber has excellent resistance to radiation, the simulant, and a combination of these factors. These results suggest that EPDM is an excellent seal material to withstand aqueous mixed wastes having similar composition to the one used in this study.

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APPENDIX A

EPDM Rubber Material Information

Material Supplier: Parker Seal Group[a]
O-Ring Division
2360 Palumbo Drive
P.O. Box 11751
Lexington, KY 40512
(606) 269-2351

Measurement	Cure Date[b]	Batch Number
Specific Gravity	CD 1Q95	B317472
Dimensional	CD 1Q95	B317472
Mass CD 1Q95	B317472	
Hardness	CD 1Q95	B317472
Compression Set	CD 1Q95	B317472
Vapor Transport Rates	CD 1Q95	B317472
Tensile Property	CD 1Q95 CD 4Q95	B317472 B318624

a. Procured from Parker Seal Group (E0540-80) through Southwest Seal and Supply, 1413 1st Street NW, Albuquerque, NM 87102-1533, (505) 247-0265. This material was obtained in the form of molded sheets. The 12″ (30.5 cm) square sheets were ~0.125″ (0.317 cm) thick. Cost: ~$42/ft^2 (~ $0.046/cm^2)
b. Cure data (CD) nomeclature indicates the quarter and year in which the rubber was prepared. For example, 1Q95 represents material prepared during the first quarter of 1995.

APPENDIX B
EPDM Specific Gravity Data

AVERAGE SPECIFIC GRAVITY (SP. GR.) AND % CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SP. GR.	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE
0K	1.2421	1.2511	0.72	1.2479	0.47	1.2490	0.56	1.2547	1.01
143K	1.2486	1.2491	0.04	1.2500	0.11	1.2506	0.16	1.2516	0.24
286K	1.2457	1.2514	0.46	1.2522	0.52	1.2518	0.49	1.2439	-0.14
571K	1.2498	1.2518	0.16	1.2513	0.12	1.2520	0.18	1.2534	0.29
3670K	1.2478	1.2520	0.34	1.2514	0.29	1.2507	0.23	1.2486	0.06
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SP. GR.	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE
0K	1.2497	1.2522	0.20	1.2466	-0.25	1.2533	0.29	1.2492	-0.04
143K	1.2489	1.2516	0.22	1.2472	-0.14	1.2546	0.46	1.2565	0.61
286K	1.2478	1.2520	0.34	1.2514	0.29	1.2544	0.53	1.2561	0.67
571K	1.2499	1.2531	0.26	1.2532	0.26	1.2545	0.37	1.2578	0.63
3670K	1.2507	1.2524	0.14	1.2529	0.18	1.2525	0.14	1.2499	-0.06
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SP. GR.	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE	SP. GR.	% CHANGE
0K	1.2487	1.2510	0.18	1.2526	0.31	1.2536	0.39	1.2521	0.27
143K	1.2502	1.2526	0.19	1.2535	0.26	1.2546	0.35	1.2540	0.30
286K	1.2503	1.2513	0.08	1.2522	0.15	1.2556	0.42	1.2529	0.21
571K	1.2491	1.2536	0.36	1.2543	0.42	1.2550	0.47	1.2590	0.79
3670K	1.2480	1.2551	0.57	1.2546	0.53	1.2547	0.54	1.2530	0.40

APPENDIX C
EPDM Mass Data

MASS (g) AND % CHANGE: EPDM

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	7.5433	7.5433	0.00	7.5432	0.00	7.5459	0.03	7.5543	0.15
143K	7.4999	7.5084	0.11	7.5084	0.11	7.5097	0.13	7.5172	0.23
286K	7.7003	7.7011	0.01	7.7010	0.01	7.7022	0.02	7.7102	0.13
571K	7.4268	7.4360	0.12	7.4362	0.13	7.4380	0.15	7.4447	0.24
3670K	7.5181	7.5187	0.01	7.5195	0.02	7.5222	0.05	7.5309	0.17
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	7.5613	7.5663	0.07	7.5737	0.16	7.5785	0.23	7.5853	0.32
143K	7.4642	7.4767	0.17	7.4788	0.20	7.4807	0.22	7.4919	0.37
286K	7.4769	7.4897	0.17	7.4887	0.16	7.4936	0.22	7.5048	0.37
571K	7.7076	7.7200	0.16	7.7231	0.20	7.7253	0.23	7.7370	0.38
3670K	7.7965	7.8051	0.11	7.8089	0.16	7.8152	0.24	7.8311	0.44
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	7.5015	7.5107	0.12	7.5020	0.01	7.5213	0.26	7.5354	0.45
143K	7.5718	7.5922	0.27	7.5947	0.30	7.5976	0.34	7.6153	0.57
286K	7.5439	7.5543	0.14	7.5567	0.17	7.5588	0.20	7.5757	0.42
571K	7.5590	7.5743	0.20	7.5786	0.26	7.5810	0.29	7.5995	0.54
3670K	7.6194	7.6251	0.07	7.6316	0.16	7.6352	0.21	7.6579	0.51

APPENDIX D
EPDM Dimensional Data

VOLUME (mm^3) AND % CHANGE: EPDM

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	6061	6050	-0.18	6060	-0.02	6055	-0.10	6051	-0.16
143K	6031	6028	-0.05	6006	-0.41	6009	-0.36	6020	-0.18
286K	6203	6204	0.02	6170	-0.53	6176	-0.44	6193	-0.16
571K	5976	5945	-0.52	5969	-0.12	5962	-0.23	5958	-0.30
3670K	6044	6032	-0.20	6032	-0.20	6034	-0.17	6031	-0.22
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	6087	6070	-0.28	6083	-0.07	6090	0.05	6070	-0.28
143K	5997	6002	0.08	5990	-0.12	5972	-0.42	5981	-0.27
286K	6007	6018	0.18	6018	0.18	5987	-0.33	5995	-0.20
571K	6193	6174	-0.31	6196	0.05	6186	-0.11	6180	-0.21
3670K	6261	6259	-0.03	6248	-0.21	6269	0.13	6261	0.00
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	6027	6012	-0.25	6032	0.08	6026	-0.02	6019	-0.13
143K	6080	6084	0.07	6087	0.12	6066	-0.23	6082	0.03
286K	6065	6063	-0.03	6053	-0.20	6023	-0.69	6047	-0.30
571K	6058	6051	-0.12	6065	0.12	6045	-0.21	6051	-0.12
3670K	6116	6115	-0.02	6111	-0.08	6113	-0.05	6106	-0.16

LENGTH (mm) AND % CHANGE: EPDM

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	76.01	75.98	-0.04	75.97	-0.05	75.93	-0.11	75.93	-0.11
143K	76.06	76.07	0.01	76.05	-0.01	76.05	-0.01	76.04	-0.03
286K	76.04	76.02	-0.03	76.00	-0.05	76.00	-0.05	76.02	-0.03
571K	76.01	75.99	-0.03	76.02	0.01	76.00	-0.01	76.01	0.00
3670K	76.04	75.99	-0.07	76.03	-0.01	75.99	-0.07	75.98	-0.08
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	76.04	76.02	-0.03	76.02	-0.03	76.00	-0.05	75.95	-0.12
143K	76.04	76.03	-0.01	76.01	-0.04	76.00	-0.05	76.00	-0.05
286K	76.10	76.08	-0.03	76.07	-0.04	76.02	-0.11	76.01	-0.12
571K	76.07	75.93	-0.18	76.05	-0.03	76.00	-0.09	75.89	-0.24
3670K	76.06	75.97	-0.12	75.97	-0.12	76.01	-0.07	75.93	-0.17
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	76.05	76.04	-0.01	76.06	0.01	76.06	0.01	76.01	-0.05
143K	76.06	76.06	0.00	76.07	0.01	76.04	-0.03	76.02	-0.05
286K	76.05	76.03	-0.03	76.03	-0.03	76.00	-0.07	76.00	-0.07
571K	76.03	75.96	-0.09	75.99	-0.05	75.84	-0.25	75.91	-0.16
3670K	75.99	75.84	-0.20	75.86	-0.17	75.83	-0.21	75.79	-0.26

APPENDIX D (cont.)
EPDM Dimensional Data

WIDTH (mm) AND % CHANGE: EPDM

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.33	25.32	-0.04	25.33	0.00	25.34	0.04	25.29	-0.16
143K	25.37	25.36	-0.04	25.33	-0.16	25.33	-0.16	25.34	-0.12
286K	25.40	25.40	0.00	25.34	-0.24	25.34	-0.24	25.36	-0.16
571K	25.36	25.34	-0.08	25.35	-0.04	25.34	-0.08	25.32	-0.16
3670K	25.34	25.31	-0.12	25.31	-0.12	25.30	-0.16	25.30	-0.16
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.38	25.37	-0.04	25.38	0.00	25.37	-0.04	25.32	-0.24
143K	25.37	25.37	0.00	25.35	-0.08	25.33	-0.16	25.32	-0.20
286K	25.33	25.33	0.00	25.33	0.00	25.29	-0.16	25.31	-0.08
571K	25.37	25.36	-0.04	25.35	-0.08	25.34	-0.12	25.35	-0.08
3670K	25.35	25.36	0.04	25.34	-0.04	25.34	-0.04	25.34	-0.04
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.34	25.37	0.12	25.36	0.08	25.34	0.00	25.30	-0.16
143K	25.35	25.33	-0.08	25.33	-0.08	25.33	-0.08	25.35	0.00
286K	25.35	25.33	-0.08	25.31	-0.16	25.25	-0.39	25.32	-0.12
571K	25.34	25.34	0.00	25.33	-0.04	25.32	-0.08	25.31	-0.12
3670K	25.33	25.36	0.12	25.35	0.08	25.32	-0.04	25.29	-0.16

THICKNESS (mm) AND % CHANGE: EPDM

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	THICKNESS	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
0K	3.15	3.14	-0.32	3.15	0.00	3.15	0.00	3.15	0.00
143K	3.13	3.13	0.00	3.12	-0.32	3.12	-0.32	3.12	-0.32
286K	3.21	3.21	0.00	3.20	-0.31	3.21	0.00	3.21	0.00
571K	3.10	3.09	-0.32	3.10	0.00	3.10	0.00	3.10	0.00
3670K	3.14	3.14	0.00	3.13	-0.32	3.14	0.00	3.14	0.00
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	THICKNESS	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
0K	3.15	3.15	0.00	3.15	0.00	3.16	0.32	3.16	0.32
143K	3.11	3.11	0.00	3.11	0.00	3.1	-0.32	3.11	0.00
286K	3.12	3.12	0.00	3.12	0.00	3.11	-0.32	3.12	0.00
571K	3.21	3.21	0.00	3.21	0.00	3.21	0.00	3.21	0.00
3670K	3.25	3.25	0.00	3.25	0.00	3.25	0.00	3.25	0.00
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	THICKNESS	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
0K	3.13	3.12	-0.32	3.13	0.00	3.13	0.00	3.13	0.00
143K	3.15	3.16	0.32	3.16	0.32	3.15	0.00	3.16	0.32
286K	3.15	3.15	0.00	3.15	0.00	3.14	-0.32	3.14	-0.32
571K	3.14	3.14	0.00	3.15	0.32	3.15	0.32	3.15	0.32
3670K	3.18	3.18	0.00	3.18	0.00	3.18	0.00	3.19	0.31

APPENDIX E
EPDM Hardness Data

AVERAGE HARDNESS (Type A) AND % CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	76.6	76.8	0.3	76.5	-0.1	76.3	-0.4	75.4	-1.6
143K	76.3	75.8	-0.7	76.0	-0.4	75.8	-0.7	75.2	-1.4
286K	76.4	75.9	-0.7	76.0	-0.5	76.0	-0.5	75.6	-1.0
571K	76.8	77.3	0.7	76.6	-0.3	76.7	-0.1	76.0	-1.0
3670K	76.8	76.9	0.1	76.8	0.0	76.5	-0.4	75.4	-1.8
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	76.5	76.3	-0.3	76.2	-0.4	76.1	-0.5	75.5	-1.3
143K	76.5	75.6	-1.2	75.8	-0.9	75.5	-1.3	75.5	-1.3
286K	76.4	75.6	-1.0	75.6	-1.0	75.2	-1.6	75.6	-1.0
571K	76.1	75.6	-0.7	75.1	-1.3	75.1	-1.3	75.3	-1.1
3670K	76.4	76.4	0.0	76.6	0.3	76.4	0.0	75.1	-1.7
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	76.3	76.3	0.0	75.8	-0.7	76.0	-0.4	75.5	-1.0
143K	76.1	75.9	-0.3	75.8	-0.4	75.4	-0.9	75.7	-0.5
286K	75.7	75.0	-0.9	74.9	-1.1	74.7	-1.3	75.3	-0.5
571K	76.2	76.0	-0.3	75.3	-1.2	75.5	-0.9	75.7	-0.7
3670K	76.0	76.1	0.1	75.9	-0.1	75.4	-0.8	75.4	-0.8

APPENDIX F
EPDM Compression Set Data

COMPRESSION SET (SET, %) AND CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	9.57	9.09	-0.48	11.37	1.80	11.32	1.75	11.22	1.65
143K	9.57	6.94	-2.63	9.39	-0.18	8.80	-0.77	7.83	-1.74
286K	9.57	7.21	-2.36	7.73	-1.84	5.94	-3.63	8.18	-1.39
571K	9.57	5.71	-3.86	9.72	0.15	8.67	-0.90	8.91	-0.66
3670K	9.57	9.52	-0.05	10.20	0.63	8.47	-1.10	9.85	0.28
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	9.57	10.73	1.16	13.62	4.05	12.56	2.99	12.62	3.05
143K	9.57	8.26	-1.31	12.73	3.16	10.86	1.29	9.46	-0.11
286K	9.57	7.80	-1.77	12.17	2.60	9.61	0.04	9.65	0.08
571K	9.57	8.33	-1.24	10.90	1.33	10.48	0.91	10.75	1.18
3670K	9.57	11.70	2.13	11.83	2.26	10.50	0.93	12.23	2.66
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	9.57	13.43	3.86	13.27	3.70	12.38	2.81	12.09	2.52
143K	9.57	8.44	-1.13	13.00	3.43	10.57	1.00	10.57	1.00
286K	9.57	7.77	-1.80	12.00	2.43	9.43	-0.14	9.59	0.02
571K	9.57	7.98	-1.59	11.11	1.54	11.06	1.49	11.50	1.93
3670K	9.57	11.23	1.66	12.43	2.86	11.70	2.13	12.56	2.99
18 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
143K	9.57	8.84	-0.73	8.80	-0.77	10.19	0.62	9.86	0.29
286K	9.57	7.05	-2.52	8.81	-0.76	9.17	-0.40	8.73	-0.84
571K	9.57	6.10	-3.47	10.14	0.57	6.93	-2.64	10.65	1.08
3670K	9.57	9.90	0.33	10.73	1.16	9.64	0.07	9.80	0.23
50 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
143K	9.57	9.55	-0.02	10.00	0.43	11.21	1.64	8.18	-1.39
286K	9.57	8.73	-0.84	10.04	0.47	9.61	0.04	8.42	-1.15
571K	9.57	8.17	-1.40	10.63	1.06	10.61	1.04	7.92	-1.65
3670K	9.57	9.74	0.17	10.87	1.30	10.44	0.87	9.85	0.28
60 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
143K	9.57	8.97	-0.60	10.71	1.14	11.06	1.49	8.89	-0.68
286K	9.57	9.01	-0.56	8.85	-0.72	10.50	0.93	8.76	-0.81
571K	9.57	7.58	-1.99	10.84	1.27	10.75	1.18	7.62	-1.95
3670K	9.57	10.99	1.42	12.43	2.86	10.93	1.36	9.81	0.24

APPENDIX G
EPDM Vapor Transport Rate Data

VAPOR TRANSMISSION RATE (g/hr/m²): EPDM				
18 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
OK	0.2666	0.2429	0.1780	0.0776
143K	0.0474	0.0359	0.0264	0.0169
286K	0.1746	0.1049	0.0619	0.0262
571K	0.2152	0.1265	0.0748	0.0166
3670K	0.0514	0.0298	0.0156	0.0035
50 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
OK	0.4574	0.3167	0.2033	0.0982
143K	0.0076	0.0099	0.0110	0.0182
286K	0.5917	0.4522	0.3479	0.0900
571K	0.4263	0.3553	0.2166	0.0821
3670K	0.1611	0.1123	0.0660	0.0801
60 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
OK	0.5671	0.3817	0.2971	0.1526
143K	0.2328	0.1714	0.2977	0.0868
286K	0.0217	0.0223	0.0294	0.0558
571K	0.4047	0.2341	0.1242	0.1349
3670K	0.0257	0.0616	0.0558	0.1577

APPENDIX H
EPDM Tensile Strength Data

TENSILE STRENGTH (TENS. STR., MPa) AND % CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
0K	12.5	12.5	0.0	12.1	-3.3	12.4	-0.6	13.6	8.8
143K	12.5	13.0	3.9	12.7	1.7	12.3	-1.7	12.8	2.8
286K	12.5	12.6	1.1	12.9	3.3	12.4	-0.6	12.8	2.2
571K	12.5	13.1	5.0	12.4	-0.6	12.2	-2.2	12.7	1.7
3670K	12.5	12.7	1.7	11.9	-5.0	12.0	-3.9	12.1	-2.8
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
0K	12.5	11.9	-4.4	12.2	-2.2	11.9	-4.4	13.0	3.9
143K	12.5	13.1	5.0	13.2	6.1	12.5	0.0	13.0	3.9
286K	12.5	12.8	2.8	13.0	4.4	12.6	1.1	12.7	1.7
571K	12.5	12.7	1.7	12.9	3.3	12.4	-0.6	12.5	0.0
3670K	12.5	12.6	1.1	12.1	-3.3	12.0	-3.9	11.9	-4.4
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
0K	12.5	11.8	-5.5	12.1	-2.8	12.2	-2.2	12.6	1.1
143K	12.5	12.9	3.3	13.0	3.9	13.0	4.4	13.0	3.9
286K	12.5	13.0	3.9	13.1	5.0	12.8	2.2	12.6	1.1
571K	12.5	12.4	-0.6	12.8	2.8	11.9	-5.0	12.4	-0.6
3670K	12.5	12.5	0.6	12.2	-2.2	11.7	-6.1	11.9	-5.0
18 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
143K	12.5	13.2	6.1	11.9	-5.0	13.1	5.0	12.6	1.1
286K	12.5	12.5	0.6	12.7	1.7	12.1	-2.8	12.9	3.3
571K	12.5	12.5	0.0	12.3	-1.7	12.8	2.8	12.5	0.6
3670K	12.5	13.0	3.9	12.1	-2.8	12.0	-3.9	12.8	2.8
50 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
143K	12.5	12.3	-1.1	11.7	-6.1	12.8	2.8	12.6	1.1
286K	12.5	12.6	1.1	12.6	1.1	12.2	-1.9	12.8	2.2
571K	12.5	12.5	0.6	12.6	1.1	12.3	-1.7	11.9	-5.0
3670K	12.5	12.7	1.7	12.0	-3.9	11.8	-5.5	12.0	-3.9
60 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	TENS. STR.	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE	TENS. STR.	% CHANGE
143K	12.5	12.6	1.1	11.2	-9.9	12.4	-0.6	12.1	-2.8
286K	12.5	11.8	-5.5	12.0	-3.9	12.3	-1.7	13.2	5.5
571K	12.5	12.0	-3.9	11.4	-8.8	12.6	1.1	13.2	5.5
3670K	12.5	11.9	-4.4	10.4	-16.9	11.2	-9.9	11.6	-7.2

APPENDIX I
EPDM Ultimate Elongation Data

ULTIMATE ELONGATION (ELONG., %) AND CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	164	157	-7	159	-5	148	-16	159	-5
143K	164	171	7	177	13	161	-3	170	6
286K	164	163	-1	164	0	156	-8	162	-2
571K	164	155	-9	153	-11	151	-13	158	-6
3670K	164	146	-18	150	-14	133	-31	148	-16
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	164	165	1	159	-5	158	-6	170	6
143K	164	162	-2	175	11	156	-8	166	2
286K	164	189	25	198	34	189	25	169	5
571K	164	162	-2	154	-10	158	-6	151	-13
3670K	164	144	-20	141	-23	136	-28	143	-21
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	164	174	10	168	4	162	-2	162	-2
143K	164	164	0	155	-9	162	-2	163	-1
286K	164	153	-11	158	-6	199	35	170	6
571K	164	154	-10	145	-19	144	-20	148	-16
3670K	164	153	-11	144	-20	145	-19	140	-24
18 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
143K	164	164	0	170	6	160	-4	157	-7
286K	164	210	46	194	30	172	8	156	-8
571K	164	151	-13	154	-10	159	-5	160	-4
3670K	164	158	-6	158	-6	145	-19	153	-11
50 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
143K	164	151	-13	159	-5	151	-13	143	-21
286K	164	156	-8	150	-14	154	-10	154	-10
571K	164	158	-6	156	-8	166	2	169	5
3670K	164	157	-7	175	11	154	-10	155	-9
60 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
143K	164	151	-13	158	-6	154	-10	141	-23
286K	164	146	-18	150	-14	149	-15	155	-9
571K	164	147	-17	153	-11	151	-13	154	-10
3670K	164	141	-23	162	-2	141	-23	138	-26

APPENDIX J
EPDM Tensile Stress Data

TENSILE STRESS (STRESS,MPa) AND % CHANGE: EPDM									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	7.45	7.58	1.85	8.41	13.0	8.48	13.9	8.41	13.0
143K	7.45	7.65	2.78	7.17	-3.70	7.79	4.63	7.58	1.85
286K	7.45	7.93	6.48	8.00	7.41	8.27	11.1	8.07	8.33
571K	7.45	8.62	15.7	8.62	15.7	8.27	11.1	8.21	10.2
3670K	7.45	8.83	18.5	6.38	-14.3	9.03	21.3	8.48	13.9
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	7.45	6.62	-11.1	7.58	1.85	7.38	-0.93	8.07	8.33
143K	7.45	7.86	5.56	6.87	-7.69	8.21	10.2	8.14	9.26
286K	7.45	6.64	-10.8	6.70	-10.0	6.65	-10.6	7.45	0.00
571K	7.45	8.07	8.33	8.55	14.8	8.00	7.41	8.55	14.8
3670K	7.45	8.83	18.5	8.07	8.33	8.62	15.7	8.69	16.7
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	7.45	7.65	2.78	7.58	1.85	7.65	2.78	7.93	6.48
143K	7.45	8.07	8.33	7.72	3.70	8.27	11.1	8.34	12.0
286K	7.45	8.48	13.9	8.34	12.0	6.63	-10.9	7.79	4.63
571K	7.45	8.21	10.2	8.21	10.2	8.41	13.0	8.69	16.7
3670K	7.45	8.48	13.9	7.86	5.56	8.27	11.1	8.48	13.9
18 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
143K	7.45	8.27	11.1	7.86	5.56	8.41	13.0	8.27	11.1
286K	7.45	6.20	-16.8	6.70	-10.0	7.72	3.70	8.48	13.9
571K	7.45	8.69	16.7	8.27	11.1	8.34	12.0	8.14	9.26
3670K	7.45	8.62	15.7	9.03	21.3	8.34	12.0	8.69	16.7
50 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
143K	7.45	8.55	14.8	8.69	16.7	8.96	20.4	8.83	18.5
286K	7.45	8.34	12.0	8.69	16.7	8.89	19.4	8.55	14.8
571K	7.45	8.07	8.33	8.21	10.2	7.86	5.56	7.58	1.85
3670K	7.45	7.72	3.70	6.60	-11.4	7.79	4.63	7.79	4.63
60 C, RAD ONLY	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
143K	7.45	8.69	16.7	8.14	9.26	8.41	13.0	8.83	18.5
286K	7.45	8.41	13.0	8.48	13.9	8.41	13.0	8.69	16.7
571K	7.45	8.41	13.0	8.14	9.26	8.48	13.9	8.96	20.4
3670K	7.45	8.76	17.6	7.65	2.78	8.41	13.0	8.69	16.7

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