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Comprehensive Testing to Measure the Response of Butyl Rubber to Hanford Tank Waste Simulant

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Comprehensive Testing to Measure the Response of Butyl Rubber to Hanford Tank Waste Simulant

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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. Butyl 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. From the analyses, we determined that butyl rubber has relatively good resistance to radiation, this simulant, and a combination of these factors. These results suggest that butyl rubber is a relatively good 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 rubber (SBR)

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 FKM rubber 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 Sandia National Laboratories. 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.

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 EPDM rubber, this second-phase study involved the comprehensive testing of butyl 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 butyl 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 butyl rubber 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 butyl 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.

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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, butyl rubber, is an elastomer with known chemical resistance to hydraulic fluids, silicone fluids, and ketones. Butyl rubber is made by co-polymerizing isobutylene and just enough isoprene to obtain the desired degree of unsaturation necessary for vulcanization. Appendix A provides additional information on this material including its initial properties.

Simulant Preparation

The simulant mixed waste form used in this testing phase was an aqueous alkaline Hanford tank waste simulant. It was prepared by dissolving 179 g (2.10 moles) of sodium nitrate and 50 g (0.73 moles) sodium nitrite in deionized water (600 mL) using a 4-L beaker. After these salts had completely dissolved, 82 g (2.05 moles) of sodium hydroxide were stirred into the solution and slightly heated with a magnetic hotplate (Corning, Model PC-320). To this hot (~70°C), stirred solution, 17 g (0.107 moles) cesium chloride and 16 g (0.0952) 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 deionized 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). It should be mentioned that the procedure described above was scaled up threefold to give 3-L batches of the simulant. All chemicals used in the preparation of the waste simulant were American Chemical Society reagent grade chemicals. The above composition produced a mixture with 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 discs (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 discs (2.69″ diameter × 0.125″ thick, 6.83 cm diameter × 0.318 cm thick) required for VTR measurements were cut in the expulsion press fitted with an expulsion die (Part #23-00-00) specifically designed for the American Society for Testing and Materials ASTM D 814 standard testing method.[11] 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 D 412-Method A.[12]

The use of a press and dies permitted the cutting of multiple samples having uniform dimensions. For identification of samples, an identification code was developed to uniquely indicate the test type, sample number, and testing conditions. The black butyl 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 and separated from each other with ~1/16″ (~0.16 cm) thick metal pins. The required number of samples for each test was bundled together using plastic cable ties by procedures described in a subsequent section.

Sample Quantities

Some butyl rubber samples were exposed to gamma radiation alone, some to the simulant (chemicals) alone, and some 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 butyl rubber, 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 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 for these two measurements. In view of the perceived effect of radiation on compression set and tensile property measurements, the material properties of butyl rubber 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 0 krad samples (0K in the appendices) in subsequent discussions, were required for each of the seven measurements. For specific gravity and hardness measurements, a total of 12 samples was 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, a total of 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 the specific gravity and hardness measurements. 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 reused 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 butyl rubber samples were used to perform the various measurements.

Sample Irradiation

The elastomer samples were irradiated by an underwater ^{60}Co gamma source at SNL/NM. These samples were loaded into a metal basket in the same configuration that was used to condition the samples (i.e., the samples were stacked 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 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 when 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 butyl 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 7-1/2″ (19 cm) nylon cable ties. Within each bundle, the specimens were separated by ~1/16″ (0.16 cm) metal pins used as spacers. This allowed the waste of simulant ready access 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 (i.e., 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 butyl rubber discs were loosely attached to the jars with metal bands. The jars were placed in an upright configuration (butyl 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 them, the jars were placed in the chambers again in an inverted position and held at the specific test temperature for the required time period.

Experimental Approach

The material properties that should be evaluated to assess the suitability of potential elastomeric materials in mixed waste packaging designs are specific gravity changes, dimensional changes (including mass and dimensional measurements), hardness, compression set, VTR, and tensile property changes (tensile strength, tensile stress, and ultimate elongation). Since measuring all the 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. It is generally recognized that polymeric materials are susceptible to degradation due to high temperature and high radiation doses. The results of these screening studies have been previously at several technical conferences,[2,6] and in a SAND Report.[7] From the screening study it was found that all of the selected seal materials had passed the screening criteria in the aqueous simulant mixed waste. This then 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 Comprehensive Testing Phase.

Because of budget constraints imposed on this program, testing was subdivided into comprehensive testing on liner materials and seal materials. The order of testing for the 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 was evaluated last. From the data given in a previously published SAND report,[7] 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 evaluated was EPDM rubber.[16] The next elastomer to be evaluated was butyl 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 of the seal materials. Tensile properties for elastomers included tensile strength, ultimate elongation, and tensile stress. These parameters were evaluated using standardized test methods 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, each of 0.125″ (3.17 mm) thickness were held at ambient temperature with a spacer bar thickness of 4.5 mm. For VTR measurements, ASTM D 814 was used, and, 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 butyl 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 at ambient laboratory 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" is shown in the flow diagram (Path D). These samples were irradiated at three temperatures, respectively, and then exposed for four time periods at the three respective temperatures. What may not appear obvious from the flow diagram is the large number of samples being tested in the comprehensive testing phase of the program. A total of 1,738 measurements on 913 samples were analyzed (Appendices B through J).

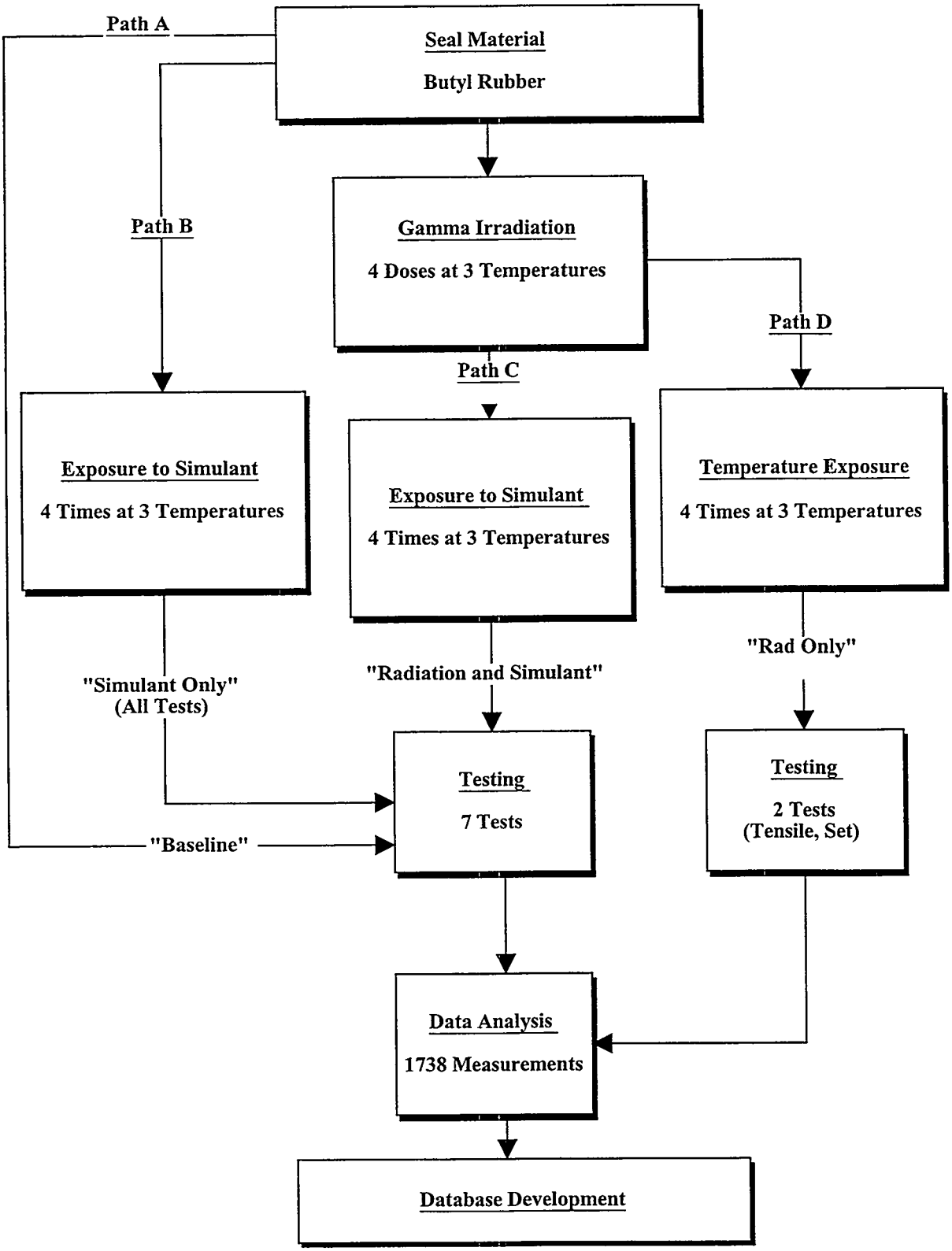


Figure 1. Comprehensive Seal Testing Strategy

RESULTS

Specific Gravity

Specific gravity measurements, also known as relative density measurements, measure the densities of materials that have been exposed to different conditions. A decrease in density of the material can indicate leaching or swelling, and 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 of the test liquid.

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

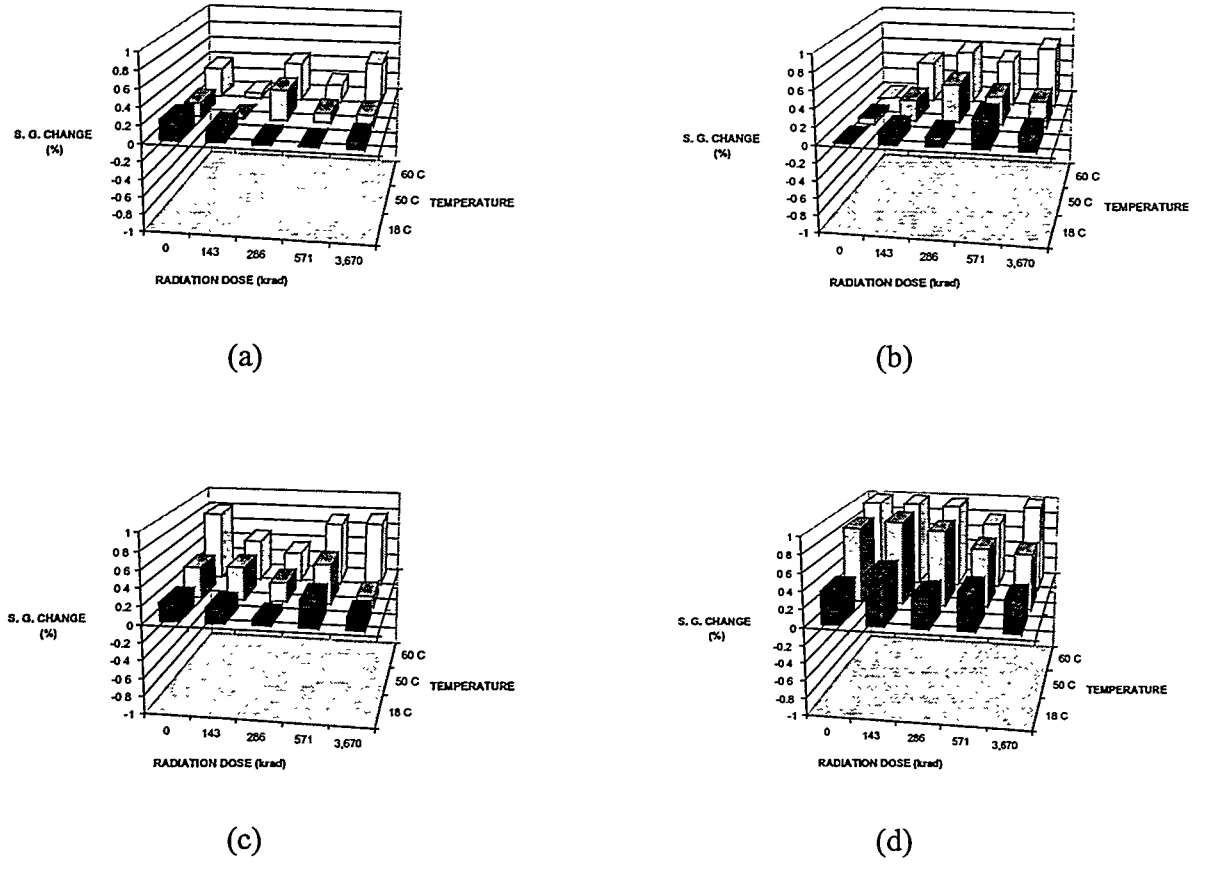


Figure 2. Specific gravity (S.G.) changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

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. Where the radiation dose is indicated as 0 krad, 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 the virgin material (i.e., the specific gravity of butyl rubber 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 the 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 the temperature of the simulant, the radiation dose, and the exposure time have effects on the specific gravity of butyl rubber. With increased temperatures and longer exposure times, increased specific gravity changes were observed. Radiation exposure appears not to exhibit a demonstrable effect on butyl rubber. However, since these changes are only at the 1% levels, the results are consistent with the known chemical resistance of this elastomer and demonstrate that butyl rubber is a suitable elastomer for use under these conditions, if specific gravity is the determining package design criterion. 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 of this report.

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

Dimensional Properties

Similar to specific gravity measurements, dimensional property measurements can provide important information about the effects of different environmental conditions on materials. Specifically, increases or decreases in the dimensions of the material may indicate material swelling or component leaching. The dimensional properties measured and reported in this section include changes in length, width, and thickness of the material. Since the standard test method ASTM D 543 is used to measure dimensional properties and includes the determination of mass as part of the test, mass was also measured. Dimensional changes are described by evaluating 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 environment conditions on the mass changes will be presented first.

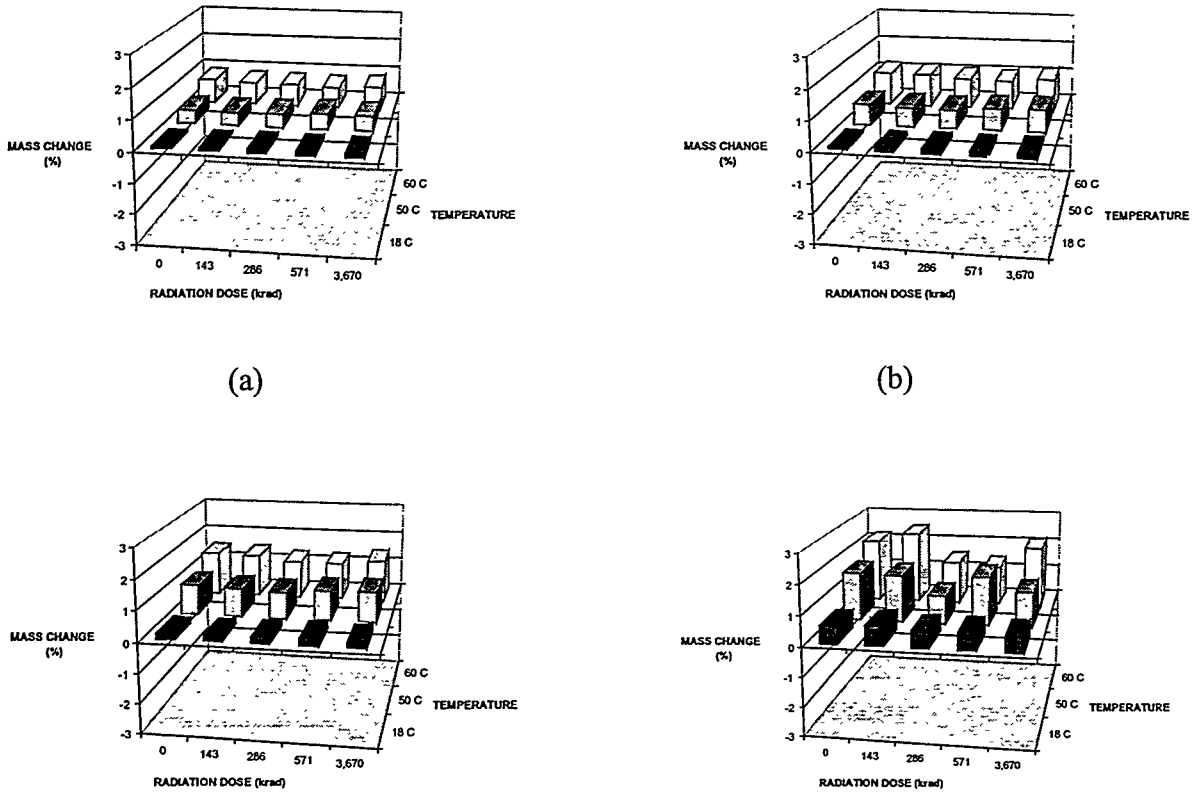


Figure 3. Mass changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on butyl rubber, 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 krad data field. Similar to data shown in the previous section, the scale for average % mass change is very small (e.g., from 0 to 3%). The sign of the mass changes indicates whether the mass of the material has increased or decreased when compared to the pristine materials (i.e., the material's mass at ambient conditions). Therefore, changes in the magnitude and the sign of % mass change values can vary 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). From an overall perspective, the data in Figure 3 show that temperature of the simulant and exposure time have some effect on the changes in mass of the material. For both of these environmental conditions, a slight but perceptible increase in mass was observed. After 180 day exposures, mass changes in excess of 1% were observed at 50 and 60°C. At higher temperatures,

the larger mass changes are observed. While the exact mass values are not obvious from the data in the previous figure, their precise values can be found in Appendix C of this report.

In Figure 4 (a)-(d), the average % volume changes of butyl rubber 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 are given. Butyl rubber had volume changes of less than ~1.4% under these conditions. In many cases the volume changes were even smaller (i.e., in the ~0.5% range). In certain instances, there were small negative volume changes, recognized by the darkly colored top surface of the bar graph. With increased exposure time and exposure temperature, there is a slight increase in the sample volume (i.e., butyl rubber appears to swell when exposed to these environmental conditions). A general trend suggests that with increasing exposure time most of the butyl rubber samples expanded. The greatest volume changes can be seen in Figure 4 (d), where butyl rubber exhibited the greatest changes in volume at 50 and 60°C. It should be noted, however, that these changes are only at the 1 - 1.5% level. While the exact volume values are not obvious from the data in the previous figure, their precise values can be found in Appendix D of this report.

Hardness Properties

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

A standard instrument manufactured by Shore Instrument Company, known as a Shore durometer, is used to measure hardness. The degree of hardness that the plastic material exhibits 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 (65 Shore A hardness points) were determined for pristine samples (i.e., samples not exposed to anything). Using these initial hardness values, % hardness changes were measured for samples exposed to the simulant alone (see 0 krad data field in Fig. 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. We will now present the results of these measurements.

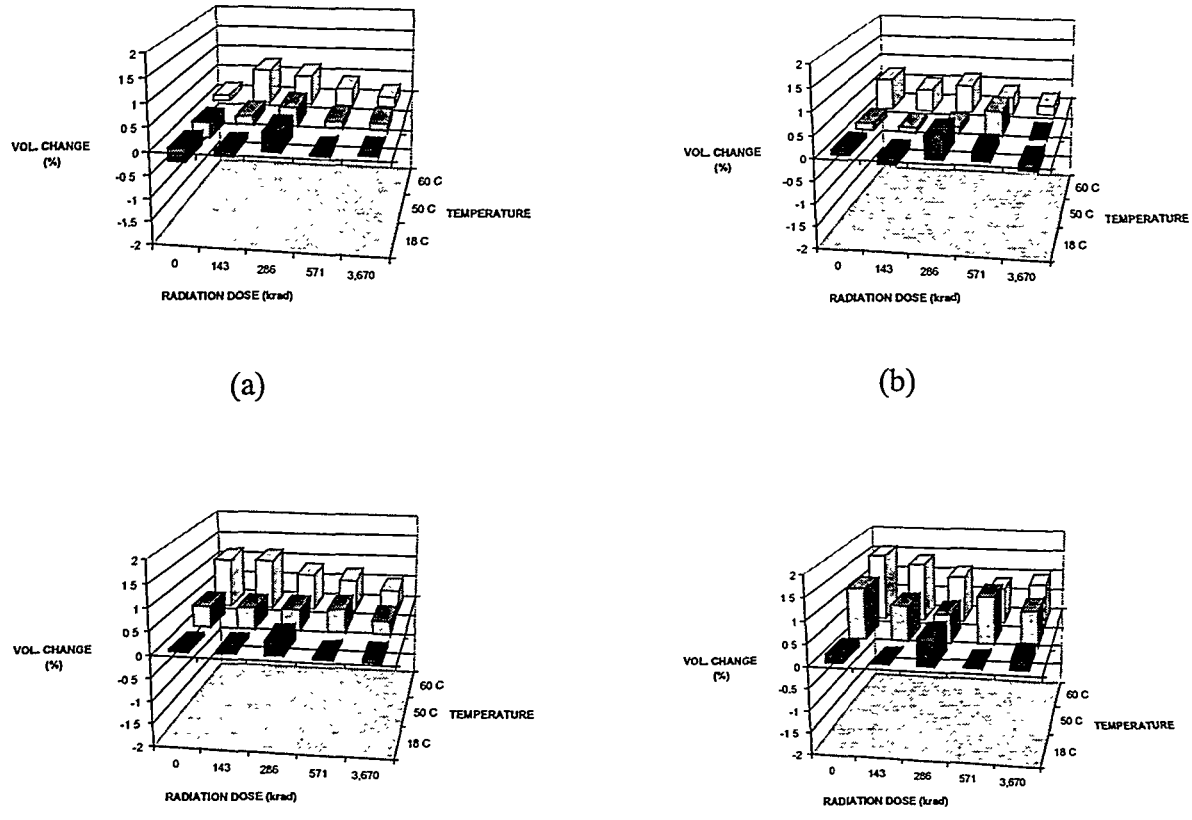


Figure 4. Volume (Vol.) changes in EPDM after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on butyl rubber, hardness testing was performed on the materials exposed only to the surrogate waste at the three temperatures and four time periods. The results are given in Figure 5 (a)-(d) below in the 0 krad data field. The sign of the hardness changes indicates whether the hardness of the material has increased or decreased when compared to 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 in Figures 5 (a)-(d), reveals that in general the hardness of butyl rubber decreases (i.e., becomes softer with increasing radiation dose, time and temperature of exposure to the simulant mixed waste). The decrease in hardness never exceeded 10.4%. The largest hardness change was observed in samples that received radiation doses of 3,670 krad and 7-day exposures to the 60°C simulant. After this relatively short exposure time, nearly all of the samples exhibited larger changes in hardness than was observed for the longer exposure times.

At the longest exposure times of 180 days, shown in Figure 5(d), a close inspection of the data revealed that many samples became harder, suggesting that prolonged exposure to this oxidizing simulant results in hardening butyl rubber. Since this hardening effect is shown most clearly in the samples that had been irradiated with a dose of 143 krad (Fig. 5d), the results suggest that low radiation dose and subsequent exposure to the simulant has a beneficial effect on retaining the hardness values of butyl rubber at these long exposure times. At the longest exposure time, highest radiation dose, and highest temperature, the hardness of butyl rubber is comparable (three points lower) to the pristine material. The results also suggest that exposure to a combination of high radiation dose and the aqueous simulant results in softening butyl rubber. Since increases in volume under these conditions (Figure 4) were observed, softening appears to be caused by swelling in the material. While the precise hardness values are not obvious from the data in the previous figure, precise values can be found in Appendix E of this report.

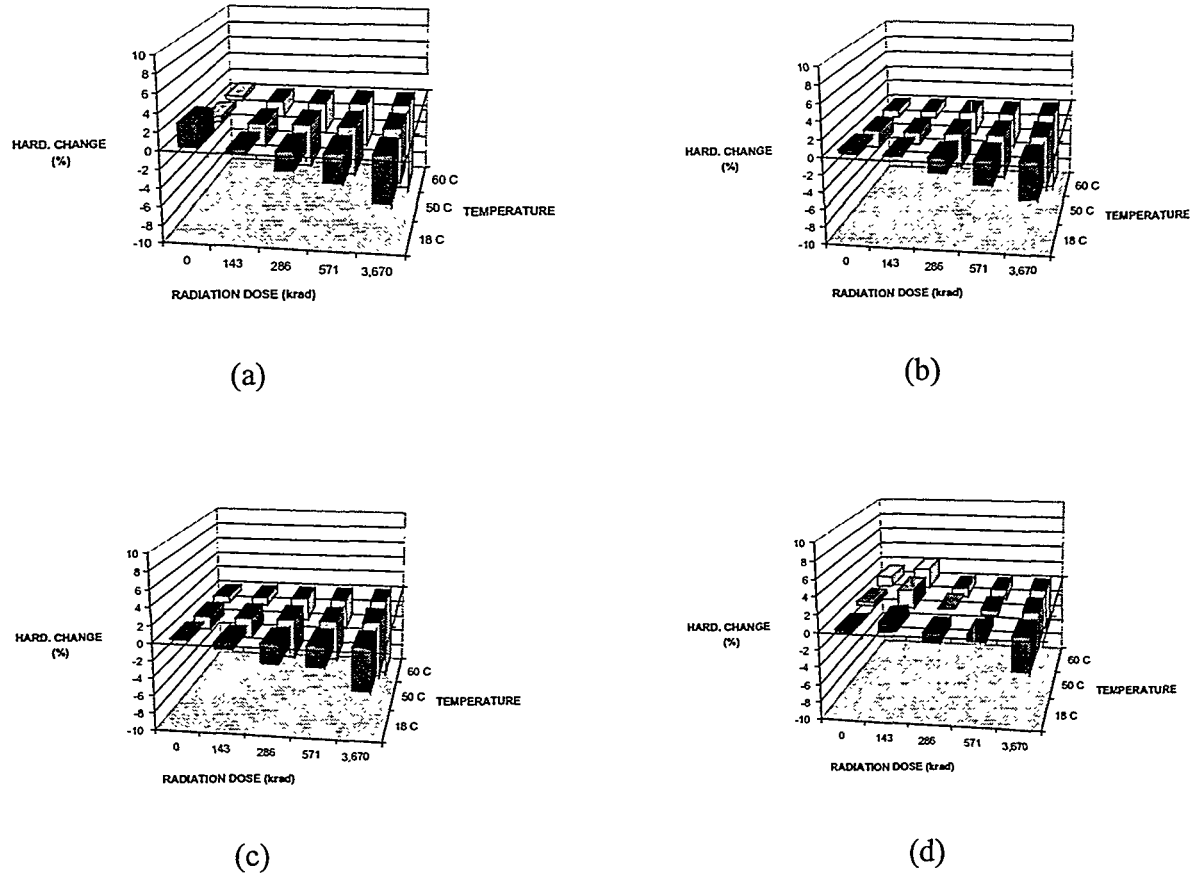
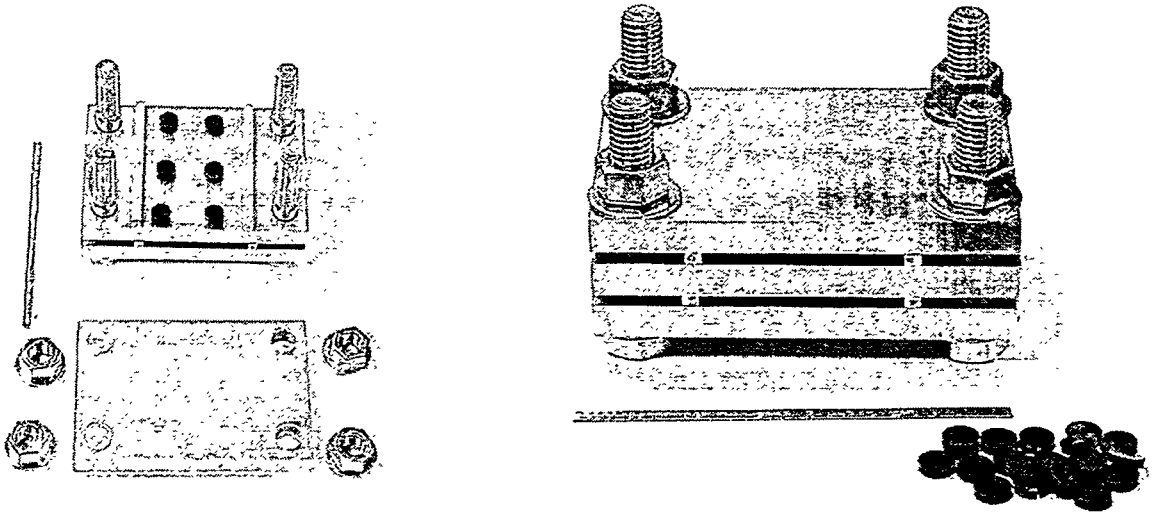


Figure 5. Hardness (Hard.) changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

Compression Set

Compression set tests are used to measure the ability of elastomers to retain elastic properties after the prolonged action of compressive stresses. Set 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%. When the elastomer does not return to its original thickness, but remains at the thickness under compression (in this case 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 since the elastomeric seal makes minimum contact with the sealing surface. Thus materials having a low set value are desirable. To measure Set, we have used standardized test method ASTM D 395. Using this method, the butyl rubber samples were held in the compression set device at room temperature (~23°C). Figure 6 shows an example of the experimental configuration used for the compression set tests.



7. (b)

Figure 6. Compression set fixture. (a) A partly assembled fixture with the 4.5 mm spacer bars and butyl rubber samples. (b) An assembled fixture with butyl rubber samples.

In order to understand effects of radiation alone on set values, a portion of the butyl rubber samples was 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. We will now proceed to discuss the results of these different measurements. It is important to mention that the results shown 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 butyl rubber samples. Because set values are expressed in percent, the change in set is the difference of these values in percent.

In Figure 7 (a)-(d), the set changes for butyl rubber samples exposed to four gamma ray doses followed by 7, 14, 28, and 180-day exposures at the three temperatures are provided. The data in Figure 7 represent a situation where butyl rubber has only been exposed to gamma radiation.

The important point to keep in mind for these measurements 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.

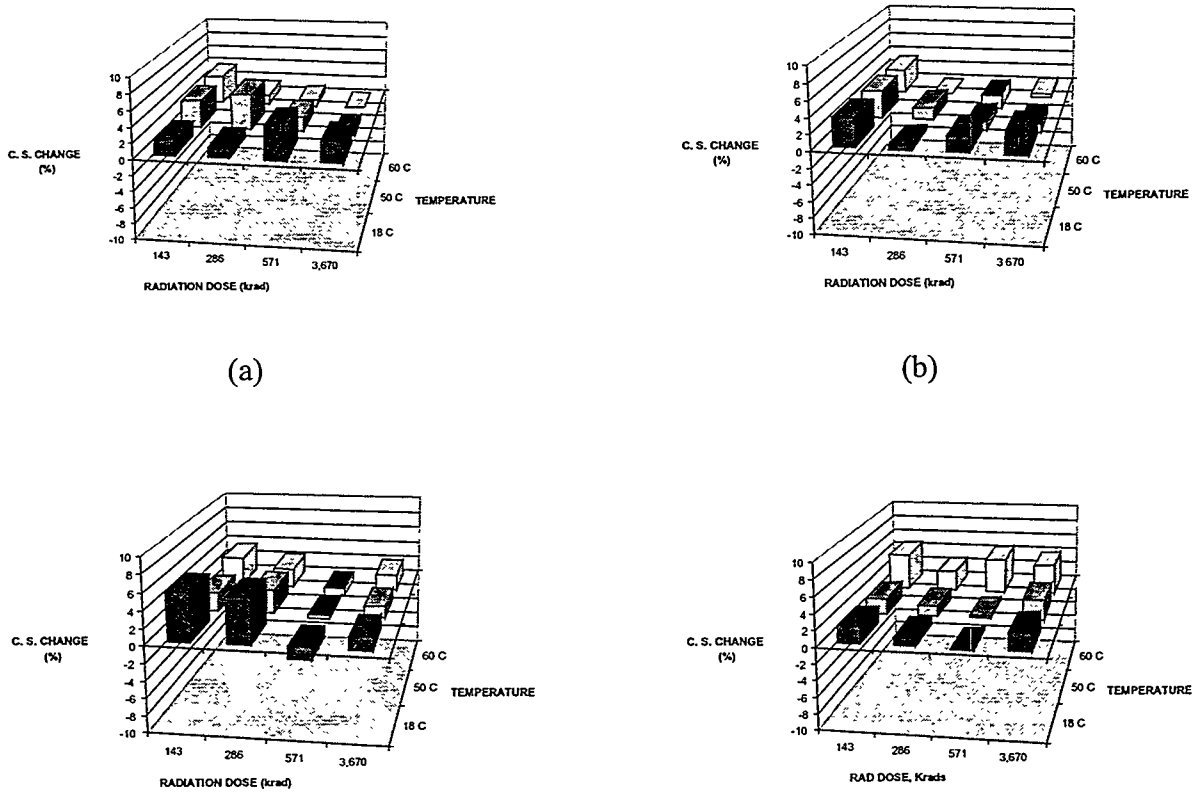


Figure 7. Compression set (C. S.) changes in butyl rubber after exposure to ~143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days , (c) 28 days, and (d) 180 days at 18, 50, and 60°C.

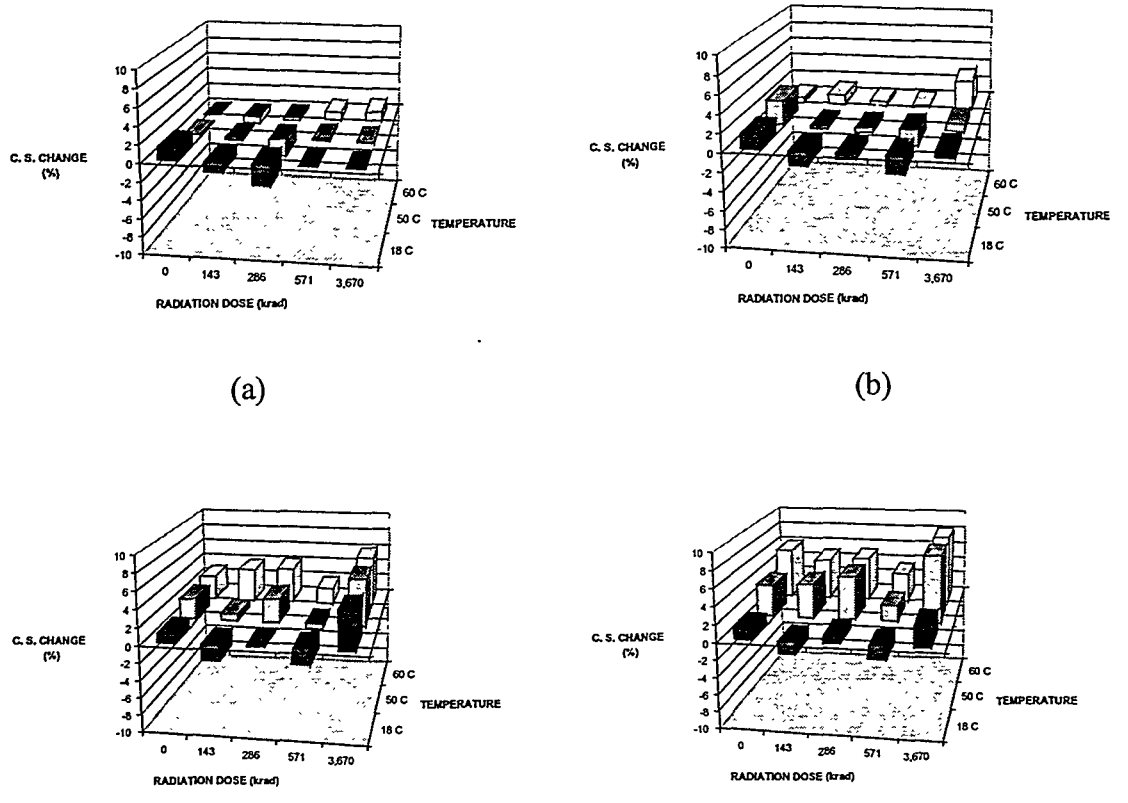


Figure 8. Compression set changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days (c), and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C, respectively.

The results show that while some samples exhibited an increase of the Set in the range of ~0 to 6%, some samples had decreases of the set in the range of ~0 to 2%. Decreases for changes in the set indicate that the samples after exposure to these environmental conditions had a smaller set than the unexposed samples (i.e., these samples were less deformed than the unexposed samples). Most of these decreases in Set were observed in samples with larger gamma radiation dose exposures and/or longer exposure times. However, no systematic trend was observed in samples exposed to increasing radiation doses, exposure time, and exposure temperatures. Results suggest that these set changes were within the experimental variability of the test results; although, an overall decrease in Set was detected with increasingly severe environmental conditions of dose, time, and temperature.

Figure 8 (a)-(d) shows, the Set changes for butyl rubber 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 changes exhibited by samples exposed to a combination of radiation and the aqueous simulant were similar (i.e., in the range of -2 to 8%). The Set in butyl rubber samples exposed to only the simulant (0 krad data) generally increased with increased temperature and increased exposure

time. The combination of radiation followed by exposure to the simulant had an adverse effect that resulted in higher compression sets (i.e., the samples became more deformed). The greatest retention of deformation was noted in samples exposed to 3,670 krad and the simulant for 28 and 180 days at 50 and 60°C.

To summarize, butyl rubber is not affected greatly by radiation, the simulant, or a combination of these two environmental conditions when exposure times were kept below 14 days. While the precise values are not clear from the data in the previous figure, these values can be found in Appendix F of this report.

Vapor Transport Rates (VTR)

VTR measurements provide a measure of the permeability of various chemical agents in 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 taken at three temperatures and four exposure times. In these experiments, one set of butyl rubber 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 used the standardized test method ASTM D 814. Using this method, the butyl rubber samples were sealed to a ground-glass surface with a metal screw band. It should be noted that VTR experiments performed with this method on butyl rubber samples exposed to only gamma radiation are not possible since the testing method requires the presence of a chemical agent. Figure 9 shows a set cells used for VTR measurements.

Figure 9. *Vapor transmission rate cells.*

For VTR measurements, it is not possible to describe these data in terms of VTR changes. The reason for this inability to determine VTR changes is that it is not possible to determine VTR on pristine butyl rubber. In other testing methods, 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 butyl rubber 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 butyl rubber (i.e., its initial value). In VTR measurements, however, a similar VTR value for pristine butyl rubber is not possible since its determination will require exposure to a simulant. However, one could show VTR changes between butyl rubber samples exposed to only the simulant and samples exposed to the combination of radiation and simulant. Because all the previously described measurements included data for butyl rubber samples exposed to the simulant alone, we retain this data format here. We will provide the actual VTR values, in g/hr/m^2, rather than changes in VTR. Figure 10 (a)-(d) shows VTR for butyl rubber 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 represents samples exposed only to the simulant for the four exposure times and temperatures. All samples 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 butyl rubber had the second lowest VTR in aqueous simulant Hanford tank wastes. It can also be seen that the VTR for butyl rubber samples generally increased with increased temperature and decreased with increasing exposure time. While the exact VTR values are not obvious from the data in the figure, their precise values are presented in Appendix G of this report.

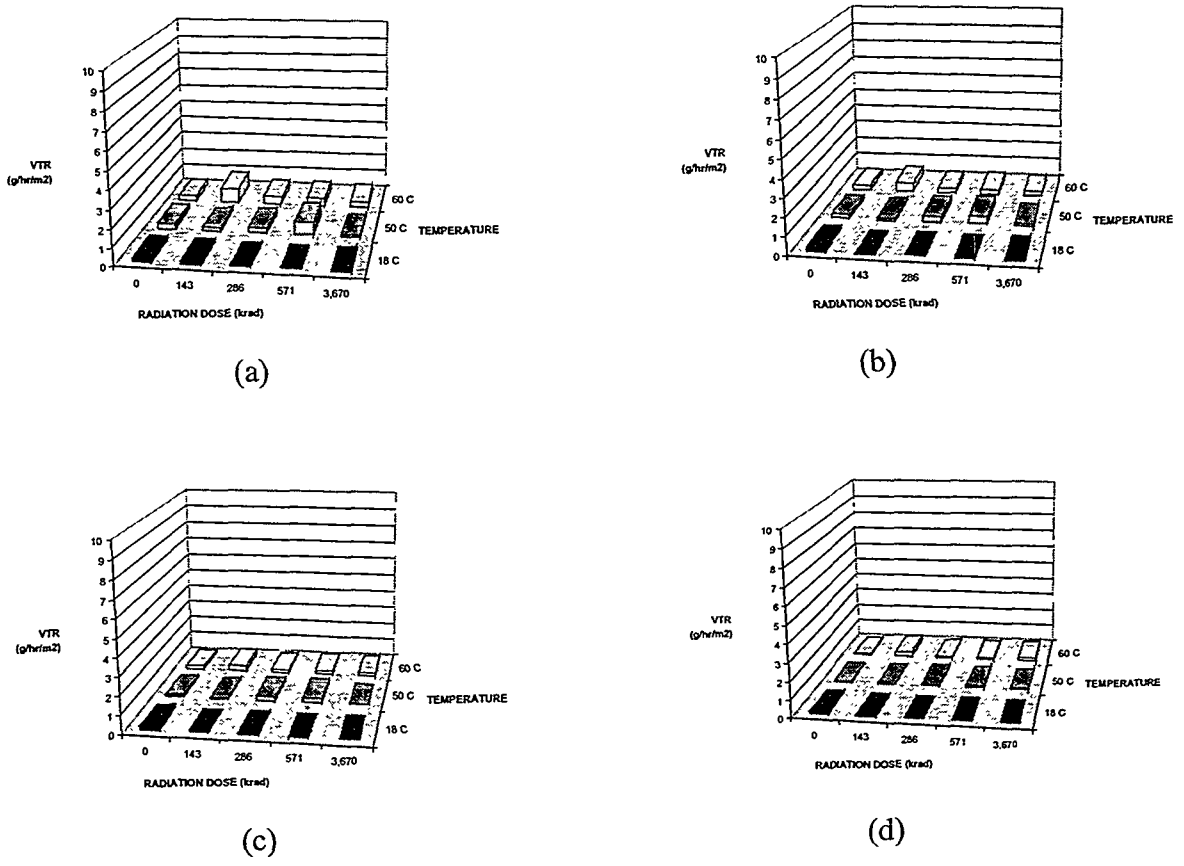


Figure 10. VTR for butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

Tensile Properties

Tensile properties, also known as mechanical properties, are the properties associated with a material's 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 at the time that the force (F) is applied. The most common engineering units of stress are pounds of 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 are always calculating the % changes in properties, the units are irrelevant. The actual values in mega pascal (MPa) are reported in Appendix.

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-in. 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 butyl rubber is a specific type of rubber, it exhibits the same 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, which might be suitable as packaging components such as seals and liners, high strengths and high strains are expected. The strains exhibited should also be elastic in nature. In certain instances, however, other specific tensile properties are desirable (i.e., high strength and low strain). It was the purpose of this study to determine 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 butyl rubber.

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 methods. These methods prescribe strain rates, breaking points, and many other experimentally important variables. The selection of these experimental variables was based on standard test method ASTM D 412. 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 that calculates numerous tensile properties and that was developed by the same manufacturer. The data discussed in this subsection required a determination of tensile strength calculated as described previously, using peak loads and a cross-sectional area. In addition, the software also calculated 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 are provided in Figure 11. In Figure 11(a)-(d), the average % tensile strength changes of butyl rubber exposed to gamma radiation alone at 18, 50, and 60°C for 7, 14, 28, and 180 days are shown. Similar to previous property measurements, these % changes were determined by measuring the change in tensile strength from that of the pristine material (11.9 MPa). When the change in tensile strength (expressed as

a percentage) is a positive value, the material tensile strength had increased under the specific exposure conditions. Negative values indicate decreases in tensile strength.

From a general perspective, Figure 11 shows no significant effect on tensile strength for most radiation doses, exposure times, and exposure temperatures tested. An exception is butyl rubber samples exposed to 3,670 krad and higher temperatures. Under these conditions, the changes in tensile strength for these samples were in the range of 10% to 20%. However, for most of the other exposure conditions, many of these changes appear to be in the range of ± 1 to 6%. At the longest exposure time (180 days) and highest radiation doses, the tensile strength of butyl rubber appears to have decreased considerably (20%).

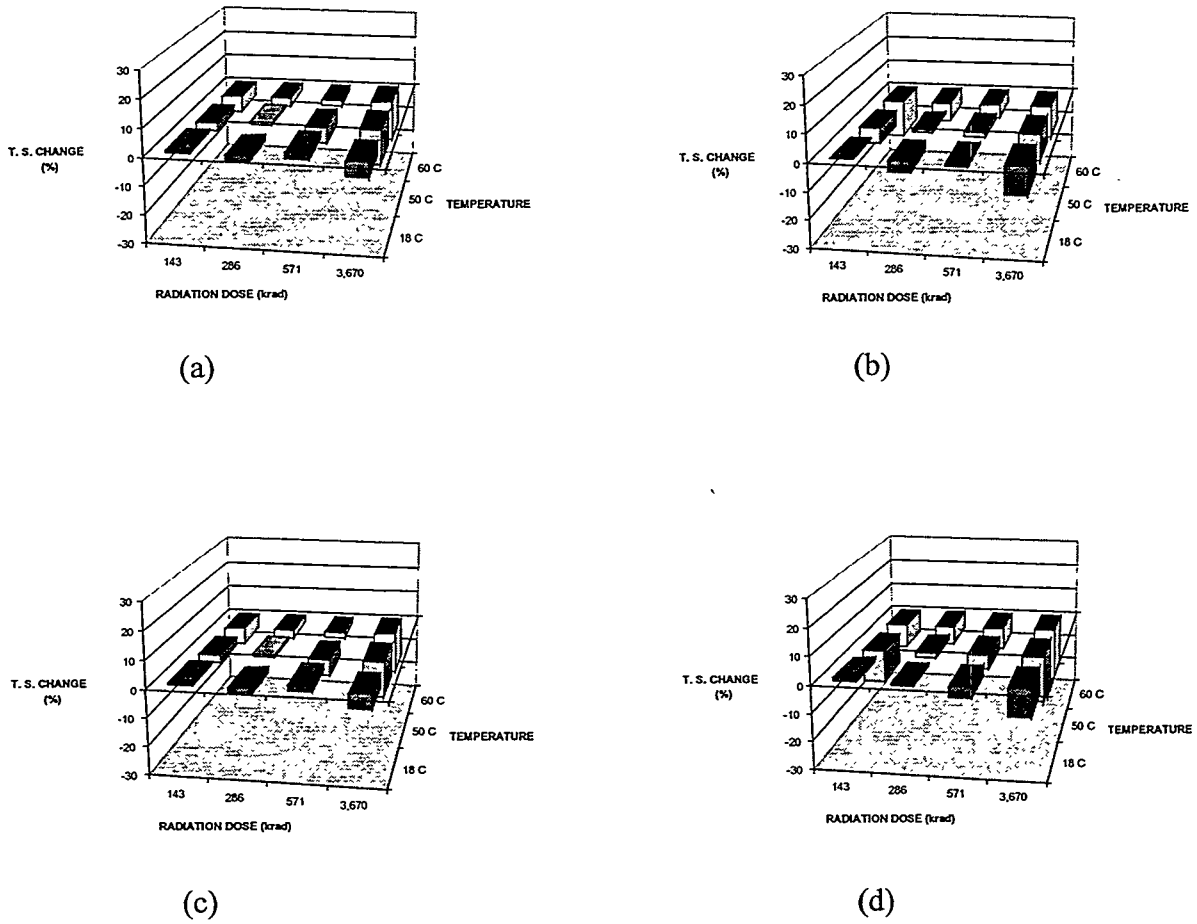


Figure 11. Tensile strength (T. S.) changes in butyl rubber after exposure to ~143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60°C.

Figure 12 shows the average values of percentage of tensile strength changes of butyl rubber 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. Butyl rubber samples that were only exposed to the simulant (0 krad radiation dose) waste showed a general decrease in tensile strength over the 180 day exposure period. The tensile strength also generally decreased with increasing exposure temperature. Samples exposed to both radiation and the simulant followed a similar trend. Another clear trend noted for the latter samples is that the tensile strength appeared to suddenly decrease when butyl rubber was exposed to gamma radiation doses of 571 and 3,670 krad. These effects can even be seen for samples that had been exposed to the simulant for only 7 days. Under this short exposure condition, tensile strength decreases of ~7 to 18% were observed. These sudden changes indicate that butyl rubber appears to have a radiation exposure threshold. Provided that this precisely undefined radiation dose threshold is not exceeded, the tensile properties are relatively unaffected in the Hanford tank simulant. While the exact tensile strength values are not obvious from the data in the figure, their precise values can be found in Appendix H of this report.

Elongation at Break or Ultimate Elongation

As discussed previously, the stress-strain diagrams of linear polymers exhibit an initial maximum stress value, which occurs at the yield point of the material. 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. It is not possible to determine elongation at yield in elastomeric materials, as opposed to thermoplastic materials, because 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:

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

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 will describe the change in elongation. These values were obtained by subtracting the ultimate elongation of the pristine material (247%) 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. Values are provided in Appendix I.

In Figure 13 (a)-(d), the average changes in ultimate elongation of butyl rubber 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 -100% to 100%. Since the pristine elongation of butyl rubber is 247%, this range corresponds to an ultimate elongation range of ~147% to 347%. While the scale is larger than in the previous property measurements, it is much less than that observed[8] for thermoplastics. For the latter thermoplastic materials, the scales ranged from -600% to 1000%. These results suggest that the necking observed in thermoplastics play an important role for accommodating deformation.

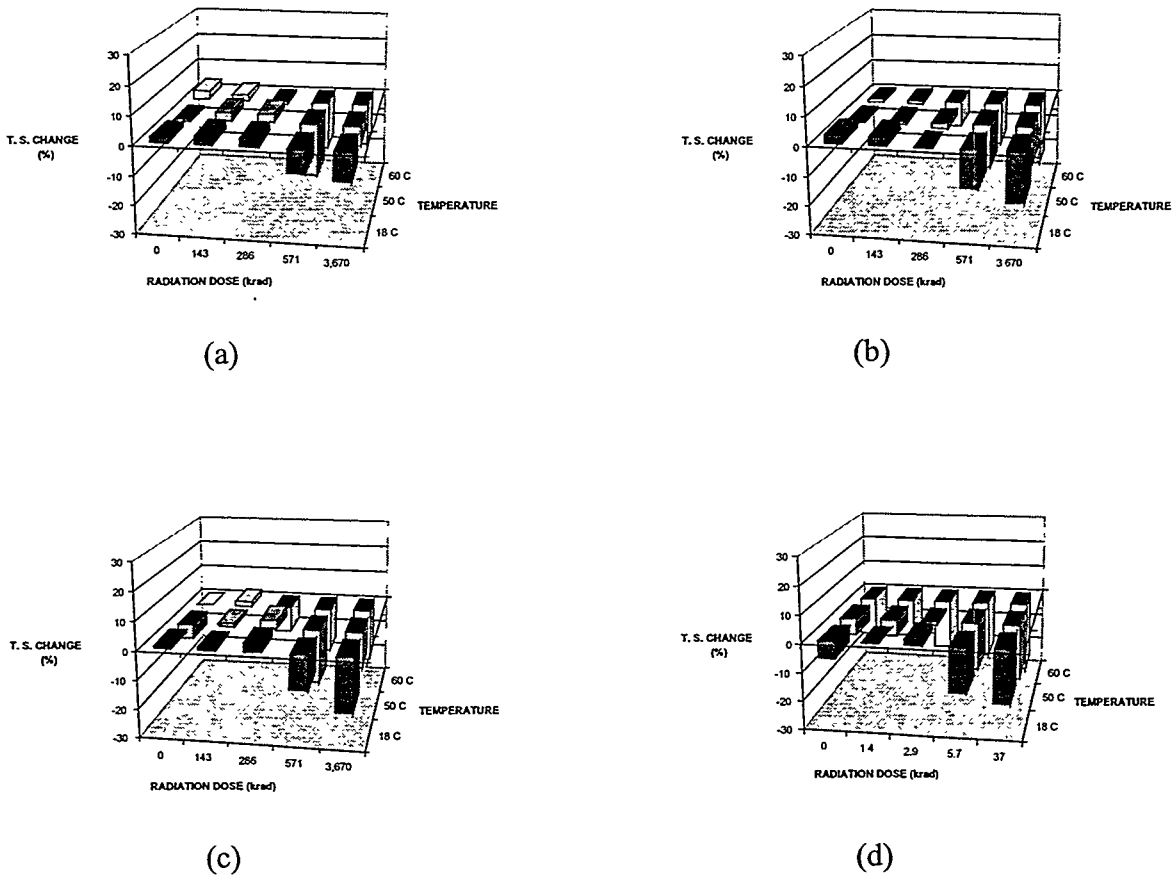


Figure 12. Tensile strength (T. S.) changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7, (b) 14, (c) 28, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

The data in Figure 13 generally showed an increase (~11%) in ultimate elongation. With increasing exposure time, there was a net decrease in ultimate elongation, but as a whole the ultimate elongation still mostly increased. At the longest exposure time of 180 days, some samples exhibited almost no change in ultimate elongation. For this exposure time, decreases in ultimate elongation of only 1 to 15% were observed. With increasing temperatures, larger decreases in ultimate elongation were observed. No general trends can be detected from the data for butyl rubber exposed to increasing radiation doses. These results indicate that the elasticity of butyl exposed is not strongly affected by gamma radiation.

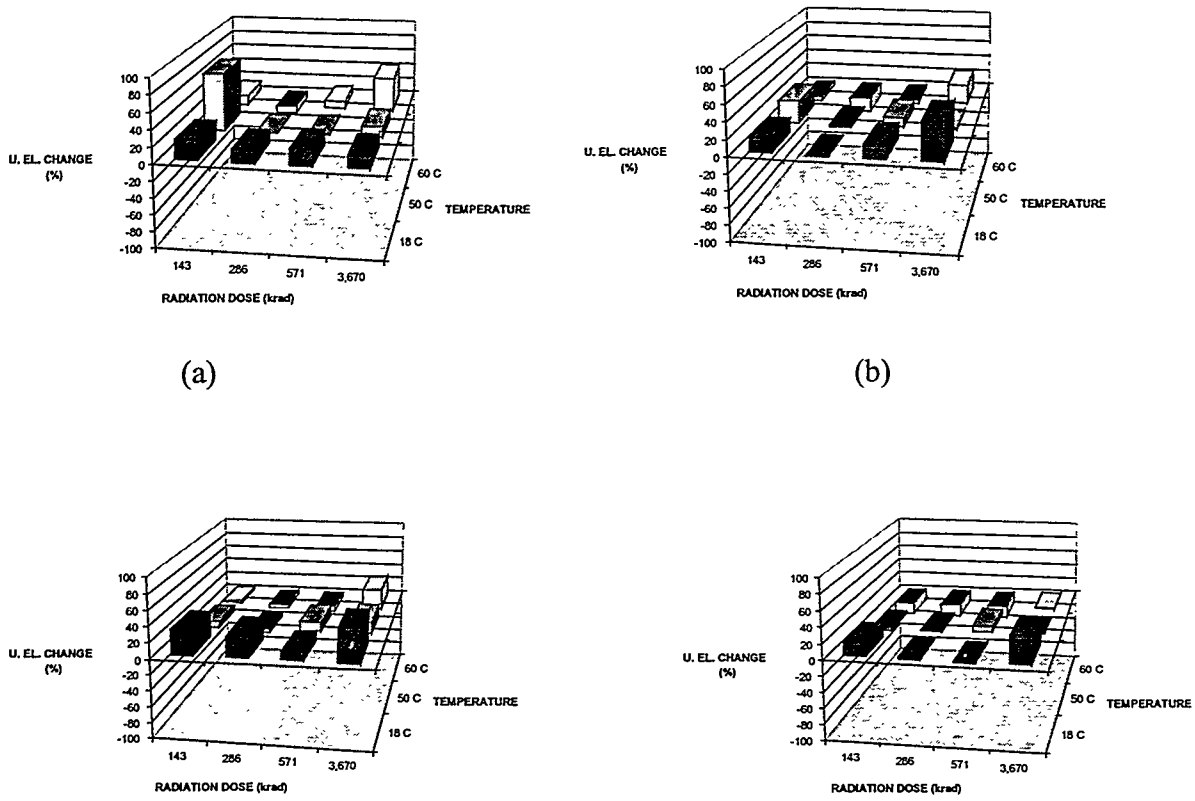


Figure 13. Ultimate elongation (U. EL.) changes in butyl rubber after exposure to ~143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for(a) 7 days, (b) 14 days, (c) 28 days, and (d) 180 days at 18, 50, and 60°C.

Figure 14 shows the average changes in ultimate elongation for butyl rubber 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. In contrast to the butyl rubber exposed only to gamma radiation, there was a general decrease in ultimate elongation with increased exposure time. The decreases in ultimate elongation are in the 1 to 45% range. The butyl rubber samples exposed to only the aqueous simulant (0 krad radiation dose) also followed 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 butyl rubber (i.e., butyl rubber is resistant to the chemical effects of this simulant). For samples that were exposed to 3,670 krad followed by exposure to the simulant, the ultimate elongation actually increased 72% after a 7-day exposure to the simulant at 60°C (Figure 14a). With increasing exposure times, the magnitude of these increases in ultimate elongation decreased but still remained positive (i.e., resulted in a net increase in ultimate elongation). The net increase at the longest exposure time and highest exposure temperature shown in Figure 14(d) was 20%. These results indicate that when butyl rubber receives a combination of high radiation doses and chemical exposure, the plasticity of the material increases.

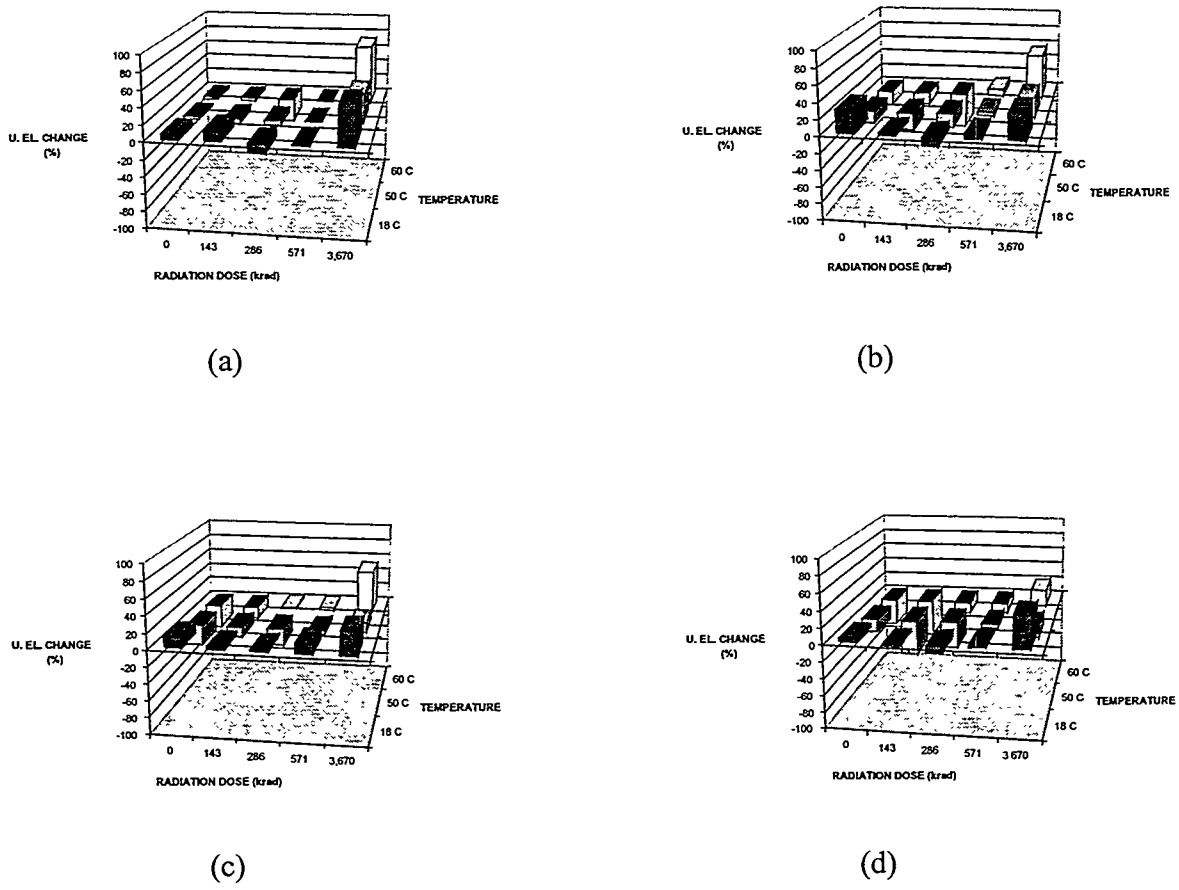


Figure 14. Ultimate elongation (U. EL.) changes in butyl rubber after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7, (b) 14, (c) 28, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

However, it should be recalled that the tensile strength decreased and that the compression set increased under these conditions. These results suggest that butyl rubber has become less elastic and more plastic. The actual ultimate elongation values are provided in Appendix I of this report.

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 is expected to be in the material. Modulus has the same units as stress (psi or MPa). The rubber industry also refers to the modulus of a compound and gives it a specific designation such as 100% or 300% modulus because the value generated is not an engineering modulus, as mentioned previously, but is 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 (3.96 MPa), we will discuss the % 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 % tensile stress indicate that the material of interest required greater application of stress to elongate the elastomer to 100% than for pristine material. Negative values indicate that the material of interest required less application of stress than the pristine material. Appendix J provides the precise tensile stress values of butyl rubber under the different environmental conditions along with the % change.

In Figure 15 (a)-(d), the average % change in tensile stress of butyl rubber exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60°C for 7, 14, 28, and 180 days is given. Increasing exposure to gamma radiation doses did not result in large increases in tensile stress. Similarly, increasing the exposure temperatures had no dramatic effect on the tensile stress of butyl rubber. The changes ranged from -25% to just over 13%. Even though many of the samples exhibited a decrease in tensile stress, some of the samples had increases in tensile stress. At higher radiation doses and temperatures, there is a general trend to decrease tensile stress. Consistent with previous tensile property measurements, the larger changes were observed for samples exposed to the highest radiation dose (3,670 krad). Over the four exposure times the decreases in tensile stress ranged from 11 to 24%. These trends are generally consistent with softening in the material (i.e., increased plasticity of the polymer chains). The latter observation is in agreement with a decrease in the rubbery qualities of the material and has been confirmed by decreases in hardness (Figure 5), decreases in tensile strength (Figure 12), and increasing ultimate elongation (Figure 13).

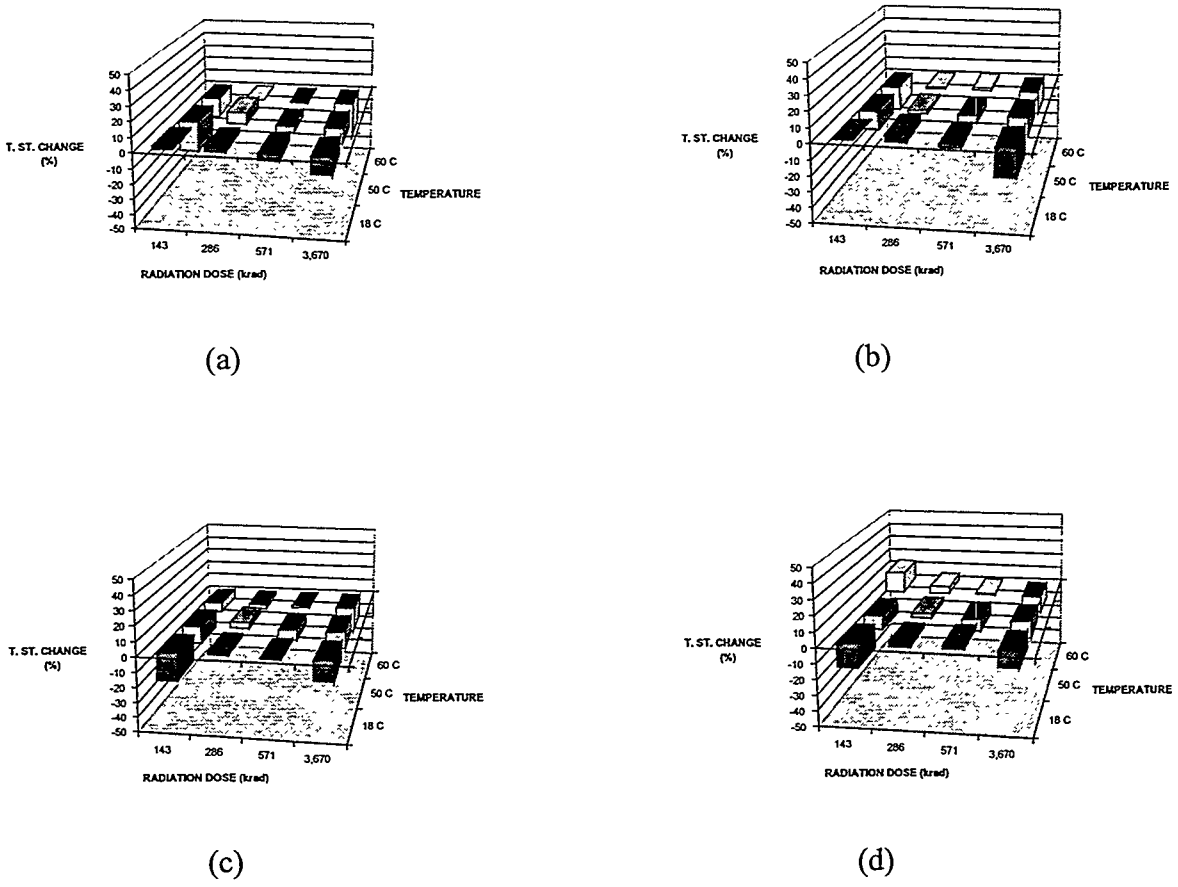


Figure 15. Tensile stress (T. ST.) changes in butyl rubber after exposure to ~143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7, (b) 14, (c) 28, and (d) 180 days at 18, 50, and 60°C.

Figure 16 (a)-(d) shows the average % change in tensile stress of butyl rubber exposed to the four gamma radiation doses followed by exposure at 18, 50, and 60°C to the aqueous simulant waste for 7, 14, 28, and 180 days. Similar to the *Rad-only* data in Figure 15, the larger changes in tensile stress are observed in samples exposed to the higher (571 and 3,670 krad) radiation doses. The largest of these is on the order of ~40%. At the lower (<571 krad) radiation doses, the tensile stress values ranged from ~-15% to 21% of the pristine butyl rubber's tensile stress values. Comparing the results of Figures 15 and 16, butyl rubber exposed to both radiation and the simulant waste had considerably lower tensile stress values at the higher radiation doses. Since tensile stress is a measurement of the stiffness[21] of the elastomer, the combination of radiation and chemical exposure has resulted in a decrease in the stiffness of the material. These interesting results suggest that the simulant has counteracted the embrittling action of radiation (i.e., the simulant appears to have caused some plasticizing action). Further studies are required to more fully understand this interesting phenomenon. It should be mentioned that plasticizing agents are compounding ingredients in rubber formulations that contribute to the rubbery properties of elastomers. The action of the simulant under these environmental conditions

appears to have resulted in plasticization of butyl rubber. With increasing exposure time, the tensile stress values appeared to decrease somewhat. This again points to a loss in stiffness of the elastomer. For virtually all the exposure times, the tensile stress changes were similar for butyl rubber samples exposed to only the simulant and for those samples having been exposed to both environmental conditions. The results in Figure 16 also show that increased exposure temperatures led to generally slight increases in tensile stress at low radiation doses. It appears that butyl rubber was remarkably resistant to the effects of low radiation doses, the simulant, and both environmental conditions. However, at the higher radiation doses of 571 and 3,670 krad, loss of tensile properties in butyl rubber were evident.

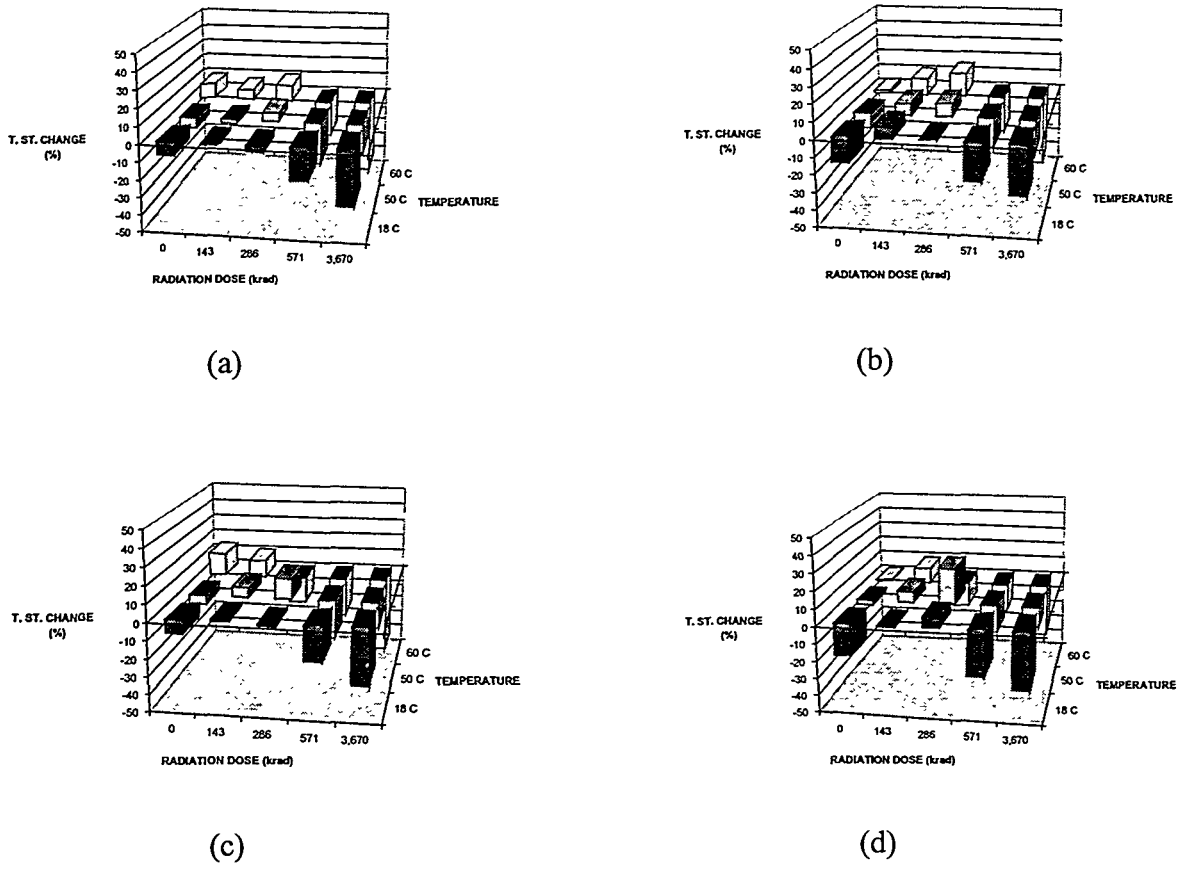


Figure 16. Tensile stress (T. ST.) changes in EPDM after exposure to ~0, 143, 286, 571, and 3,670 krad of gamma radiation followed by exposure for (a) 7, (b) 14, (c) 28, and (d) 180 days to the aqueous simulant waste at 18, 50, and 60°C.

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DISCUSSION

The purpose of the Chemical Interaction Project, previously referred to as the Chemical Compatibility Program, is to provide a scientifically defensible methodology for measuring the chemical interactions of polymeric liner and seal materials with hazardous wastes. The change in program names reflects an evolution in programmatic emphasis by the U.S. DOE. These polymeric materials are those which may be used in current and future container designs for the transportation of hazardous and mixed wastes throughout the DOE complex.

With 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 after exposure to the simulant Hanford tank waste, ten materials needed to be subjected to the test matrix resulting in an extremely large sample and test set. In view of manpower and budget constraints, the comprehensive testing phase of the program was subdivided into the testing of liner materials and seal materials; the results of liner testing were the subject of a previous SAND Report.[8] Also because of funding constraints, the comprehensive testing of seal materials was subdivided into the testing of individual elastomers. In previously published reports,[16,22] we discussed the results of testing of the elastomeric seal materials, EPDM and FKM rubber. This report describes the testing results of the next elastomeric seal material, butyl rubber. A subsequent report will discuss the testing results for the remaining elastomer, SBR exposed to simulant Hanford tank waste. The results obtained for each of the properties measured starting with specific gravity and ending with tensile stress of butyl rubber will be discussed.

From an overall perspective, the specific gravity data show that simulant temperature, radiation dose, and exposure time have some effect on the specific gravity of butyl rubber. After more than 14 day exposures (i.e., 28 days and 180 days, specific gravity changes in excess of 0.2% were observed). These results are consistent with the known chemical resistance of this elastomer and demonstrate that butyl rubber is suitable for use under these conditions if specific gravity is the determining design criterion for selection of packaging seal components. Increasing exposure times, radiation doses, and exposure temperatures generally caused increases in specific gravity of slightly greater than 1%. The greatest changes were noted for the samples exposed to the most extreme exposure conditions (i.e., 180 days, 3,670 krad, and 60°C). The butyl rubber samples that were not irradiated sometimes displayed smaller increases in specific gravity than samples exposed to both radiation and the simulant. However, at longest exposure times, similar values in specific gravity were observed. These results indicated that butyl rubber may be affected to a greater extent by the combination of radiation and chemical exposure and less resistant to radiation exposure.

The mass of butyl rubber increased slightly after exposure to the simulant or the combination of radiation and simulant at increasing exposure times and exposure temperatures. These increases were more noticeable after more than 14-day exposures. For these conditions, mass increases of more than 0.6% were observed at 50°C; the largest increases in mass of ~2.5% were observed after 180-day exposures. Since the mass increases were not very substantial, the slight increases in specific gravity noted earlier must have been caused by slight changes in dimensions. Specifically, the volume of the butyl rubber must decrease with a slight increase in mass, resulting in a net increase in specific gravity, and this was observed. For most sample volumes, smaller volume changes were observed. These combined results point to a slight swelling of the material ~0 to 2%. 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, which 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 are that butyl rubber O-rings, even when directly exposed to a Hanford tank waste under similar conditions as used in this study, are not expected to expand significantly.

As was previously discussed for dimensional property changes, the hardness of butyl rubber decreased with increasing exposure to both radiation and the simulant. For samples exposed to only the simulant, the hardness did not change significantly. Additionally, certain radiation levels appeared to exert a beneficial effect on the retention of hardness by butyl rubber. This was found to be especially true for the case where butyl rubber was exposed for 180 days. Under these conditions, most of the butyl rubber samples for all radiation doses became harder after previously becoming softer at the lower exposure times. Since butyl rubber swelled slightly under these conditions, the observed hardening of the material at these severe conditions cannot be ascribed purely to a swelling phenomenon. Hardening in the presence of swelling could be due to chain cross-linking in the polymer, but confirmation of this process will require additional tests. The observation that radiation in combination with chemical exposure may have a beneficial effect on hardness suggests that the cross-linking and chain-scission processes are occurring simultaneously. Possibly the combination of processes leads to a polymeric structure having generally shorter polymer segments that are cross-linked by radiation and chemical reactions.

Compression set measures the retention of elastic properties of material after exposure to compressive stresses. When butyl rubber samples were exposed to only gamma radiation, set changes in the range of -2 to 6% were found. For samples exposed to both radiation and the simulant, the compression set range of values increased slightly from -2 to 8%. The combined effects of radiation and chemical exposure resulted in increased compression sets (i.e., the material has become more deformed). These deformations are most pronounced in samples exposed for more than 14 days to the simulant at 50° and 60°C. Based on the hardness results, the butyl rubber became slightly harder at the longest exposure time. Its elastic properties, however, appeared to have suffered under these conditions. 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 (i.e., oils, vulcanizing aids, fillers, etc.) at these environmental conditions would need to be considered.

The VTR of butyl rubber changed very little when exposed to radiation and the aqueous simulant and 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, the VTRs also increased. The interesting aspect of the results is that the VTRs appeared to decrease with increased exposure time. A possible explanation is that the presence of the inorganic salts, especially the precipitate found in the simulant, may clog microscopic pores in butyl rubber, thereby reducing the transport of water vapor.

The tensile strength of butyl rubber also exhibited minimal changes when exposed to radiation, the simulant, and both radiation and simulant, provided that radiation dose levels, exposure temperatures, and exposure times were low. Many of the samples decreased less than 7% in

tensile strength. The combination of high radiation doses (>286 krad) and chemical exposure resulted in up to 20% decreases in tensile strength. At the highest radiation dose, the scission of polymeric chains may dominate as the determining process that leads to lower strength. While the material's strength may be retained at the less severe environmental conditions, the materials elasticity be decreasing. This is supported by the data for ultimate elongation discussed below.

The elastic property of materials can be measured by evaluating their degree of ultimate elongation. For butyl rubber samples exposed to only gamma radiation, a general decrease in elongation was observed with increased exposure time. These results indicate that the material is becoming more elastic at lower exposure times. However, because most butyl rubber samples were still rather elastic (i.e., stretching more than ~200% , a change of ~10% still results in rather elastic material). Butyl rubber exposed to both radiation and simulant, while general decreasing in elongation, still retained elasticity compared with samples only exposed to radiation. These results again point to the plasticizing effects of the simulant.

Tensile stress or 100% modulus measurements provide a measure of the stiffness 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 butyl rubber did not increase by more than 14%, nor did they decrease by more than 25% (i.e., tensile stress increases of 14% and decreases of 25% were observed). The effects of radiation on butyl rubber resulted in slightly stiffer material. For samples exposed to either only the simulant or to a combination of both radiation and simulant, decreases in tensile stress of up to 18% and 40%, respectively, were observed. These results suggest that the simulant counteracted somewhat the effect of radiation to reduce the stiffness, acting as a plasticizing agent. Alternatively, the combination of radiation and simulant exposure resulted in butyl rubber becoming less elastic and assuming a more plastic character. Hardness, tensile strength, and tensile stress decreased, while compression set and ultimate elongation increased, suggesting that butyl rubber lost some of its elastic properties and became more plastic. Butyl rubber exposed to higher radiation doses may exhibit increased plasticity (i.e., the material's original dimensions under an applied load are not recovered when the load is removed).

In summary, the measurement of changes in specific gravity, mass, volume, hardness, compression set, vapor transmission rates indicated that butyl rubber is remarkably resistant to the effects of radiation and the aqueous simulant at the temperatures and exposure times tested. From the tensile testing results, consisting of tensile strength, ultimate elongation, and tensile stress measurements, butyl rubber appears to be more susceptible to the effects of radiation and the aqueous simulant. When compared to the previously obtained tensile testing results for EPDM rubber, butyl rubber does not have comparable resistance to these environmental conditions. The beneficial effect of both radiation and the simulant in helping to reduce the changes in some material properties was noted. These results suggest that the type of aqueous mixed wastes used in this study have relatively small effects on butyl rubber.

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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 butyl rubber, a packaging seal material. This effort involved the comprehensive testing of butyl rubber 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 butyl rubber rubber has relatively good resistance to radiation, the simulant, and a combination of these environmental factors. These results suggest that butyl rubber is a relatively good seal material to withstand aqueous mixed wastes having similar composition to the one used in this study. However, butyl rubber appears to be less satisfactory based on tensile testing results when compared to the previously studied rubber, EPDM.

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APPENDIX A
BUTYL 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	Initial Value	Cure Date[b]	Batch Number
Specific Gravity	1.150	CD 1Q96	B319593
Dimensional	NA	CD 1Q96	B319593
Mass	NA	CD 1Q96	B319593
Hardness (Shore A)	65.4 points	CD 1Q96	B319593
Compression Set	12.6	CD 1Q96	B319593
Vapor Transport Rates	NA	CD 1Q96	B319593
Tensile Property		CD1Q95 CD1Q96	B316710 B319593
Tensile Strength	11.9 Mpa		
Ultimate Elongation	247%		
Tensile Stress	3.96 MPa		

a. Procured from Parker Seal Group (B0612-70) 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: ~$24/ft^2 (~$0.026/cm^2)
b. Cure Date (CD) nomenclature indicates the quarter and year in which the rubber was prepared. For example, 1Q96 represents material prepared during the first quarter of 1996.

APPENDIX B
BUTYL RUBBER SPECIFIC GRAVITY DATA*

AVERAGE SPECIFIC GRAVITY (SP. GR.) AND % CHANGE: BUTYL									
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	1.1503	1.1530	0.23	1.1512	-0.02	1.1542	0.21	1.1546	0.37
143K	1.1479	1.1497	0.16	1.1481	0.15	1.1510	0.17	1.1546	0.58
286K	1.1487	1.1495	0.04	1.1500	0.11	1.1495	0.07	1.1530	0.37
571K	1.1485	1.1488	0.02	1.1523	0.33	1.1522	0.32	1.1533	0.44
3670K	1.1492	1.1504	0.10	1.1514	0.19	1.1509	0.15	1.1535	0.37
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	1.1494	1.1513	0.17	1.1469	-0.07	1.1535	0.36	1.1586	0.87
143K	1.1508	1.1508	0.00	1.1536	0.24	1.1552	0.38	1.1618	0.96
286K	1.1506	1.1547	0.36	1.1558	0.45	1.1531	0.22	1.1606	0.87
571K	1.1533	1.1546	0.11	1.1571	0.33	1.1584	0.46	1.1612	0.68
3670K	1.1498	1.1511	0.11	1.1534	0.29	1.1514	0.11	1.1572	0.64
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	1.1463	1.1504	0.36	1.1463	0.00	1.1555	0.80	1.1591	1.12
143K	1.1475	1.1477	0.06	1.1529	0.47	1.1530	0.48	1.1604	1.12
286K	1.1480	1.1533	0.46	1.1551	0.62	1.1524	0.35	1.1593	0.98
571K	1.1489	1.1517	0.21	1.1550	0.53	1.1573	0.73	1.1579	0.78
3670K	1.1508	1.1566	0.50	1.1588	0.70	1.1594	0.75	1.1638	1.13

* In all appendices, the data in the "0 K" represents samples exposed to only the simulant (i.e., *Simulant Only* samples) while the other data represents samples that received both radiation and simulant exposure.

APPENDIX C
BUTYL RUBBER MASS DATA

MASS (g) AND % CHANGE: BUTYL									
18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	6.7766	6.7812	0.07	6.7843	0.11	6.7895	0.19	6.8168	0.59
143K	6.6369	6.6429	0.09	6.6465	0.14	6.6509	0.21	6.6764	0.60
286K	7.1101	7.1196	0.13	7.1223	0.17	7.1265	0.23	7.1505	0.57
571K	7.2423	7.2519	0.13	7.2549	0.17	7.2594	0.24	7.2848	0.59
3670K	7.0576	7.0668	0.13	7.0694	0.17	7.0733	0.22	7.0953	0.53
50 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	6.9681	7.0003	0.46	7.0166	0.70	7.0373	0.99	7.0808	1.62
143K	6.8003	6.8305	0.44	6.8450	0.66	6.8632	0.92	6.9095	1.61
286K	6.8387	6.8700	0.46	6.8827	0.64	6.8981	0.87	6.9041	0.96
571K	6.4088	6.4418	0.51	6.4555	0.73	6.4720	0.99	6.5149	1.66
3670K	6.2352	6.2666	0.50	6.2821	0.75	6.2978	1.00	6.3094	1.19
60 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WEIGHT	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
0K	6.6578	6.7120	0.81	6.7340	1.14	6.7545	1.45	6.8018	2.16
143K	6.1306	6.1771	0.76	6.1990	1.12	6.2177	1.42	6.2818	2.47
286K	6.3430	6.3900	0.74	6.4084	1.03	6.4230	1.26	6.4351	1.45
571K	6.5828	6.6296	0.71	6.6481	0.99	6.6642	1.24	6.6716	1.35
3670K	6.5107	6.5596	0.75	6.5824	1.10	6.6000	1.37	6.6460	2.08

APPENDIX D
BUTYL RUBBER DIMENSIONAL DATA

VOLUME (mm^3) AND % CHANGE: BUTYL

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	5838	5822	-0.27	5845	0.12	5842	0.07	5849	0.19
143K	5730	5723	-0.12	5721	-0.16	5735	0.09	5732	0.03
286K	6113	6139	0.43	6145	0.52	6133	0.33	6153	0.65
571K	6284	6281	-0.05	6297	0.21	6281	-0.05	6286	0.03
3670K	6129	6131	0.03	6119	-0.16	6125	-0.07	6144	0.24
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	6010	5989	-0.35	6020	0.17	6039	0.48	6080	1.16
143K	5893	5904	0.19	5899	0.10	5922	0.49	5942	0.83
286K	5914	5940	0.44	5923	0.15	5943	0.49	5953	0.66
571K	5526	5535	0.16	5557	0.56	5554	0.51	5586	1.09
3670K	5366	5373	0.13	5363	-0.06	5381	0.28	5408	0.78
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	VOLUME	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
0K	5724	5732	0.14	5765	0.72	5789	1.14	5815	1.59
143K	5279	5294	0.28	5306	0.51	5340	1.16	5353	1.40
286K	5475	5511	0.66	5509	0.62	5520	0.82	5535	1.10
571K	5697	5719	0.39	5719	0.39	5738	0.72	5745	0.84
3670K	5658	5670	0.21	5670	0.21	5686	0.49	5713	0.97

LENGTH (mm) AND % CHANGE: BUTYL

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	75.72	75.68	-0.05	75.74	0.03	75.68	-0.05	75.81	0.12
143K	75.80	75.70	-0.13	75.67	-0.17	75.74	-0.08	75.79	-0.01
286K	75.66	75.73	0.09	75.69	0.04	75.76	0.13	75.90	0.32
571K	75.78	75.79	0.01	75.73	-0.07	75.71	-0.09	75.85	0.09
3670K	75.63	75.62	-0.01	75.57	-0.08	75.62	-0.01	75.74	0.15
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	75.79	75.75	-0.05	75.80	0.01	75.87	0.11	75.97	0.24
143K	75.73	75.78	0.07	75.74	0.01	75.86	0.17	75.89	0.21
286K	75.83	75.87	0.05	75.88	0.07	75.93	0.13	76.01	0.24
571K	75.79	75.86	0.09	75.84	0.07	75.92	0.17	76.07	0.37
3670K	75.80	75.76	-0.05	75.83	0.04	75.86	0.08	75.96	0.21
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	LENGTH	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
0K	75.77	75.82	0.07	75.88	0.15	75.96	0.25	75.95	0.24
143K	75.81	75.86	0.07	75.91	0.13	75.99	0.24	75.99	0.24
286K	75.79	75.86	0.09	75.90	0.15	75.98	0.25	76.01	0.29
571K	75.91	75.97	0.08	75.96	0.07	76.01	0.13	76.07	0.21
3670K	75.88	75.89	0.01	75.94	0.08	75.97	0.12	76.01	0.17

APPENDIX D (cont.)
BUTYL RUBBER DIMENSIONAL DATA

WIDTH (mm) AND % CHANGE: BUTYL

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.30	25.27	-0.12	25.27	-0.12	25.29	-0.04	25.30	0.00
143K	25.33	25.30	-0.12	25.30	-0.12	25.33	0.00	25.32	-0.04
286K	25.25	25.27	0.08	25.32	0.28	25.27	0.08	25.30	0.20
571K	25.41	25.39	-0.08	25.38	-0.12	25.39	-0.08	25.37	-0.16
3670K	25.40	25.34	-0.24	25.39	-0.04	25.39	-0.04	25.41	0.04
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.27	25.25	-0.08	25.26	-0.04	25.29	0.08	25.37	0.40
143K	25.32	25.33	0.04	25.33	0.04	25.35	0.12	25.40	0.32
286K	25.32	25.33	0.04	25.34	0.08	25.37	0.20	25.36	0.16
571K	25.35	25.36	0.04	25.38	0.12	25.36	0.04	25.38	0.12
3670K	25.34	25.31	-0.12	25.31	-0.12	25.34	0.00	25.36	0.08
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	WIDTH	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
0K	25.26	25.27	0.04	25.33	0.28	25.36	0.40	25.36	0.40
143K	25.35	25.36	0.04	25.41	0.24	25.44	0.36	25.43	0.32
286K	25.33	25.37	0.16	25.38	0.20	25.40	0.28	25.41	0.32
571K	25.38	25.41	0.12	25.42	0.16	25.45	0.28	25.39	0.04
3670K	25.42	25.39	-0.12	25.42	0.00	25.44	0.08	25.40	-0.08

THICKNESS (mm) AND % CHANGE: BUTYL

18 C	INITIAL	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
RAD DOSE	THICKNESS	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
0K	3.05	3.04	-0.33	3.05	0.00	3.05	0.00	3.05	0.00
143K	2.98	2.99	0.34	2.99	0.34	2.99	0.34	2.99	0.34
286K	3.20	3.21	0.31	3.21	0.31	3.20	0.00	3.20	0.00
571K	3.26	3.26	0.00	3.28	0.61	3.27	0.31	3.27	0.31
3670K	3.19	3.20	0.31	3.19	0.00	3.19	0.00	3.19	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	3.14	3.13	-0.32	3.14	0.00	3.15	0.32	3.15	0.32
143K	3.07	3.08	0.33	3.08	0.33	3.08	0.33	3.08	0.33
286K	3.08	3.09	0.32	3.08	0.00	3.09	0.32	3.09	0.32
571K	2.88	2.88	0.00	2.89	0.35	2.88	0.00	2.89	0.35
3670K	2.79	2.80	0.36	2.79	0.00	2.80	0.36	2.81	0.72
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	THICKNESS	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
0K	2.99	2.99	0.00	3.00	0.33	3.01	0.67	3.02	1.00
143K	2.75	2.75	0.00	2.75	0.00	2.76	0.36	2.77	0.73
286K	2.85	2.86	0.35	2.86	0.35	2.86	0.35	2.87	0.70
571K	2.96	2.96	0.00	2.96	0.00	2.97	0.34	2.97	0.34
3670K	2.93	2.94	0.34	2.94	0.34	2.94	0.34	2.96	1.02

APPENDIX E
BUTYL RUBBER HARDNESS DATA

AVERAGE HARDNESS (TYPE A) AND % CHANGE: BUTYL									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	65.4	67.1	2.6	65.7	0.5	65.5	0.2	65.2	-0.3
143K	65.9	65.5	-0.6	66.0	0.2	65.3	-0.9	66.6	1.1
286K	66.2	64.8	-2.1	65.1	-1.7	64.7	-2.3	65.5	-1.1
571K	65.4	63.4	-3.1	63.6	-2.8	63.8	-2.4	64.9	-0.8
3670K	67.3	63.9	-5.1	64.4	-4.3	64.0	-4.9	64.7	-3.9
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	65.1	65.5	0.6	63.8	-2.0	64.1	-1.5	65.4	0.5
143K	66.7	65.0	-2.5	65.7	-1.5	65.1	-2.4	68.1	2.1
286K	66.9	63.8	-4.6	64.2	-4.0	63.9	-4.5	67.0	0.1
571K	66.1	62.5	-5.4	62.7	-5.1	63.1	-4.5	65.7	-0.6
3670K	67.3	63.1	-6.2	63.1	-6.2	63.0	-6.4	64.4	-4.3
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	HARDNESS	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
0K	64.8	65.1	0.5	64.2	-0.9	64.2	-0.9	65.6	1.2
143K	66.2	65.1	-1.7	65.7	-0.8	65.6	-0.9	67.7	2.3
286K	66.7	64.3	-3.6	64.9	-2.7	64.9	-2.7	66.0	-1.0
571K	65.1	61.9	-4.9	62.5	-4.0	62.9	-3.4	64.4	-1.1
3670K	65.3	58.5	-10.4	59.2	-9.3	59.3	-9.2	62.2	-4.7

APPENDIX F
BUTYL RUBBER COMPRESSION SET DATA

COMPRESSION SET (SET, %) AND CHANGE: BUTYL									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	12.58	14.11	1.53	14.20	1.62	13.69	1.11	13.77	1.19
143K	12.58	11.50	-1.08	11.11	-1.47	10.71	-1.87	11.16	-1.42
286K	12.58	10.22	-2.36	11.98	-0.60	12.81	0.23	13.41	0.83
571K	12.58	12.56	-0.02	10.68	-1.90	10.77	-1.81	11.06	-1.52
3670K	12.58	12.50	-0.08	13.29	0.71	17.03	4.45	14.98	2.40
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	12.58	12.71	0.13	15.24	2.66	15.06	2.48	16.30	3.72
143K	12.58	12.27	-0.31	12.32	-0.26	13.36	0.78	16.57	3.99
286K	12.58	10.65	-1.93	12.04	-0.54	15.38	2.80	17.65	5.07
571K	12.58	12.83	0.25	10.76	-1.82	12.05	-0.53	14.48	1.90
3670K	12.58	12.69	0.11	13.40	0.82	18.09	5.51	20.47	7.89
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	SET	SET	CHANGE	SET	CHANGE	SET	CHANGE	SET	CHANGE
0K	12.58	12.56	-0.02	13.15	0.57	15.42	2.84	18.50	5.92
143K	12.58	11.76	-0.82	13.61	1.03	16.48	3.90	17.39	4.81
286K	12.58	12.27	-0.31	13.04	0.46	16.67	4.09	17.68	5.10
571K	12.58	13.45	0.87	12.74	0.16	14.42	1.84	15.93	3.35
3670K	12.58	13.64	1.06	15.73	3.15	18.44	5.86	20.63	8.05
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	12.58	14.59	2.01	16.09	3.51	18.18	5.60	14.69	2.11
286K	12.58	13.87	1.29	13.07	0.49	17.88	5.30	13.57	0.99
571K	12.58	16.78	4.20	14.55	1.97	11.22	-1.36	12.39	-0.19
3670K	12.58	15.23	2.65	15.33	2.75	14.12	1.54	14.79	2.21
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	12.58	16.02	3.44	15.98	3.40	14.79	2.21	14.55	1.97
286K	12.58	17.12	4.54	14.09	1.51	15.44	2.86	13.87	1.29
571K	12.58	14.37	1.79	11.49	-1.09	12.09	-0.49	12.92	0.34
3670K	12.58	12.17	-0.41	11.47	-1.11	13.90	1.32	15.14	2.56
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	12.58	16.25	3.67	15.63	3.05	16.09	3.51	17.26	4.68
286K	12.58	13.89	1.31	12.58	0.00	14.84	2.26	15.13	2.55
571K	12.58	13.37	0.79	10.88	-1.70	11.58	-1.00	16.99	4.41
3670K	12.58	12.63	0.05	13.02	0.44	14.48	1.90	16.36	3.78

APPENDIX G
BUTYL RUBBER VAPOR TRANSPORT RATE DATA

VAPOR TRANSMISSION RATE (g/hr/m^2): BUTYL				
18 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
0K	0.2071	0.1969	0.1638	0.1023
143K	0.1597	0.0568	0.0416	0.0215
286K	0.0609	0.0548	0.0531	0.0370
571K	0.0406	0.0453	0.0392	0.0186
3670K	0.0392	0.0609	0.0514	0.0252
50 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
0K	0.3302	0.2138	0.1286	0.0419
143K	0.2220	0.1313	0.0727	0.0216
286K	0.2937	0.3532	0.2487	0.0901
571K	0.7254	0.4439	0.2467	0.0831
3670K	0.1489	0.0961	0.0565	0.0281
60 C	**7 DAYS**	**14 DAYS**	**28 DAYS**	**180 DAYS**
RADIATION DOSE	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION	VAPOR TRANSMISSION
0K	0.2801	0.2734	0.1621	0.0859
143K	0.8080	0.4737	0.2876	0.2532
286K	0.4047	0.2307	0.1265	0.0821
571K	0.4209	0.2707	0.1590	0.0915
3670K	0.3113	0.2226	0.1235	0.1335

APPENDIX H
BUTYL RUBBER TENSILE STRENGTH DATA

TENSILE STRENGTH (TENS. STR., MPa) AND % CHANGE: BUTYL									
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	11.9	12.1	1.7	12.2	2.9	11.9	0.6	11.2	-5.8
143K	11.9	12.2	2.9	12.3	3.5	12.0	1.2	11.9	0.0
286K	11.9	12.3	3.5	11.9	0.0	12.3	3.5	12.1	2.3
571K	11.9	11.0	-7.6	10.3	-12.8	10.4	-12.2	9.9	-16.3
3670K	11.9	10.6	-10.5	9.8	-17.4	9.6	-19.2	9.6	-19.2
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	11.9	11.8	-0.6	11.7	-1.2	11.3	-4.7	11.1	-6.4
143K	11.9	12.2	2.9	11.8	-0.6	11.9	0.6	11.1	-6.4
286K	11.9	12.3	3.5	11.6	-2.3	12.2	2.9	11.7	-1.2
571K	11.9	9.7	-18.0	10.1	-15.1	9.6	-19.2	9.8	-17.4
3670K	11.9	11.0	-7.0	10.3	-12.8	10.3	-13.4	9.5	-19.8
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	11.9	12.2	2.9	11.8	-0.6	11.9	0.0	10.2	-14.0
143K	11.9	12.1	2.3	11.8	-0.6	12.1	1.7	10.2	-14.0
286K	11.9	11.7	-1.2	10.8	-9.3	10.8	-9.3	9.7	-18.0
571K	11.9	9.8	-17.4	10.1	-14.5	10.0	-15.7	9.4	-20.9
3670K	11.9	10.1	-15.1	9.2	-22.1	9.6	-19.2	8.8	-25.6
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	11.9	11.9	0.6	11.9	0.0	10.8	-8.7	11.9	0.6
286K	11.9	11.6	-2.3	11.4	-4.1	11.4	-3.5	11.8	-0.6
571K	11.9	12.1	1.7	11.7	-1.2	11.5	-2.9	11.4	-4.1
3670K	11.9	11.2	-5.2	10.7	-9.9	10.5	-11.6	10.7	-9.9
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	11.9	11.5	-2.9	11.1	-6.4	10.8	-8.7	10.5	-11.6
286K	11.9	11.9	0.6	11.8	-0.6	11.7	-1.7	11.6	-2.3
571K	11.9	11.2	-5.8	11.6	-2.3	11.4	-3.5	11.3	-4.7
3670K	11.9	10.3	-13.4	10.6	-10.5	10.7	-9.9	9.9	-16.9
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	11.9	11.2	-5.8	10.2	-14.0	10.8	-8.7	10.8	-8.7
286K	11.9	11.5	-2.9	11.0	-7.0	11.4	-4.1	11.0	-7.0
571K	11.9	11.6	-2.3	11.3	-4.7	11.4	-4.1	10.9	-8.1
3670K	11.9	10.1	-14.5	10.4	-12.2	10.2	-14.0	9.5	-19.8

APPENDIX I
BUTYL RUBBER ULTIMATE ELONGATION DATA

ULTIMATE ELONGATION (ELONG., %) AND CHANGE: BUTYL									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	247	253	6	276	29	260	13	252	5
143K	247	260	13	249	2	251	4	244	-3
286K	247	236	-11	237	-10	250	3	238	-9
571K	247	248	1	253	6	259	12	250	3
3670K	247	296	49	279	32	275	28	286	39
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	247	244	-3	232	-15	222	-25	231	-16
143K	247	241	-6	225	-22	234	-13	205	-42
286K	247	241	-6	230	-17	226	-21	215	-32
571K	247	246	-1	251	4	242	-5	242	-5
3670K	247	284	37	272	25	258	11	233	-14
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	ELONG.	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE	ELONG.	CHANGE
0K	247	244	-3	230	-17	219	-28	215	-32
143K	247	244	-3	233	-14	233	-14	202	-45
286K	247	220	-27	204	-43	249	2	233	-14
571K	247	246	-1	255	8	250	3	236	-11
3670K	247	319	72	301	54	299	52	267	20
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	247	272	25	265	18	280	33	265	18
286K	247	263	16	247	0	274	27	249	2
571K	247	267	20	264	17	259	12	246	-1
3670K	247	263	16	294	47	290	43	281	34
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	247	318	71	274	27	254	7	243	-4
286K	247	247	0	244	-3	242	-5	245	-2
571K	247	249	2	259	12	260	13	255	8
3670K	247	260	13	250	3	263	16	246	-1
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	247	259	12	242	-5	250	3	233	-14
286K	247	238	-9	230	-17	242	-5	232	-15
571K	247	256	9	243	-4	241	-6	232	-15
3670K	247	289	42	270	23	273	26	249	2

APPENDIX J
BUTYL RUBBER TENSILE STRESS DATA

TENSILE STRESS (STRESS, MPa) AND % CHANGE: BUTYL									
18 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	3.96	3.65	-7.84	3.36	-15.2	3.65	-7.67	3.22	-18.6
143K	3.96	3.91	-1.22	4.22	6.62	4.00	1.05	3.92	-1.05
286K	3.96	3.81	-3.66	3.98	0.52	3.89	-1.74	4.18	5.57
571K	3.96	3.22	-18.6	3.10	-21.8	3.17	-19.9	2.89	-27.0
3670K	3.96	2.68	-32.2	2.81	-28.9	2.70	-31.7	2.62	-33.8
50 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	3.96	3.72	-6.10	3.61	-8.89	3.75	-5.23	3.85	-2.79
143K	3.96	3.86	-2.44	4.23	6.97	4.19	5.75	4.22	6.62
286K	3.96	4.16	5.05	4.27	8.01	4.43	12.0	4.80	21.3
571K	3.96	3.00	-24.2	3.25	-17.9	3.09	-22.0	3.32	-16.0
3670K	3.96	3.27	-17.4	3.14	-20.7	3.38	-14.6	3.48	-12.2
60 C	**INITIAL**	**7 DAYS**		**14 DAYS**		**28 DAYS**		**180 DAYS**	
RAD DOSE	STRESS	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE	STRESS	% CHANGE
0K	3.96	4.30	8.71	4.03	1.92	4.48	13.2	3.99	0.87
143K	3.96	4.20	6.10	4.36	10.3	4.35	9.93	4.31	8.89
286K	3.96	4.34	9.58	4.53	14.5	3.35	-15.3	3.39	-14.3
571K	3.96	3.12	-21.1	3.08	-22.1	3.08	-22.3	3.30	-16.7
3670K	3.96	2.27	-42.7	2.32	-41.5	2.25	-43.0	2.71	-31.5
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	3.96	4.04	2.09	3.96	0.00	3.23	-18.3	3.36	-15.2
286K	3.96	4.07	2.96	4.15	4.88	4.05	2.44	4.06	2.61
571K	3.96	3.80	-4.01	3.88	-1.92	3.91	-1.22	4.05	2.26
3670K	3.96	3.50	-11.7	3.23	-18.5	3.41	-13.8	3.54	-10.6
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	3.96	3.12	-21.1	3.45	-12.7	3.46	-12.5	3.57	-9.76
286K	3.96	4.27	7.84	4.03	1.74	4.10	3.66	4.06	2.61
571K	3.96	3.77	-4.70	3.75	-5.23	3.68	-6.97	3.65	-7.84
3670K	3.96	3.52	-11.0	3.50	-11.7	3.52	-11.1	3.51	-11.3
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	3.96	3.43	-13.4	3.32	-16.2	3.70	-6.62	4.51	13.9
286K	3.96	3.98	0.52	4.01	1.39	3.84	-2.96	4.15	4.88
571K	3.96	3.93	-0.70	4.03	1.74	3.92	-1.05	4.01	1.22
3670K	3.96	2.98	-24.7	3.36	-15.2	3.28	-17.1	3.52	-11.0

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