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Comprehensive Testing to Measure the Response of Liner Materials to Hanford Tank Waste Simulant

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Comprehensive Testing to Measure the Response of Liner Materials to Hanford Tank Waste Simulant

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Abstract

This report is to present the findings of the Chemical Compatibility Program developed for the evaluation of plastic transportation packaging components that may be incorporated in packaging mixed-waste forms. Consistent with the methodology outlined in this report, we have performed the second phase of this experimental program to determine the effects of simulant Hanford tank mixed wastes on packaging liner materials. This effort involved the comprehensive testing of five plastic liner materials in the aqueous mixed-waste simulant. The testing protocol involved exposing the respective materials to ~140, 290, 570, and 3,670 krads of gamma radiation and followed by 7-, 14-, 28-, 180-day exposures to the waste simulant at 18, 50, and 60°C. From the data analyses performed, we have identified the fluorocarbon Kel-F™ as having the greatest chemical durability after having been exposed to gamma radiation and followed by exposure to the Hanford tank simulant mixed waste. The most striking observation from this study was the extremely poor performance of Teflon® under the given test conditions.

ACKNOWLEDGMENTS

The support of our sponsor, the U. S. Department of Energy, Office of Transportation, Emergency Management, and Analytical Services, EM-761 is gratefully appreciated. Specifically, the encouragement provided by Michael Keane, Ashook Kapoor and others in this DOE/HQ Office are acknowledged.

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INTRODUCTION

Hazardous and radioactive materials packaging is designed to transport and store materials without posing a threat to the health or property of the general public. U.S. regulations have been written that 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, i.e., 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 design requirements for both hazardous [49 CFR 173.24 (e)(1)] and radioactive [49 CFR 173.412 (g)] materials packaging specify packaging compatibility. That is, the materials of the packaging and any contents must be chemically compatible with each other. 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 these national requirements, a Chemical Compatibility Testing Program was developed in the Transportation Systems Department at Sandia National Laboratories (SNL). The program attempts to assure any regulatory body that the issue of packaging material compatibility with hazardous and radioactive materials has been addressed. This program has been described in considerable detail in a milestone report[1] submitted to the Department of Energy (DOE). The results obtained from this testing program were reported to the U.S. DOE in various unpublished milestone documents. In addition, the results of this program have been reported in several externally published papers.[2-6]

The milestone report, entitled *Chemical Compatibility Test Plan and Procedure Report* (CCTP&PR), describes a program for the evaluation of plastic transportation packaging components that may be used in transporting mixed-waste forms. Consistent with the methodology developed in the CCTP&PR, the first phase of this experimental program has been completed. This effort involved the screening of ten plastic materials in four simulant mixed-waste types.[6] These plastics were

- butadiene-acrylonitrile copolymer rubber
- cross-linked polyethylene (XLPE)
- epichlorohydrin rubber
- ethylene-propylene rubber (EPDM)
- fluorocarbons (VITON® or Kel-F™)
- polytetrafluoroethylene (Teflon®)
- high-density polyethylene (HDPE)
- isobutylene-isoprene copolymer rubber (Butyl)
- polypropylene (PP), and
- styrene-butadiene rubber (SBR).

The selected simulant mixed wastes were

- an aqueous alkaline mixture of sodium nitrate and sodium nitrite
- a chlorinated hydrocarbon mixture
- a simulant liquid scintillation fluid, and
- a mixture of ketones.

The testing protocol involved exposing the respective materials to 286,000 rads of gamma radiation followed by 14-day exposures to the waste types at 60°C. The seal materials or rubbers were tested using vapor transport rate (VTR) measurements while the liner materials were tested using specific gravity as a metric. For these tests, a screening criteria of ~1 $g/hr/m^2$ for VTR and specific gravity change of 10% were used. Those materials which failed to meet these criteria were judged to have failed the screening tests and were excluded in the next phase of this experimental program. Based on this work, it was concluded that while all seal materials passed exposure to the aqueous simulant mixed waste, EPDM and SBR had the lowest VTRs. In the chlorinated hydrocarbon simulant mixed waste, only VITON® passed the screening tests. 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 with the exception of polypropylene passed the screening criteria, Kel-F™, HDPE, and XLPE were found to offer the greatest resistance to the combination of radiation and chemicals.

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

In this report, we present the results of the second phase of this testing program. This phase involved the comprehensive testing of the above-described five candidate liners. The comprehensive testing protocol involved exposing the respective materials to a matrix of four gamma radiation doses (~140, 290, 570, and 3,670 krads), three temperatures (18, 50, and 60°C), and four exposure times (7, 14, 28, and 180 days). The temperature and exposure times were based on values found in 49 CFR 173, Appendix B. Following their exposure to these combinations of conditions, the materials were evaluated by measuring five material properties. These properties were specific gravity, dimensional changes, hardness, stress cracking, and tensile properties.

EXPERIMENTAL

In this section, we describe the experimental aspects of the comprehensive phase of the chemical compatibility-testing program.

Materials

The selected materials were five plastics having known chemical resistance to a large number of classes of chemicals. The term plastic, as used in this paper, refers to polymeric materials. The selected plastics were HDPE, XLPE, PP, Kel-F™, and Teflon®. Appendix A provides additional information on these materials.

Simulant Preparation

The simulant mixed-waste form used in this testing phase was an aqueous alkaline simulant Hanford Tank waste. This simulant was developed locally based on more complex formulations used by researchers at the Hanford site. It was prepared by dissolving 179 g (2.10 moles) of sodium nitrate and 50 g (0.73 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 was added under stirring and slight heating using a magnetic hotplate (Corning, Model PC-320). To this hot (~ 70°C) stirred solution, 17 g (0.107 moles) of cesium chloride and 16 g (0.0952) of strontium chloride were added. Finally, 32 g (0.301 moles) of sodium carbonate were added to the solution. This latter addition resulted in the formation of a copious amount of white precipitate. Based on its insolubility, it is believed that this precipitate is strontium carbonate. To the resulting mixture was added another 400 mL of deionized water 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. This composition produces 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 in. x 2 in. x 0.125 in.) 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 in. x 3 in. x 0.125 in.) samples required for dimensional measurements were cut in the expulsion press fitted with an Expulsion Straight Edge Die (Part #23-10-07). Rectangular (0.5 in. x 1.5 in. x 0.125 in.) samples required for stress cracking measurements were cut in the expulsion press fitted with an expulsion straight edge die (part #23-14-36). Similarly, the Type IV samples required for tensile testing were cut in the expulsion press fitted with an expulsion die (part #23-14-23) specifically designed for the American Society for Testing and Materials (ASTM) Standard Test Method D 638.[7] The use of the press and dies permitted the cutting of multiple samples of uniform dimensions. When attempting to cut out the harder materials such as HDPE, PP, and Kel-F™ with the expulsion press, considerable difficulty was encountered. This problem necessitated machining the required "dog bone" samples of the materials to Type IV specifications. The individual samples were visually checked to ensure that none had nicks or other imperfections prior to their use. A matrix was developed for labeling samples according to test method, sample number, and testing conditions. The samples were individually labeled with the use of 1/8-in. steel letter and number stamp sets. Because of the limited space available on the specimens, the tensile testing specimens were labeled with 1/16-in. steel letter and number stamps. As recommended by ASTM D 618,[8] the plastics were conditioned at a standard temperature of 23°C (73.4°F) 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) that was 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.[9] During conditioning, the samples were stacked atop each other and separated with metal pins.

Sample Irradiation

For specific gravity measurements, 20 samples (four samples per material, with five materials used) were cut out for each radiation dose, temperature, and exposure time for a total of 420 samples. For dimensional measurements, 180 samples were prepared. Hardness measurements involved 180 samples. Stress cracking measurements involved 1,200 samples while tensile testing involved 2,400 samples. The above-mentioned sample numbers include only those samples which were exposed to gamma radiation from an underwater ^{60}Co source at SNL. These samples were loaded into a metal basket in the same configuration as was used to condition the samples; i.e., the samples were stacked atop each other and separated by a metal spiral or by metals pins. The basket was then inserted into a watertight stainless steel canister (volume ~4 L). The canister was sealed and lowered into the pool to a depth of 6 feet, purged with slow a steady flow (~ 30 mL/min) of dry air, and allowed to come to thermal equilibrium at either ambient (~32°C), 50, or 60°C.[10] Once thermal equilibrium was obtained 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 Facility is ~200 krads/hr. Thus, for irradiation where a gamma-ray dose of ~143 krads was required, the samples were exposed for approximately

0.75 hours. For doses of ~290, 570, and 3,670 krads (~3.7 Mrads), 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 wastes or the test temperatures.

Sample Exposure to Chemicals

The general exposure protocol for specific gravity involved placing four specimens of each plastic material into a container (cell) and exposing them to the specific testing conditions. The four specimens were bundled together using 7.5-in. nylon cable ties. Within each bundle, the specimens were separated by ~1/16-in. metal pins, used as spacers. This allowed for the ready access of the waste simulant to all surfaces of each specimen. A 2-L glass bottle 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, stress cracking tests, and tensile tests. In the case of stress-cracking experiments, the samples were held in specially designed stainless steel specimen holders described in ASTM D 1693.[11] The samples held in the specimen holders were placed in the jars containing the aqueous waste simulant. For specific gravity measurements, 240 samples were cut out for the combination of three temperatures and four exposure times to the simulant alone. For dimensional measurements, 45 samples were prepared for exposure to only the simulant. Hardness measurements involved 45 samples. Stress-cracking measurements involved 240 samples, while tensile testing involved 300 samples. Thus, for all five measurements, 1,070 samples were prepared for exposure to only the simulant at the three temperatures and four exposure times.

Approach

The material properties that should be evaluated to assess the suitability of potential liner materials in mixed-waste packaging designs are mass and density changes, hardness, modulus of elasticity, tensile strength, elongation, and stress cracking in polyethylene materials. Since the measurement of all material properties was expected to be costly and time-consuming, screening tests with relatively severe exposure conditions such as high temperatures and high radiation levels were implemented to quickly reduce the number of possible materials for full evaluation. The results of these screening studies have been described in a previous milestone.[12] From this screening study it was found that all of the selected liner materials had passed the screening criteria in the aqueous simulant mixed waste. This then necessitated the testing of five materials by exposure to a matrix of four radiation doses, three temperatures, and four exposure times in the simulant waste. In view of the extensive number of materials and exposure conditions, this second phase of the program was referred to as the comprehensive testing phase. The evaluation parameters used in this comprehensive testing phase consisted of measuring the specific gravity changes, dimensional changes, hardness changes, stress cracking in polyethylene materials, and tensile property changes of potential liner materials. These parameters were evaluated using standardized test methods such as those developed by the ASTM. For specific gravity changes, ASTM D 792[13] was used. In evaluating dimensional changes, ASTM D 543[14] was used. For hardness changes, ASTM D 2240[15] was used. In evaluating stress cracking in polyethylene materials, ASTM D 1693 was used. Finally, for evaluating tensile property changes, ASTM D 638 was used.

Before describing the results of this study, we will describe the comprehensive testing strategy. This strategy is shown in the flow diagram in Figure 1. The materials were subjected to four different protocols (Paths A-D). To determine the intrinsic properties of the materials, the baseline samples (Path A) were prepared for each of the five tests. In order to differentiate the effects on the materials by radiation and chemicals, one series of samples was only exposed to the simulant (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 and stress cracking, where the effects of radiation and temperature alone could have significant impact on the properties, a series of samples described as "Radiation Only" is shown in the flow diagram (Path D). These samples were irradiated at three temperatures, respectively, and then held for the four exposure times at the respective temperatures. What may not appear obvious from the flow diagram is the large number of samples being tested in this comprehensive testing phase of the program. The total data sets being analyzed after testing number about 5,300.

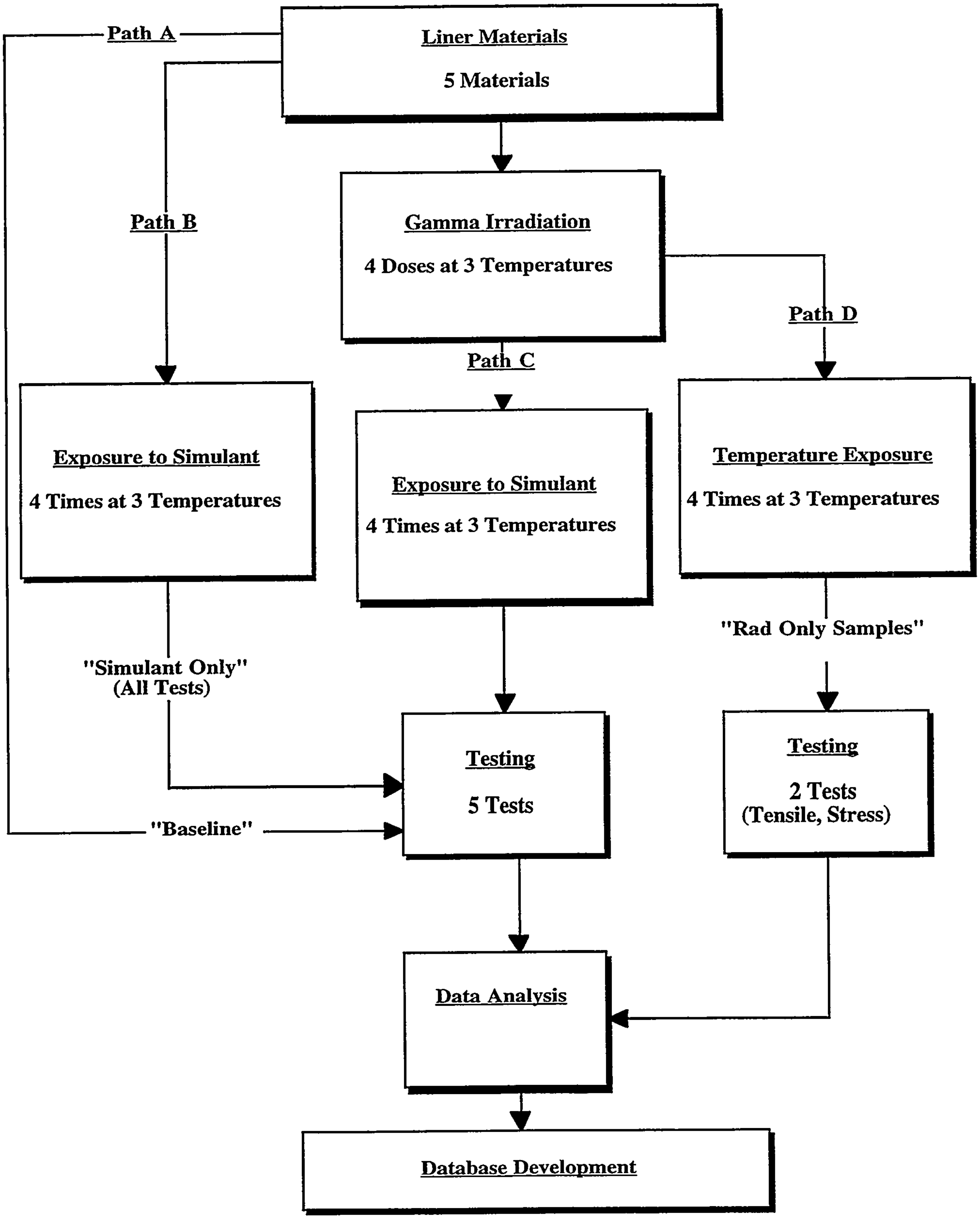

Figure 1. Comprehensive testing strategy.

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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. Swelling can lead to increases in permeability. Increases in density are caused by absorption of the test liquid, indicating high permeability to the test liquid.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on the five materials, baseline specific gravity testing was performed. The results are shown in Figure 2.

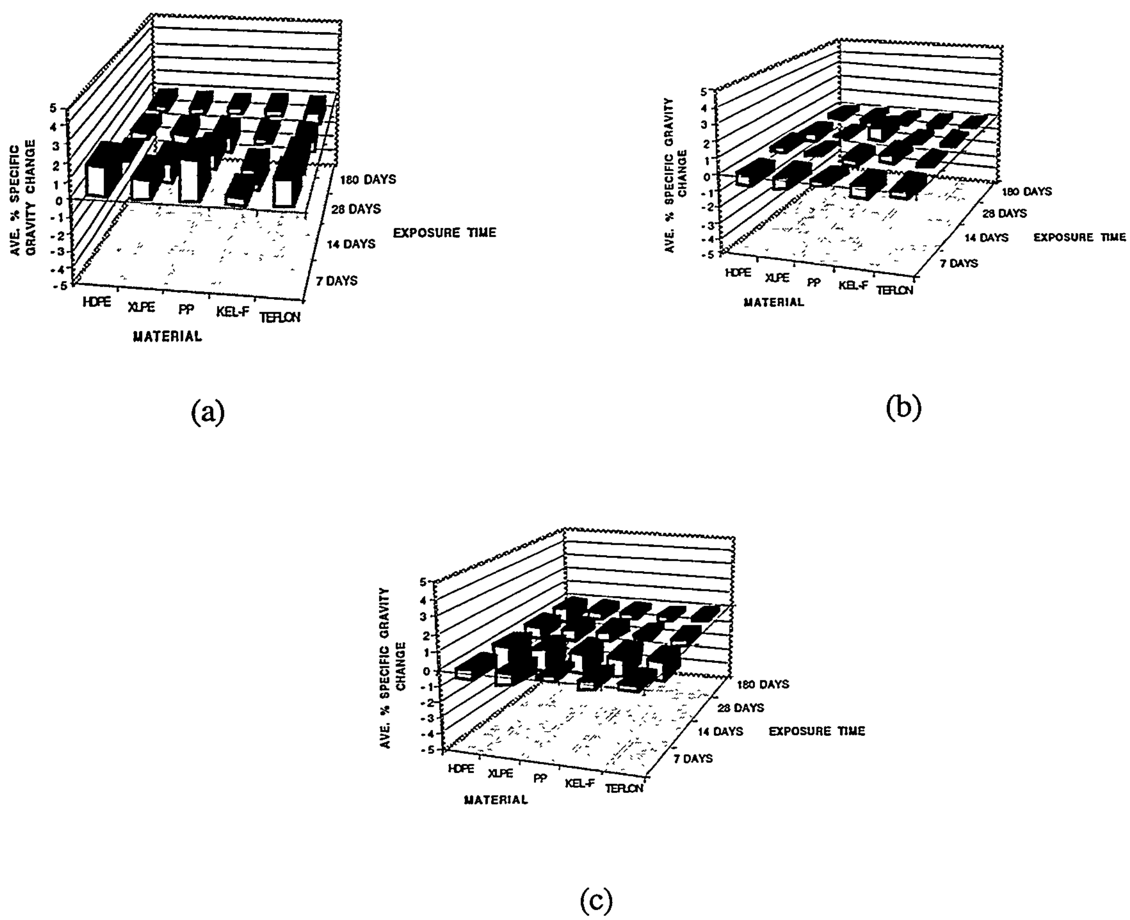


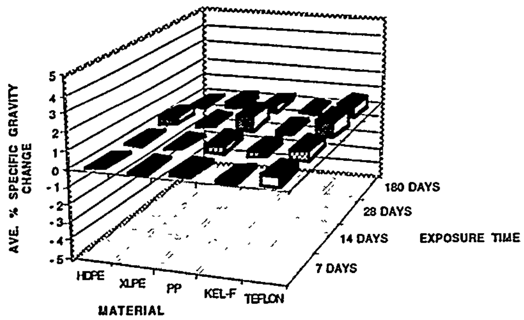
Figure 2. Baseline-specific gravity testing results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

These three-dimensional bar graphs provide a plot of material, exposure time, and average percent specific gravity change (% S.G. change) in the x,y, and z directions, respectively. It should be noted that the scale for % S.G. change is rather small, e.g., from 1 to 5%, and either positive or negative. In Figure 2 and all subsequent figures, negative changes can be recognized by the very dark-colored bars, which also project into the negative portion of the bar graphs. The sign of the specific gravity indicates whether specific gravity has increased or decreased when compared to the pristine materials, i.e., the materials' specific gravity 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 effected by contents of the package; i.e., the mixed wastes, materials exhibiting the smallest changes in specific gravity, should be selected as packaging components. From an overall perspective, the data in Figure 2 show that neither temperature of the simulant nor exposure time has any dramatic effect on the specific gravity of the materials since changes in excess of 2% are not observed. These results are consistent with the known chemical resistance of these materials. However, since the main purpose of these baseline measurements was to help understand the effects of a combination of gamma radiation and chemicals on the material, we now proceed to describe these data.

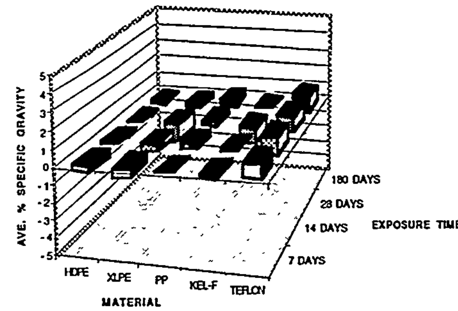
Figure 3 shows the results of four gamma ray doses followed by exposure to the aqueous simulant waste at 18°C for 7, 14, 28, and 180 days. All materials, with the exception of Teflon®, had specific gravity changes of less than 1% under these conditions. For Teflon®, it can be observed that, starting at the lowest gamma dose of 140 krads (Figure 3a), specific gravity changes progressively increase to nearly 2%. The latter value is reached for Teflon® exposed to ~3.7 Mrads of gamma radiation followed by 180-day exposure to the simulant (Figure 3d).

Figure 4 shows the results of exposure to four gamma rays doses followed by exposure to the aqueous simulant waste at 50°C for 7, 14, 28, and 180 days. Similar to the data obtained at 18°C (Figure 3), Teflon® stands out in that specific gravity changes progressively increase until, in Figure 4d, values of nearly 3% can be observed. Additionally, a close comparison of the data in Figure 3a-d and Figures 4a-d shows that the higher temperature has generally increased the response of the materials, especially in Teflon®.

Figure 5 shows the results of exposure to four gamma ray doses followed by exposure to the aqueous simulant waste at 60°C for 7, 14, 28, and 180 days. Similar to the 50°C data given in Figure 4a-d, Teflon® shows the greatest response under these conditions. At the highest gamma ray dose of ~3.7 Mrads, Teflon® showed specific gravity changes as large as 2.4%.



(a)



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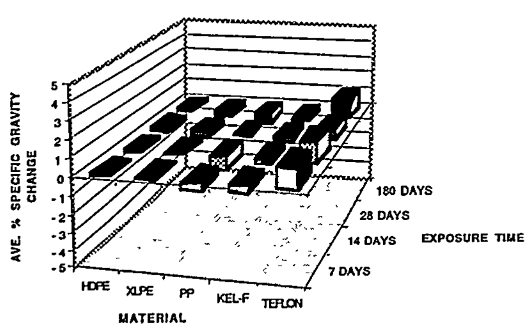

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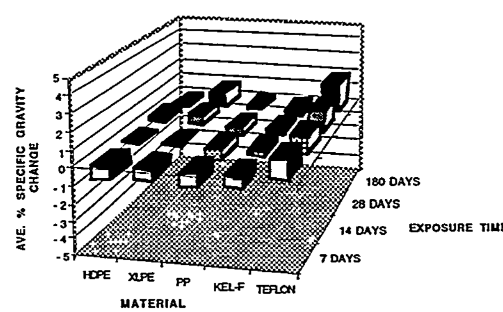
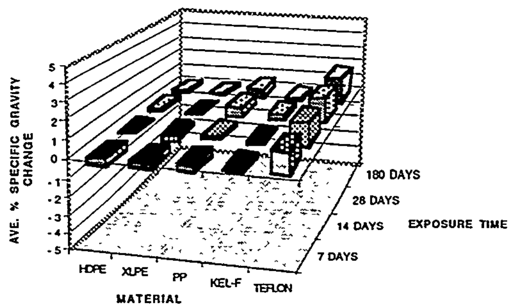
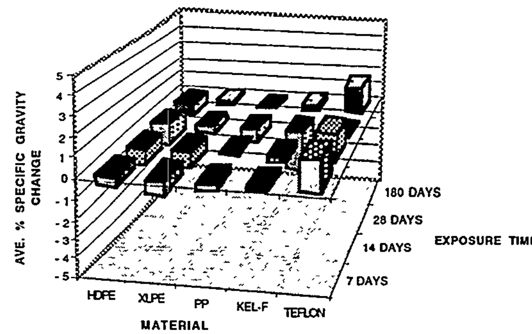


(d)

Figure 3. Specific gravity testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C.



(a)



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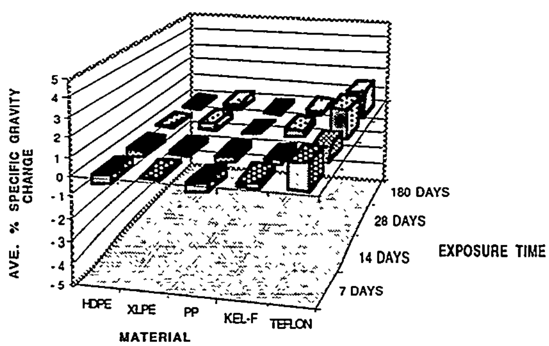
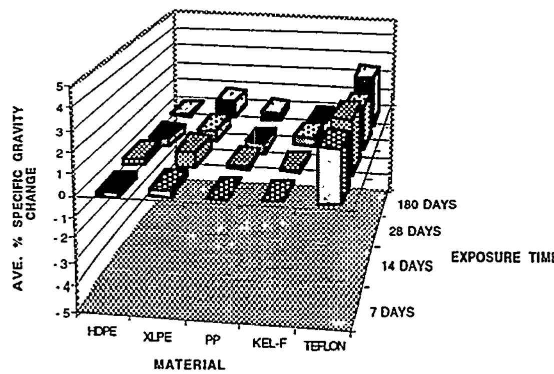


(c)



(d)

Figure 4. Specific gravity testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 50°C.

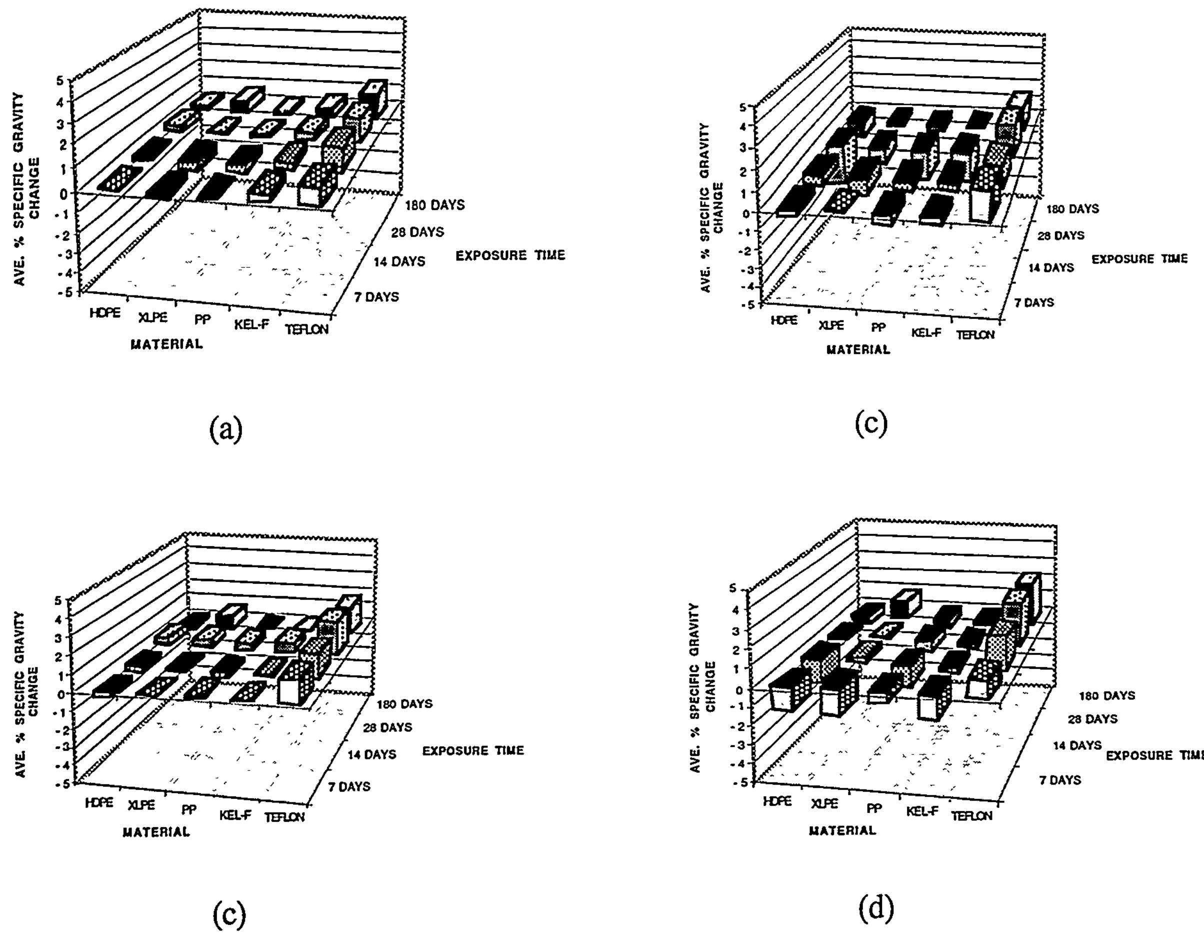


Figure 5. Specific gravity testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 60°C.

The data presented in Figures 2 through 5 are meant to provide a graphical presentation of changes in specific gravity for the baseline samples and the samples exposed to a combination of four gamma radiation doses, four exposure times, and three temperatures. From these graphs, it is very difficult to extract specific values for individual materials and exposure conditions. The data can be obtained from Appendix B. The data in Appendix B provide a listing of average specific gravity and percent specific gravity changes at the four exposure times. The appendix is divided into four sections. The first section contains baseline data, while the next three sections contain the mixed-waste simulant data. For example, the second section contains the data of the four liner materials exposed to the four gamma ray doses followed by exposure to the simulant at 18°C. The designators for the data are given by a temperature value followed by the radiation dose. An example of this designation is 18°C, 143 K. This example indicates that the data contained under this subsection involve samples that were first exposed to 143 krads of gamma radiation followed by exposure to the simulant at 18°C. The other sections contain data obtained at the other two temperatures of 50 and 60°C.

Based on the specific gravity results presented here, it is worthwhile to attempt to identify the one material that displayed the greatest chemical compatibility with the simulant mixed waste under these conditions. In order to accomplish this, a ranking scheme needed to be developed. To develop the ranking scheme, we first summed the specific gravity changes at each combination of conditions and calculated an average specific gravity change. From the data in Figure 5d, for example, the values for each of the materials at the four exposure times were added and divided by four. We therefore obtained an average specific gravity change value over the four exposure times for each of the materials. That material which was found to have the lowest absolute value of average specific gravity change, i.e., changed the least, was assigned an arbitrary value of one. The other materials were then given values from two to five in the order of increasing average property change values. Now, by adding the ranking values at each radiation exposure dose (adding the ranking values of Figure 5a-d), a total ranking value at 60°C can be calculated. Repeating this process at the other two temperatures completes this scheme. The ranking scheme developed in this manner is given in Table 1. The material with the best response should have the lowest value in specific gravity changes for all the three temperatures. This can be determined by adding the rankings for each material and choosing the material with the lowest value. As can be seen in Table 1, this very simplistic approach has selected HDPE as the material that is most compatible with this simulant mixed waste under these conditions *when specific gravity changes are used as the metric.* In fact, HDPE appears to be the best material while Teflon® was the worst. However, it can also be seen that the ranking at each temperature could be different. For example, at 60°C XLPE and PP rank equally. If one is making general comparisons, however, HDPE should be considered the material of choice.

Table 1. Material Ranking Based on Specific Gravity Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	4	11	14	11	20
50°C	9	12	10	9	20
60°C	13	8	8	11	20
Total	**26**	**31**	**32**	**31**	**60**

When a similar process is applied to the baseline samples data shown in Figure 2a-c, the ranking given in Table 2 was obtained. For this baseline data it can be seen that quite opposite results are obtained. In the absence of radiation exposure, Teflon® was found to be the best material while

HDPE was the worst material. *These results dramatically point out the need for testing of plastic packaging components under actual-use conditions rather than simply choosing materials from the many commercially available chemical resistance charts.* Since all chemical resistance data found in the literature only takes into account chemical effects, the selection of plastic packaging components from such data sources could lead to catastrophic failures of these materials in the presence of radiation and chemicals.

Table 2. Material Ranking Based on Specific Gravity Changes Without Irradiation

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	2	1	4	3	1
50°C	5	4	1	3	2
60°C	5	4	3	2	1
Total	**12**	**9**	**8**	**8**	**4**

In subsequent sections, a similar process will be used to rely on this ranking scheme to identify the best and worst materials using different metrics. These other metrics consist of dimensional changes, hardness changes, stress cracking, and tensile property changes. In the following section, we will present the results of the effects of the simulant waste and a combination of radiation and the simulant on the dimensional properties of the five materials.

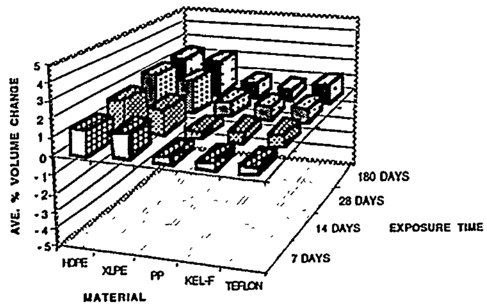
Dimensional Properties

Similar to the measurement of specific gravity, or density changes, the measurement of changes in dimensional properties can provide important information about the effects of different environments on materials. Specifically, the swelling of the material or leaching of components of the material will be manifested by increases or decreases in the dimensions of the material. The dimensional properties measured and reported in this section will be changes in length, width, and thickness of the materials. In addition, since the standard test method ASTM D-543 used to measure dimensional properties includes the determination of mass as part of the test, this property was also measured. While this mass data was acquired as part of dimensional measurements, we will not discuss it here. The data can, however, be found in Appendix C-1. Similarly, because of the large amount of data accumulated for measuring dimensional changes (length changes, width changes, and thickness changes), we have chosen to describe dimensional changes by evaluating the product of these changes, i.e., volume (length x width x 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. As for the mass change data, the respective dimensional data (volume, length, width, and thickness) can be found in Appendix C. The effects of the different environments on the volume changes will be discussed now.
To measure the effect of exposure time and exposure temperature of the aqueous simulant on the

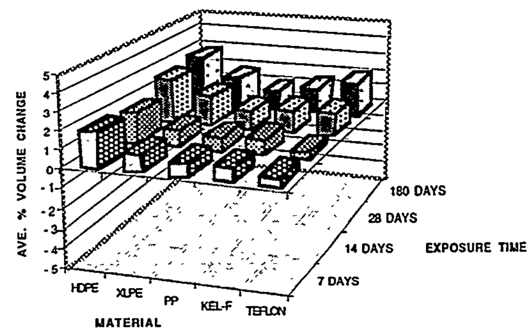
five materials, dimensional testing was performed on materials exposed only to the surrogate waste at three temperatures and four exposure times. The results are shown in Figure 6a-c. Similar to data shown in the previous section, the scale for average % volume change is relatively small, e.g., from 1 to 5%. The sign of the volume changes indicates whether the volume of the material has increased or decreased when compared to the pristine materials, i.e., material volume at ambient conditions. Therefore, changes in the magnitude and the sign of % volume change values vary for this property. The greater the absolute values of the changes, the more the materials are affected by this set of environmental conditions. Since properly engineered packaging components are not expected to be affected by contents of the package, the mixed wastes, materials exhibiting the smallest changes in volume should be selected as packaging components. From an overall perspective, the data in Figure 6 show that neither temperature of the simulant nor exposure time has any dramatic effect on the volumes of the materials since changes in excess of ~3% are not observed. A statistical analysis reveals that the standard deviations of the data vary from ~0.1 to nearly 1%. These results indicate that volume changes are certainly within the values shown in Figure 6. As can be seen from the data, an increase in temperature results in increases in volume change. The greater the temperature increase, the larger the volume changes. Also to be noted is that Teflon® exhibits the smallest changes in volume, while HDPE has the largest volume changes.

In Figure 7a-d, the average % volume changes of five liner materials exposed to four gamma radiation doses followed by exposure to the aqueous simulant waste at 18°C for 7, 14, 28, and 180 days are given. All materials had volume changes of less than ~2% under these conditions. For many of the materials, it can be observed that with increased exposure time, there is a corresponding increase in the % volume change. The greatest increase in % volume changes can be seen in Figure 7d, where XLPE and PP exhibited the greatest % changes in volume. Additionally, Teflon® appears to exhibit a decrease in (negative) % volume changes when exposed to ~570 krads followed by simulant exposure (Figure 7c). However, this trend is not continued at the higher radiation dose of ~3.7 Mrads.

In Figure 8a-d, the average % volume changes of five liner materials exposed to four gamma ray doses followed by exposure to the aqueous simulant waste at 50°C for 7, 14, 28, and 180 days are given. Under these conditions, most materials had volume changes of less than ~2%. What is also interesting to note is that Teflon® starts to decrease in volume upon exposure to ~290 krads. The data in Figure 8c-d reflect a gradual increase in the decrease of volume change, i.e., volume decreases from ~-1% to more than -2%. Another interesting aspect of this material is that, with increased exposure time, the decrease in loss of volume becomes less pronounced. This is counter-intuitive from the expected behavior. While only speculative at this point, two competing mechanisms may be operational for this behavior. The competing mechanisms involve leaching and swelling of Teflon®.



(a)



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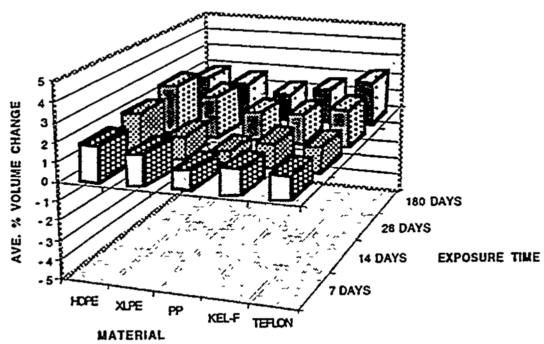
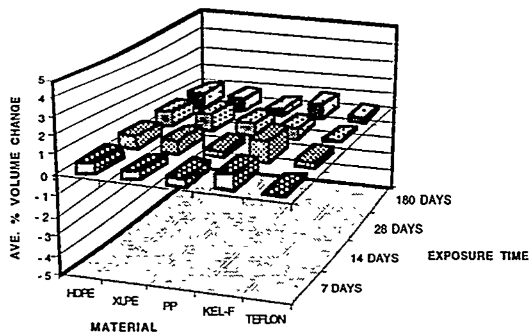
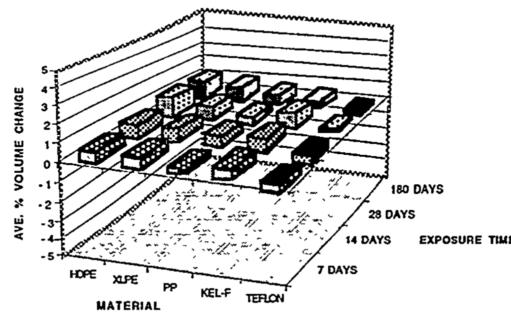


(c)

Figure 6. Dimensional testing results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).



(a)



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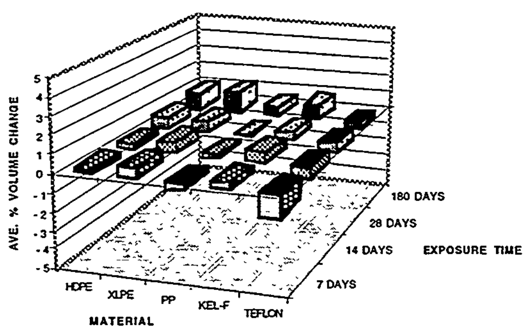
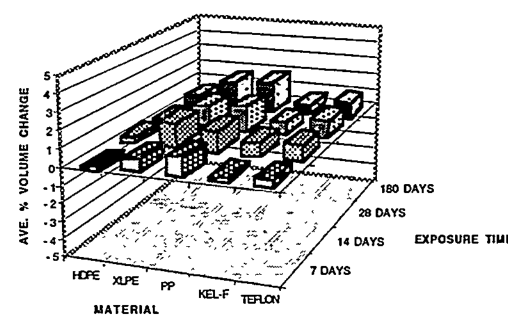


(c)



(d)

Figure 7. Dimensional testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C.

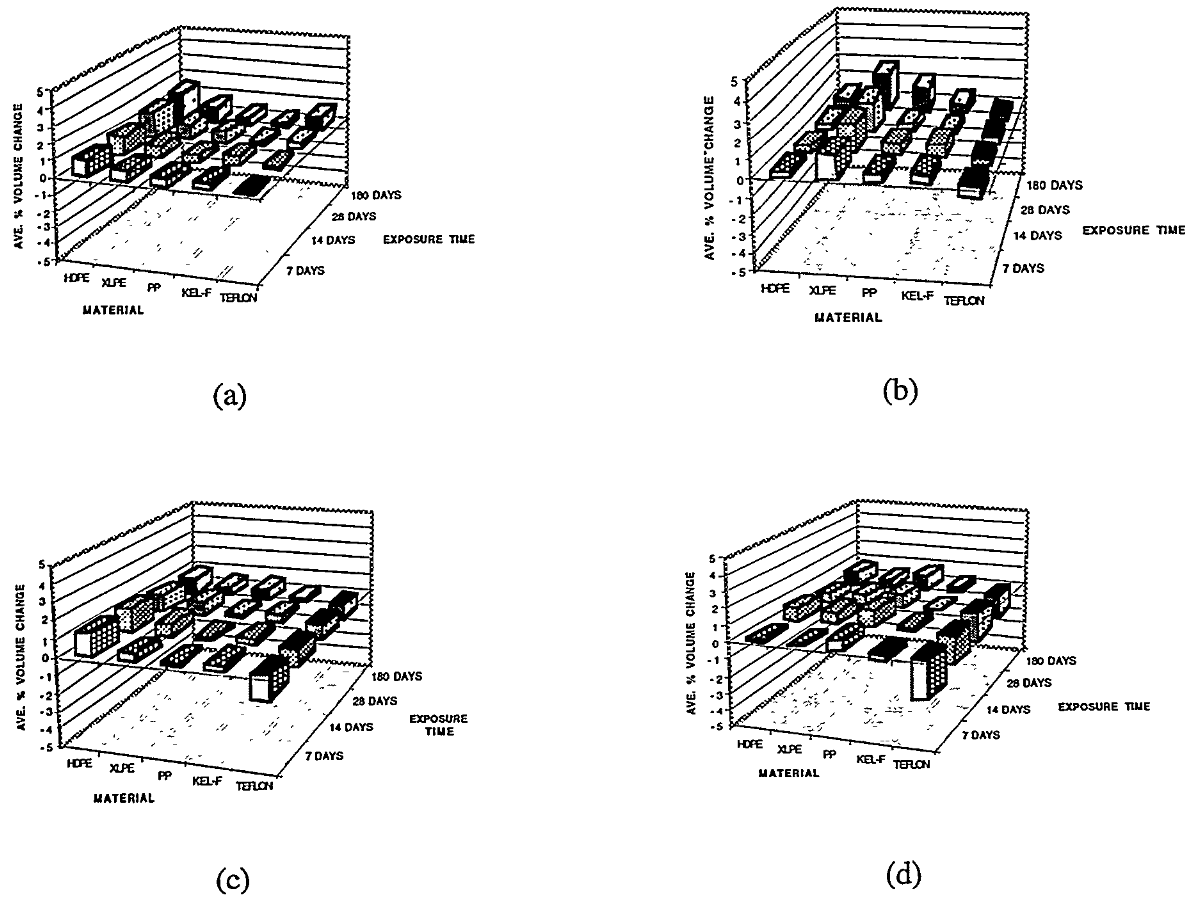
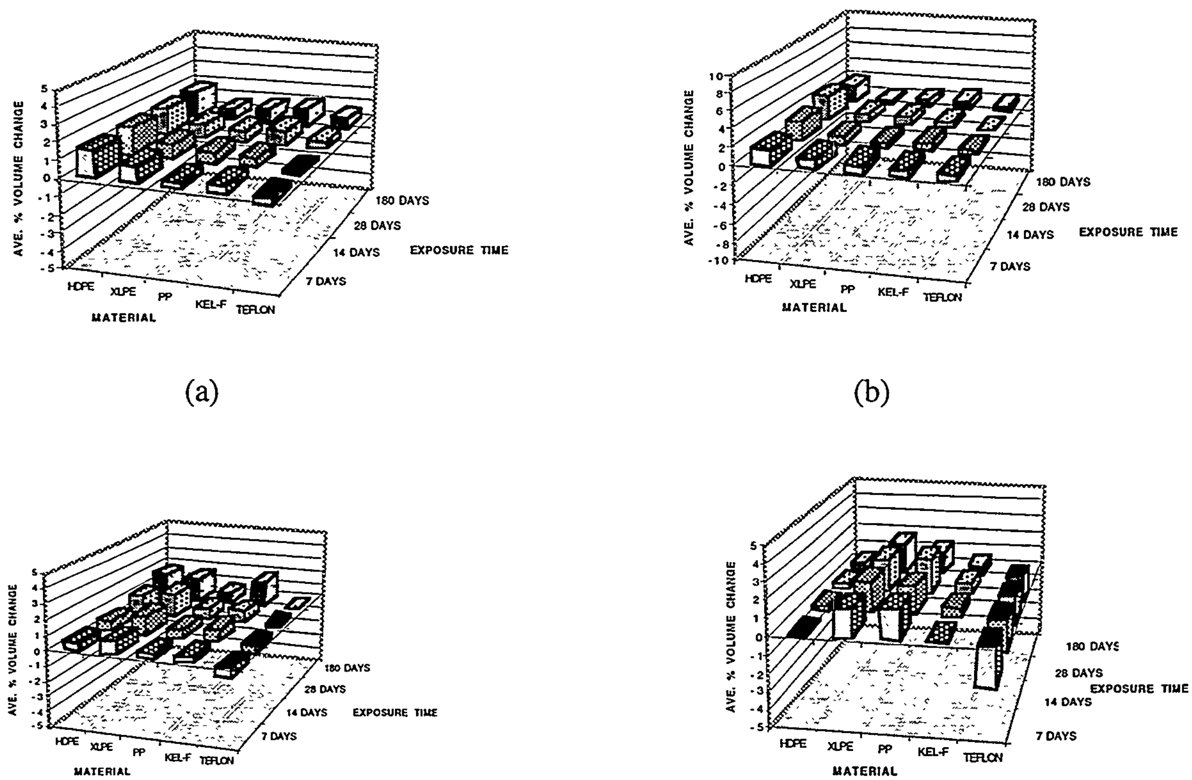


Figure 8. Dimensional testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 50°C.

In Figure 9a-d, the average % volume changes of five liner materials exposed to four gamma ray doses followed by exposure to the aqueous simulant waste at 60°C for 7, 14, 28, and 180 days are given. Under these conditions, most materials had volume changes less than ~2%. However, for XLPE and PP, an increase of volume change to above 2% can be seen after exposure to ~3.7 Mrads of gamma radiation and simulant (Figure 9d). This is in contrast to the observed response of these materials at 50°C. Similar to the behavior of Teflon® at 50°C under these conditions, the volume began to decrease after Teflon® had been exposed to ~290 krads of gamma radiation. Under these conditions, most materials had volume changes of less than ~2%.



(a) (b) (c) (d)

Figure 9. Dimensional testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 60°C.

Using the material ranking scheme discussed in the previous section, a material ranking with volume change as a metric was developed. This ranking is shown in Table 3. From these results, it can be seen that Kel-F™ had the best response, while HDPE had the worst. When a similar approach was used to develop a ranking based on the volume changes of the baseline samples (Figure 6a-c), Kel-F™ was also identified as the best material, while XLPE was the worst material.

Table 3. Material Ranking Based on Volume Changes for Radiation and Simulant Exposures

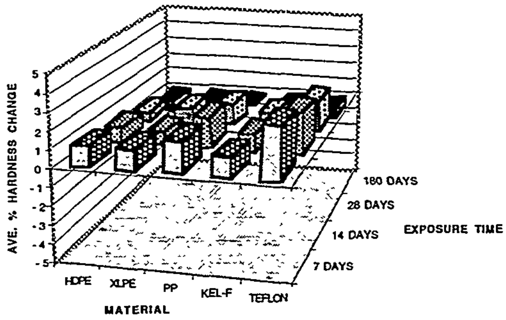
Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	13	16	10	12	10
50°C	14	14	12	7	13
60°C	16	16	10	10	8
Total	**43**	**46**	**32**	**29**	**31**

Hardness Properties

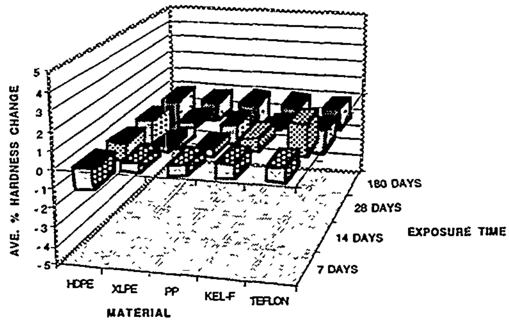
The measurement of changes in the hardness of materials can provide important clues as to the effects of environmental conditions on the material. If the hardness of the material decreased, swelling of the material may have occurred. Alternatively, the polymer may have substantially degraded. Conversely,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

The measurement of hardness involves the use of a standard instrument manufactured by Shore Instrument Company known as a Shore durometer. The degree of hardness that the plastic material exhibits will dictate the type of durometer to be used. For thermoplastics, which in relative terms tend to be rather hard, a Type D durometer is required. Similar to the approach used for the previously described property measurements, the initial hardness values were determined for pristine samples, i.e., samples not exposed to anything. Using these initial hardness values, % hardness changes were measured for samples that were exposed to only the simulant 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.

To measure the effect of exposure time and exposure temperature of the aqueous simulant on the five materials, hardness testing was performed on the materials exposed only to the surrogate waste at the three temperatures and four time periods. The results of these measurements is shown in Figure 10a-c. 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 effected by the packaging contents. Those materials with the least changes in hardness should be considered as candidate packaging components. An inspection of the results shown in Figure 10a-c, reveals that in general the hardness of the materials decreases with increasing time and temperature of exposure to the simulant. When the liner materials where exposed to the simulant at 18°C for 7 days, the hardness was found to increase from 1% to ~2% over that of the pristine materials. At longer exposure times and higher temperatures, the materials became 1 - 2% softer than the pristine materials. In fact, at 60°C (Figure 10c), nearly all materials became softer. These results suggest that exposure to the chemicals results in plasticization of the materials. Since increases in volume changes at these temperature (Figure 6a-c) were observed, this plasticization appears to be due to the swelling of the material. We will now proceed to discuss the effects of a combination of radiation and the simulants on the hardness of the materials.



(a)



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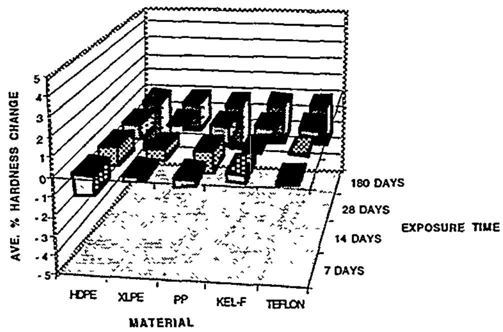


(c)

Figure 10. Hardness testing results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

In Figure 11a-d, the average % hardness changes of the five liner materials exposed to four gamma ray doses followed by exposure to the aqueous simulant waste at 18°C for 7, 14, 28, and 180 days are given. Under these conditions, most materials had volume changes of less than ~2%. The notable exception to this observation was Teflon®. Beginning at the lowest radiation dose of ~140 krads, the % hardness change decreases from ~-3% to over ~-12% for the

~3.7 Mrad dose. These results show that Teflon® is very sensitive to radiation exposure followed by simulant exposure.

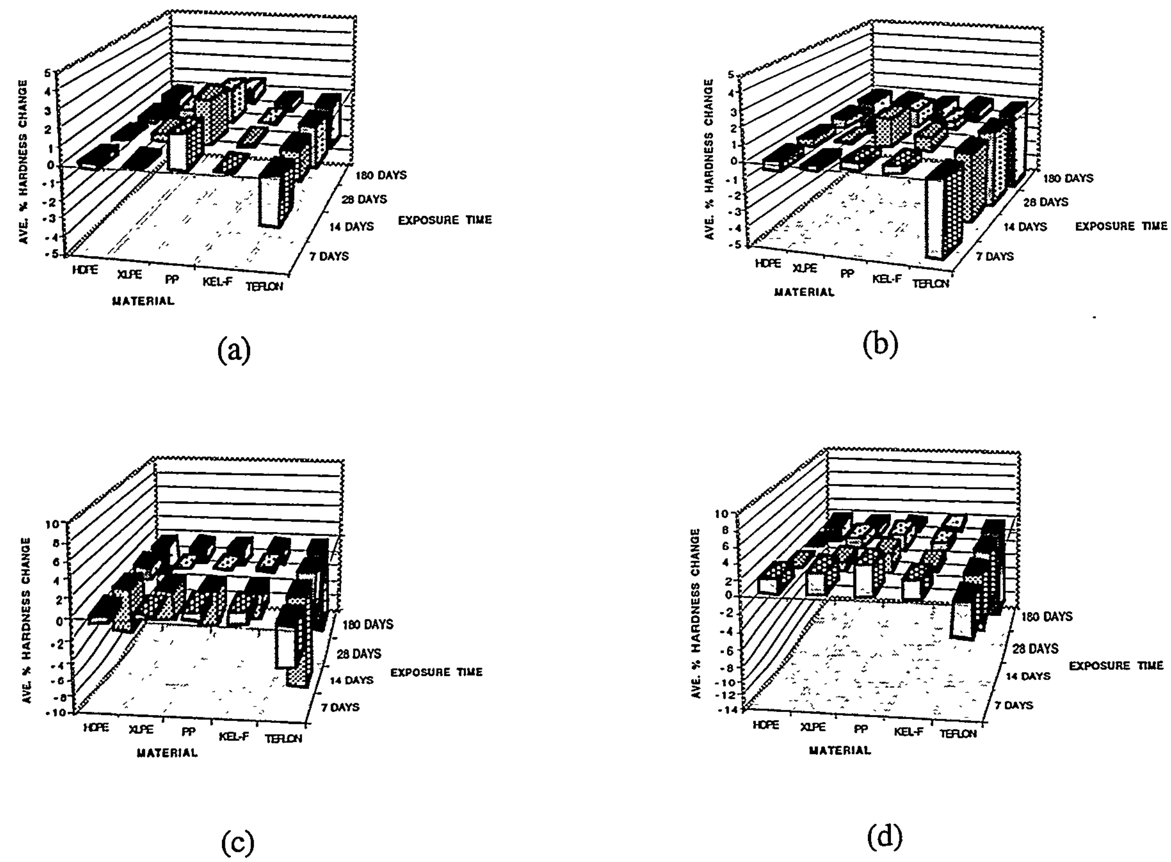


Figure 11. Hardness testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C. *Note: There is a scale change for graphs (c) and (d).*

In Figure 12a-d, the average % hardness changes of the five liner materials exposed to four gamma ray doses followed by exposure to the aqueous simulant waste at 50°C for 7, 14, 28, and 180 days are given. Under these higher temperatures, most materials again had volume changes less than ~2%. Again, the notable exception was Teflon®. Beginning at the lowest radiation dose of ~140 krads, the % hardness change decreases from ~-3% to over ~-13% for the ~3.7 Mrad dose. These results again show that, at higher temperatures, Teflon® is very sensitive to radiation exposure followed by simulant exposure. More samples became softer than the pristine material when exposed to this much higher exposure temperature, i.e., exhibited negative hardness changes.

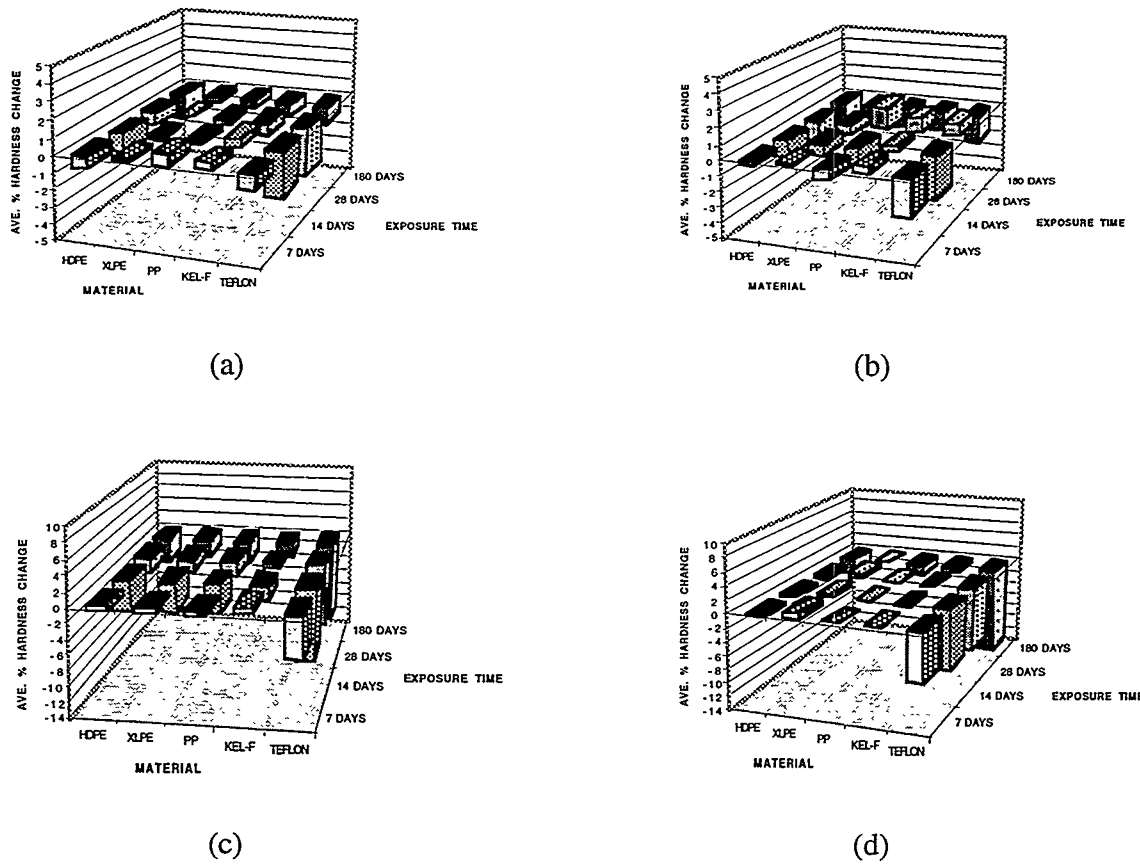
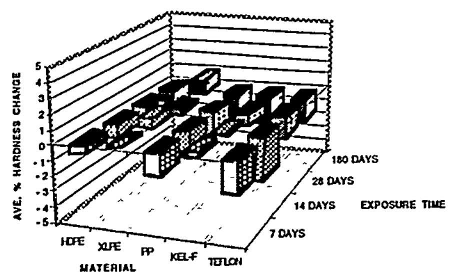
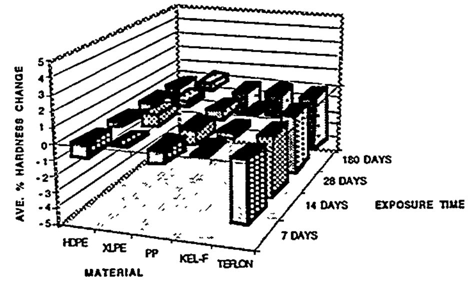


Figure 12. Hardness testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 50°C. *Note: There is a scale change for graphs (c) and (d).*

In Figure 13a-d, the average % hardness changes of the five liner materials exposed to four gamma ray doses followed by exposure to the aqueous simulant waste at 60°C for 7, 14, 28, and 180 days are given. Under these even slightly higher temperatures, most materials again had volume changes less than ~2%. Again, the notable exception was Teflon®. Beginning at the lowest radiation dose of ~140 krads, the % hardness change decreases from ~-3% to over ~-14% for the ~ 3.7 Mrad dose. These results again show that, at higher temperature, Teflon® is very sensitive to radiation exposure followed by simulant exposure. The much higher exposure temperatures also caused more materials to exhibit negative hardness changes; i.e., more samples became softer than the pristine material. Appendix D gives detailed hardness data.



(a)



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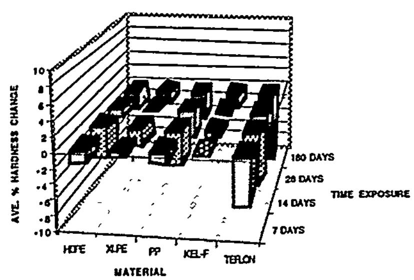
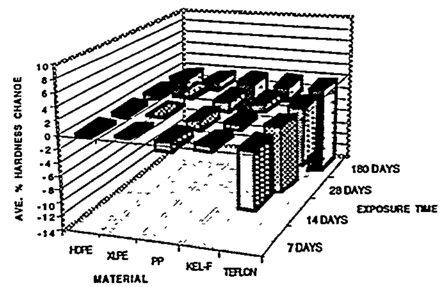


(c)



(d)

Figure 13. Hardness testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 60°C. *Note: There is a scale change for graphs (c) and (d).*

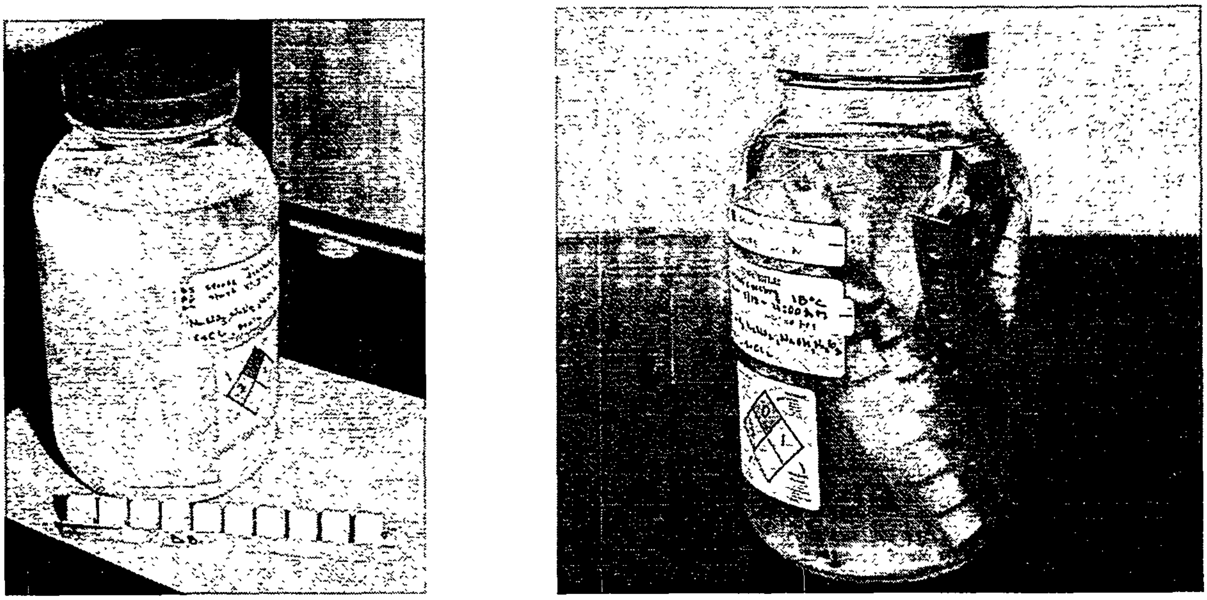
Using the material ranking scheme discussed in the previous section, a material ranking with volume change as a metric was developed. This ranking is shown in Table 4. From these results, it can be seen that Kel-F™ had the best response while HDPE had the worst. When a similar approach was used to develop a ranking based on the volume changes of the baseline samples (Figure 6a-c), Kel-F™ and XLPE were identified as the best materials while HDPE was the worst material.

Table 4. Material Ranking Based on Hardness Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	12	7	13	8	20
50°C	16	10	8	6	20
60°C	11	5	16	8	20
Total	**39**	**22**	**37**	**22**	**60**

Stress Cracking

Environmental stress cracking is a form of chemical attack in which a chemical that does not appreciably attack or dissolve a polymer in an unstressed state will cause catastrophic failure when the polymer is stressed in its presence. Initiation and propagation of cracks occur prior to physical failure of the material. The stress-cracking phenomena are a recognized potential problem with some varieties of HDPE and other semi-crystalline polymers. For this reason, a specific standardized test, ASTM D 1693, has been developed. Of the materials considered in this study, only HDPE and XLPE were subjected to this test. In this test, bent specimens of the plastic, each having a controlled imperfection on one surface, are exposed to the environmental conditions. Figure 14 shows an example of the experimental configuration used for stress-cracking experiments.

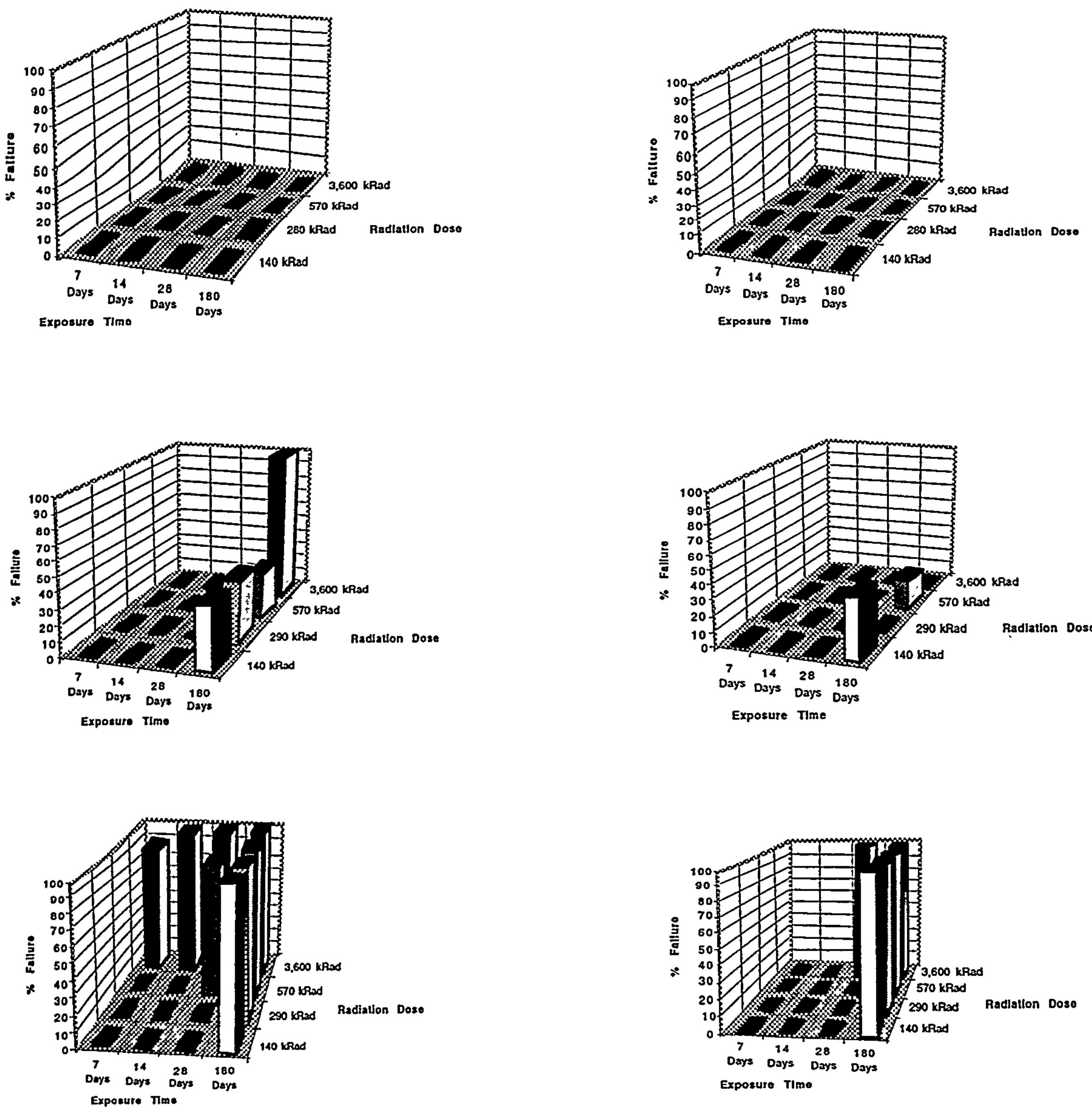


(a) (b)

Figure 14. Stress-cracking experiments. (a) Photograph shows sample fixture in front of exposure cell containing only HDPE samples. (b) Exposure cell with HDPE and XLPE samples.

Since we wanted to understand effects of radiation alone, samples exposed to only the four radiation doses (i.e., no chemical exposure), the three temperatures, and the four exposure times were analyzed. 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 discuss the results of these measurements.

In Figure 15a-b, the % failure of HDPE and XLPE exposed to four gamma ray doses followed by 7, 14, 28, and 180-day exposure at the three temperatures are given. The data at the three temperatures are shown in the graphs from the top down; i.e., the 18°C data is the first pair of graphs on the top of Figure 15, etc. Under these conditions, it can be observed that HDPE is more susceptible to stress cracking than XLPE. This is consistent with the fact that XLPE is commercially produced with chemical cross-linking agents.



(a) (b)

Figure 15. Stress cracking results of HDPE (a) and XLPE (b) after exposure to ~140, 290, 570, and 3,670 krads for 7, 14, 28, and 180 days at 18°C, 50°C, and 60°C, respectively.

Since one of the known mechanisms of radiation-induced damage in polymeric materials is polymer chain scission (polymer chains are shortened), polymers with cross-linking would retain longer polymer chain lengths and subsequently retain their strength. Additionally, it can be seen that at higher temperatures, longer exposure times, and higher radiation doses, increases in failures were observed. Failure constitutes any crack visible to the observer. The data in Figure 15 show that XLPE is superior in performance, under these conditions, to HDPE.

In Figure 16, we show a photograph of HDPE samples that had been exposed to ~3.7 Mrads (3,670 krads) of gamma radiation followed by 180 days at 60°C. As can be seen, all samples cracked at the introduced imperfection. These particular samples represent one bar in the bar graphs given in Figure 15a (180 day, 3,670 krads, 60°C).

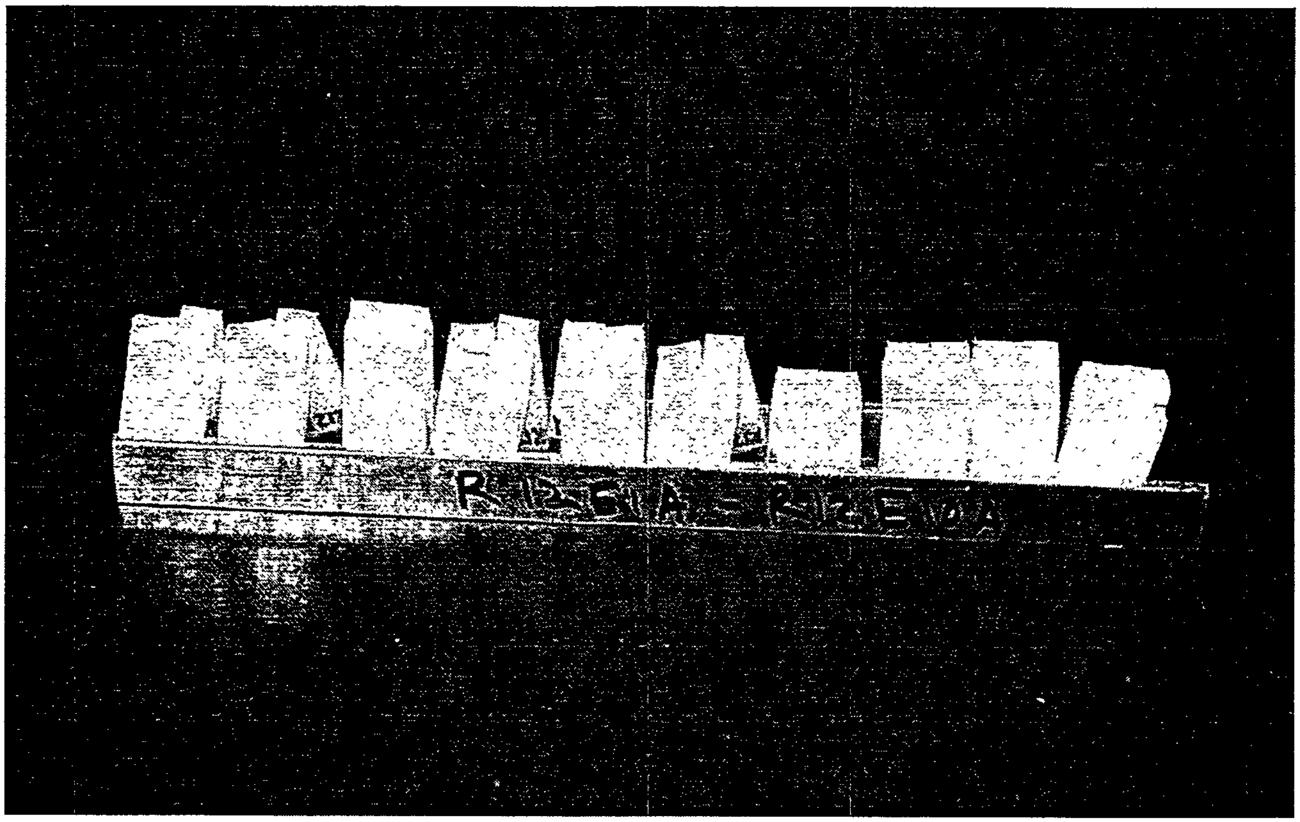
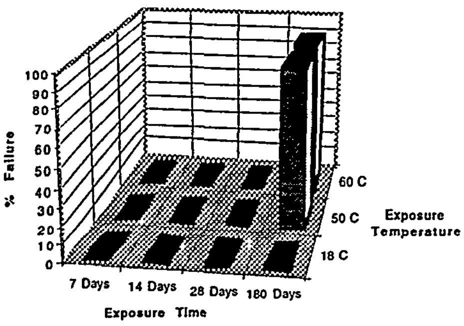
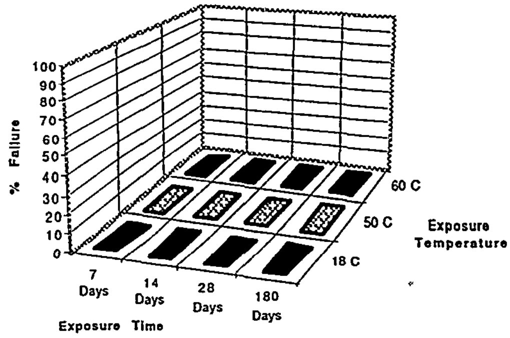


Figure 16. Stress-cracking samples exposed to ~3.7 Mrads of gamma radiation followed by a 28-day exposure at 60°C. All materials failed under these conditions.

In Figure 17, the effects of 7-, 14-, 28-, and 180-day exposure to the aqueous simulant waste at 18°C, 50°C, and 60°C are given. As can clearly be seen from this data, both HDPE and XLPE have good response to the simulant for all exposure times and exposure temperatures. However, as was found for these two materials when exposed to radiation alone, XLPE has better performance than HDPE. The latter material was found to fail after 180-day exposure to the aqueous waste at 50 and 60°C. Based on the results shown in Figures 14 and 15, radiation has a more harmful effect on these two materials than chemicals.



(a)

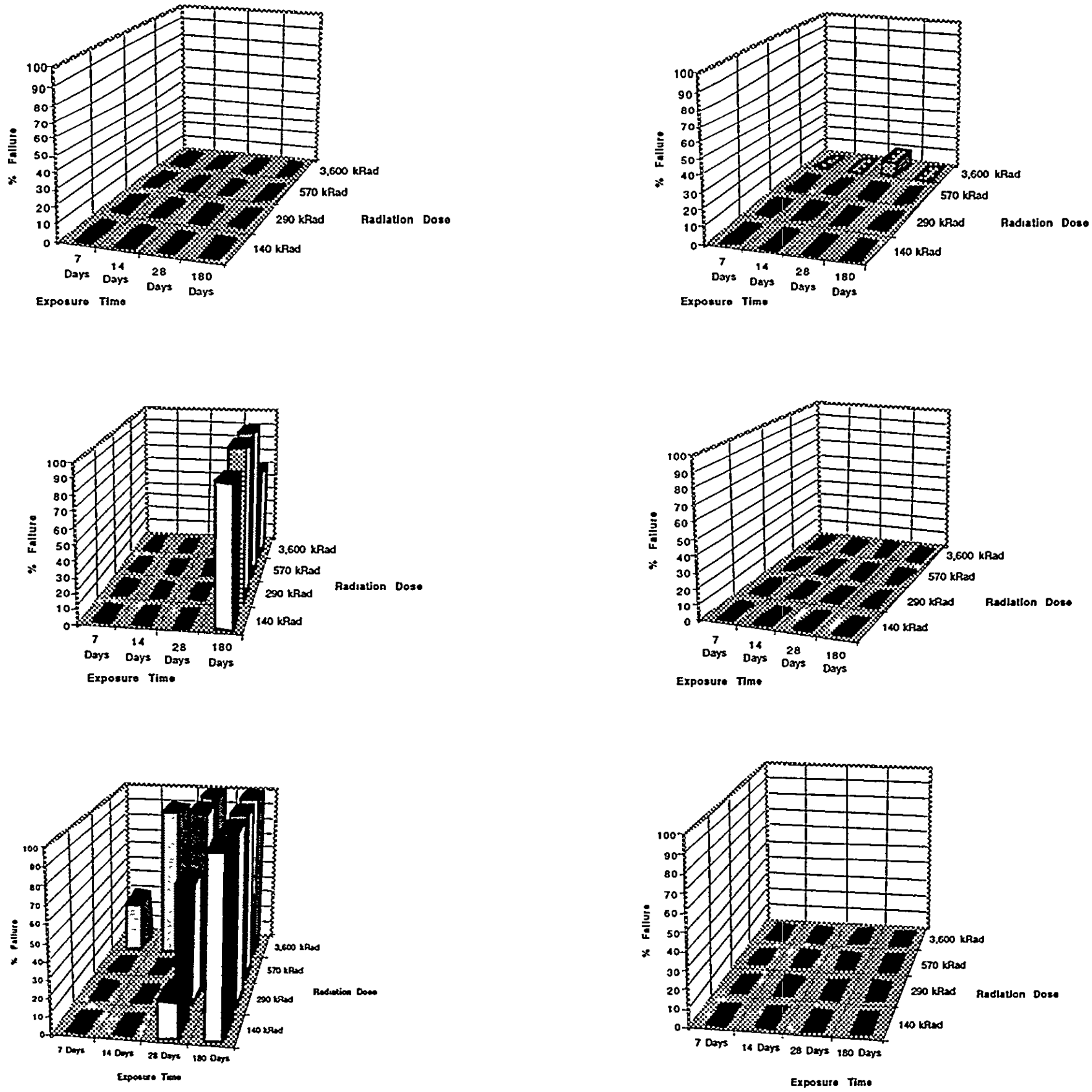


(b)

Figure 17. Stress-cracking results of HDPE (a) and XLPE (b) after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C, 50°C, and 60°C.

In Figure 18, the combined effects of radiation and chemicals are shown. Figure 18 shows the % failures of HDPE and XLPE exposed to the four gamma ray doses followed by 7-, 14-, 28-, and 180-day exposure to the aqueous simulant waste at 18°C, 50°C, and 60°C, respectively. Consistent with previous results, XLPE has better performance than HDPE under these conditions. A close comparison between the effects of radiation alone (Figure 15) and the results shown in Figure 18 reveals that the combination of radiation and chemical exposure of these two materials has a greater effect than either of these effects alone. These results clearly point to the fact that mixed waste, especially mixed waste that generates higher radiation levels, seriously affects polyethylenic materials. Similar to the previous results with radiation alone and simulant alone, increased failures are observed at the longest exposure times, the highest temperatures, and highest radiation doses. This can be seen most dramatically in Figure 18a, i.e., HDPE exposed to the different conditions at 60°C. In this graph, failures begin to be observed at a combination of conditions as low as ~140 krads of gamma radiation exposure and 7-day exposure to the simulant.

To summarize, from the stress-cracking results described previously, it should be clear that XLPE is the best choice in material selection. This is particularly true for packaging where higher radiation doses, higher temperatures, and longer transportation/storage times are involved. It should be quite obvious that the use of the traditional engineering plastic, HDPE, under these conditions is fraught with potential problems. Since the data shown in Figures 14 through 18 may not be shown quite clearly, Appendix E can be consulted for further clarification.



(a) (b)

Figure 18. Stress-cracking results of HDPE (a) and XLPE (b) after exposure to ~140, 290, 570, and 3,670 krads of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C, 50°C, and 60°C, respectively.

Tensile Properties

Tensile, or mechanical, properties of materials are the properties associated with 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 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 6895. Since we are always calculating the % changes in properties, the units are irrelevant. However, if the actual values are of interest, Appendix F should be consulted.

Another important tensile property to be considered is strain. A stressed material undergoes deformation or *strain* ε, defined quantitatively as either the incremental deformation divided by the initial dimension or as a 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. 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 plastic strain does not mean necessarily that the deformed material is a plastic.

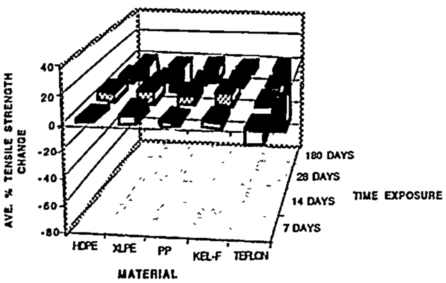
For many materials that might be suitable as plastic packaging components, such as seals and liners, high strengths and high strains are expected. The strains exhibited should also be elastic in nature. In certain instances, however, other specific tensile properties are desirable, i.e., high strength 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 the respective materials. We will now describe the results of these studies.

Tensile Strength

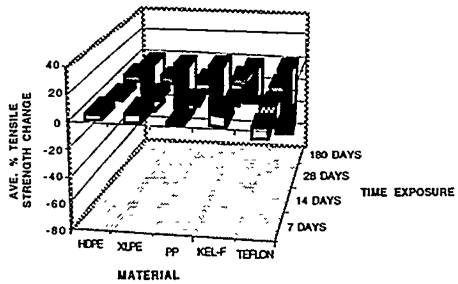
The stress σ_T, the tensile or ultimate strength, of a material is obtained by dividing the greatest load placed on the material during the tensile test by the original cross-sectional area of the material. Since many linear polymers materials exhibit stress-strain curves having an initial maximum followed by lower stresses, a judicious selection of the maximum load is required. This maximum load value was typically at the yield point of the material. For XLPE, where the yield point could not be determined by the testing software in certain instances, the data had to be manually reviewed for maximum stress levels. If this was not performed, the software calculated tensile strength based on the breaking point rather than the yield point. When comparing the tensile strengths of the different materials, it is extremely important that comparable portions of the stress-strain are used in determining σ_T.

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 using user-developed testing methods. These methods prescribe the strain rates and breaking points along with many other experimentally important variables. The selection of these experimental variables was based on the standard test method ASTM D 638. The acquired data were analyzed with software developed by this manufacturer. The software calculates numerous tensile properties. The data discussed in this subsection require a determination of tensile strength. This can be calculated as described previously, using peak loads and cross-sectional area. The calculation of peak stress by the software provides another means to obtain this value. The two sources of tensile strength values should be nearly identical. In addition, the software also provides peak stress, peak strain, break elongation, modulus, yield point, and yield elongation values. In this subsection, we are only interested in tensile strength.

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 only the simulant at the three temperatures and four exposure times are given in Figure 19. In Figure 19a-c, the average % tensile strength changes of the five liner materials exposed to only the aqueous simulant at 18°C, 50°C, and 60°C for 7, 14, 28, and 180 days is shown. Similar to previous property measurements, these % changes were determined by measuring the change in tensile strength from that of the pristine materials. Positive values of % tensile strength changes indicate that the materials' tensile strength had increased under the specific exposure conditions. Negative values indicate decreases in tensile strength.



(a)



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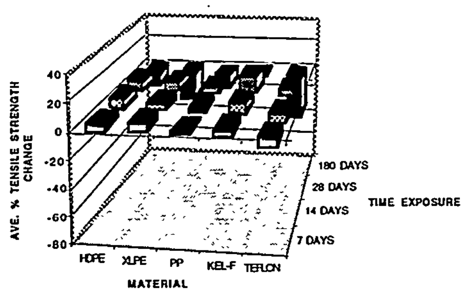


(c)

Figure 19. Tensile strength results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

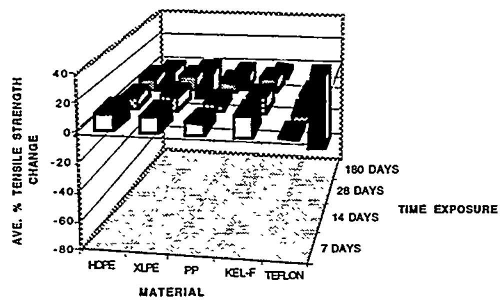
From a general perspective, the data in Figure 19 show that, for exposure times up to 28 days, the temperature of the simulant does not have a significant effect on the tensile strength of the material. Under these conditions, the changes in tensile strength appear to be less than 10%. At the longest exposure time of 180 days, tensile strengths of all the materials decreased.

Using the material ranking scheme discussed in the previous sections, a material ranking with tensile strength change as a metric for samples exposed to the aqueous waste simulant at the three temperatures and four time periods was developed. This ranking is shown in Table 5. From these results, it can be seen that HDPE had the best response, while Teflon® had the worst.

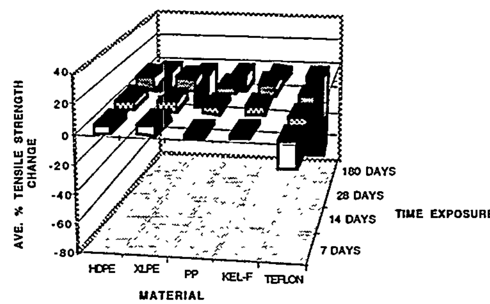
Table 5. Material Ranking Based on Tensile Strength Changes in Samples Exposed to Only the Aqueous Simulant Over All Conditions of Time and Temperature

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	1	2	2	3	4
50°C	1	3	4	2	5
60°C	2	1	1	3	4
Total	**4**	**6**	**7**	**8**	**13**

In Figure 20a-d, the average % tensile strength changes of five liner materials exposed to the four gamma radiation doses followed by exposure at 18°C for 7, 14, 28, and 180 days are given. All materials, except Teflon®, had tensile strength changes below 20% for 28-day exposure times. At the longer exposure time of 180 days, the tensile strength of all materials was negative; i.e., the tensile strength was less than that of the pristine materials. Teflon® stands out in this regard. This material, even at the lowest gamma dose of ~140 krads, has reduced tensile strength. After irradiation with ~3.7 Mrads of gamma radiation and exposure at 18°C for 180 days, Teflon®, with the lowest gamma dose of ~140 krads, has reduced tensile strength. After irradiation with ~3.7 Mrads of gamma radiation and exposure at 18°C for 180 days, Teflon® has lost 70% of its tensile strength.



(a)



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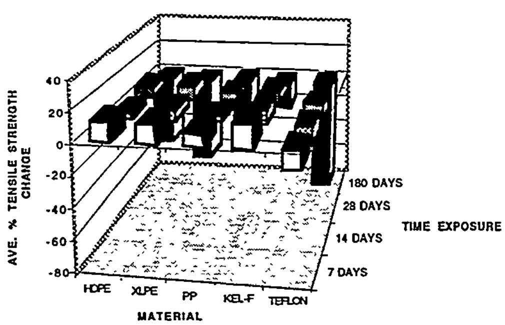

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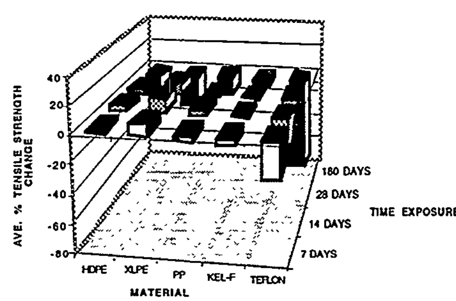


(d)

Figure 20. Tensile strength results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 18°C.

Figure 21 shows the % tensile strength changes of five liner materials exposed to four gamma radiation doses followed by exposure at 50°C for 7, 14, 28, and 180 days. Similar to the 18°C data, only at the highest exposure duration and for Teflon®, does one see decreases in tensile strength. A close inspection of the data also revealed that a trend of slight progressively increasing tensile strength appears to occur after 7-, 14-, and 28-day exposures. This could indicate that exposure to these doses of gamma radiation leads to some cross-linking in the polymer that exhibits higher tensile strength. Such a cross-linking mechanism is no longer operational when longer exposure times are involved. In this situation, a chain scission or other combination of degradation mechanisms leads to significant reductions in the tensile strength of all materials, especially in Teflon®. For the latter material, tensile strength decreases as high as 77% were observed.

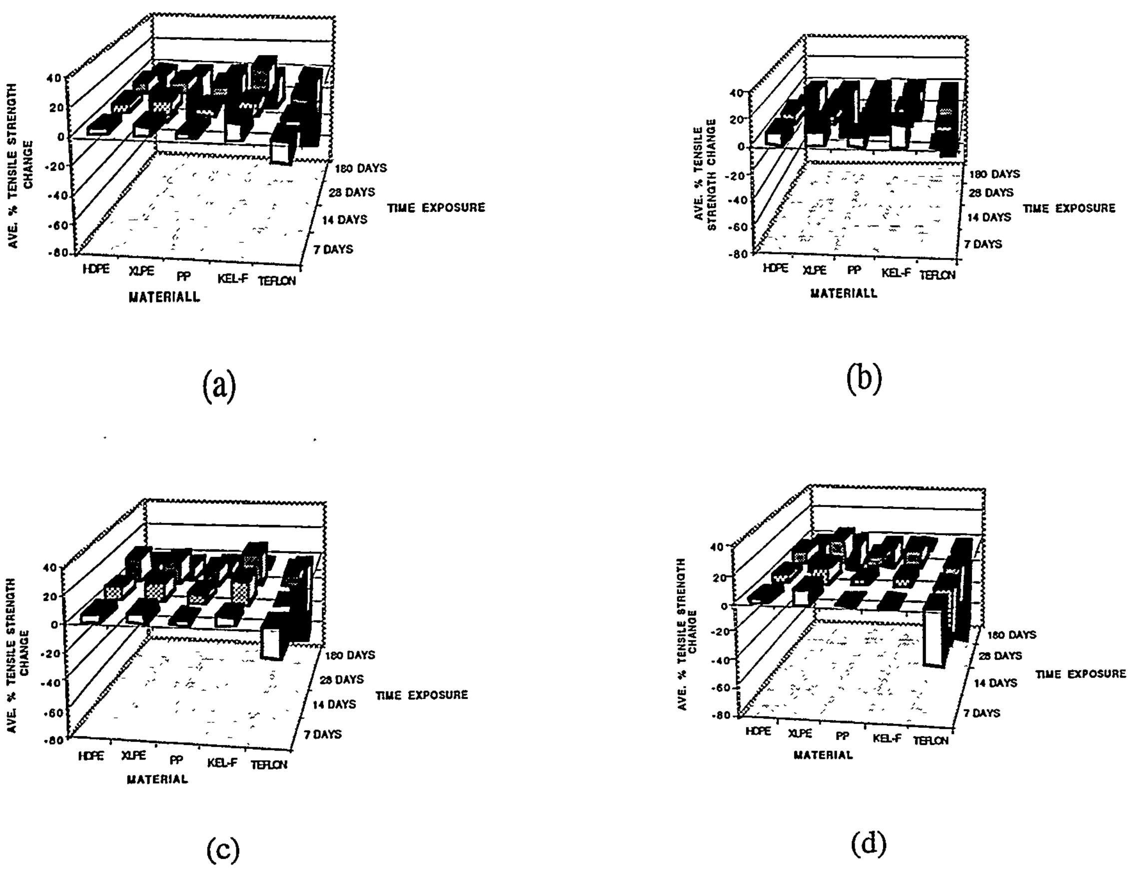


Figure 21. Tensile strength results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 50°C.

The results of exposure of the five materials to the four radiation doses followed by exposure at 60°C for 7, 14, 28, and 180 days are given in Figure 22. The trend that was discussed previously for the 50°C data has continued. All materials except Teflon® exhibit small increases in tensile strength. Teflon® at all radiation doses exhibited decreases in tensile strengths. At the highest radiation dose and longest exposure time, Teflon® lost ~80% of its tensile strength. These results are consistent with the observation that Teflon® becomes extremely brittle when exposed to gamma radiation. In fact, the material is so brittle that loads of as little as 10 lbs cause fracture of the tensile specimens. The practical implication of this experimental finding is that only a limited data set is acquired. The consequences of limited data collection is lower data quality and larger uncertainty in the data. Thus, while it is true that tensile strength has drastically decreased in Teflon® exposed to radiation, the absolute magnitude of this change has large errors associated with it.

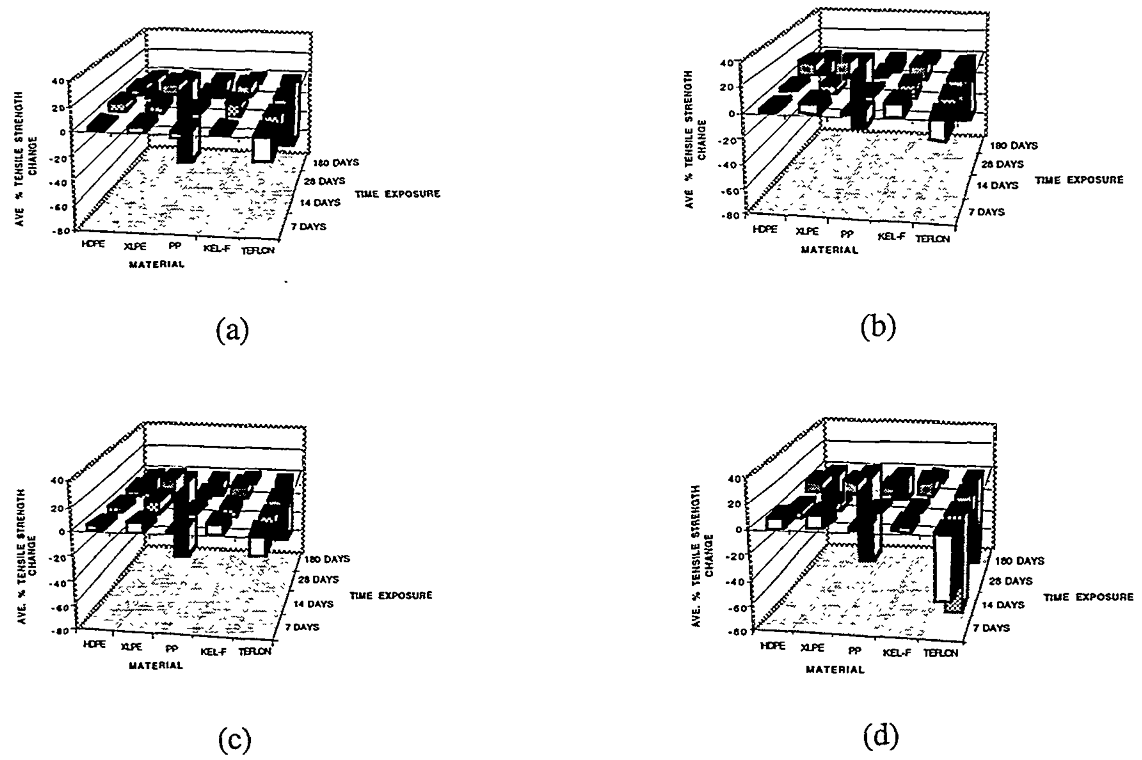


Figure 22. Tensile testing results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 60°C.

Using the material ranking scheme discussed in the previous sections, a material ranking with tensile strength change as a metric for samples exposed to gamma radiation followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 6. From these results, it can be seen that PP had the best response, while Teflon® had the worst. It should be noted that, while PP had the best performance under these conditions, HDPE performed nearly as well as PP. Teflon® stands out in that it performs poorly under all the conditions evaluated.

Table 6. Material Ranking Based on Tensile Strength Changes in Samples Exposed to Gamma Radiation

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	7	7	6	8	15
50°C	10	10	9	10	18
60°C	5	14	6	9	19
Total	**22**	**31**	**21**	**27**	**52**

Now that the effects of the simulant alone and the effects of radiation alone have been presented, we can compare these results with the effects of a combination of radiation and simulant on these materials. Figure 23 shows the % tensile strength changes of five liner materials exposed to four gamma radiation doses followed by exposure to simulant at 18°C for 7, 14, 28, and 180 days.

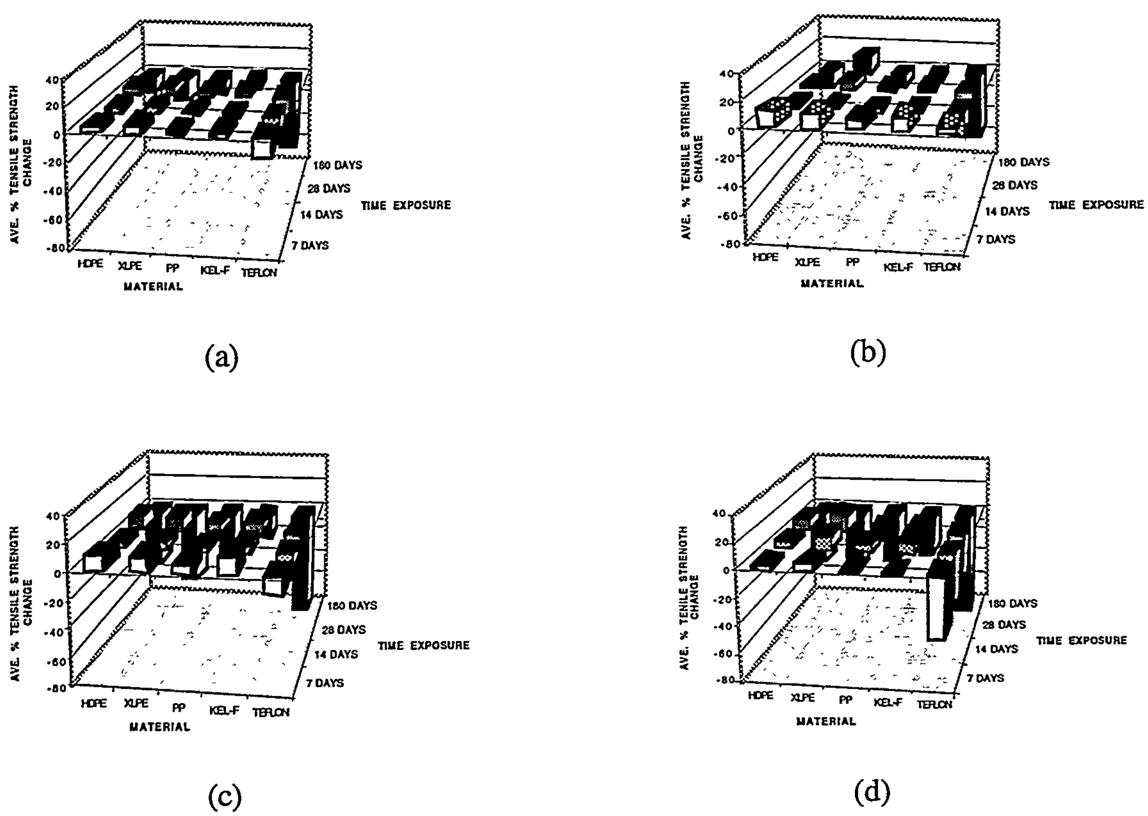


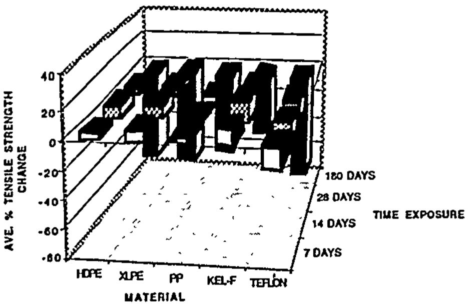
Figure 23. Tensile strength results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 18°C.

Similar to the radiation-alone and simulant-alone data, only at the highest exposure duration and in Teflon® does one see decreases in tensile strength in the materials. As can be seen in Figure 23a-d, HDPE, XLPE, PP, and Kel-F™ exposed to the four radiation doses and the simulant for exposure times up to 28 days exhibited slight increases (~10%) in tensile strength changes. Only the irradiated materials that had been exposed to the simulant for 180 days exhibited a decrease in tensile strength. Teflon® had changes as high as -90% at 18°C.

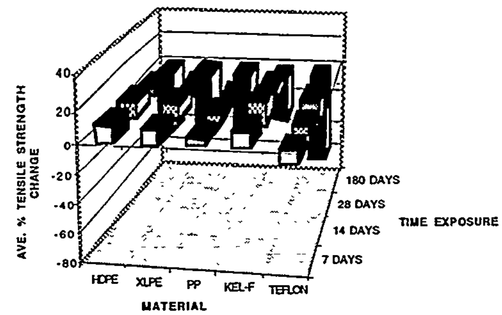
In Figure 24a-d, the average % tensile strength changes of the five liner materials exposed to four gamma radiation doses followed by exposure to the simulant waste at 50°C for 7, 14, 28, and 180 days are given. As was seen in the 18°C data, all of the materials, with the exception of Teflon®, had tensile strength increases of less than 20% for exposure times of 28 days and lower. When the liner materials were exposed to the simulant for 180 days at 50°C, a decrease in tensile strength was observed in all of the materials. The tensile strength of these materials was found to be as high as ~70% below that of the pristine materials. In the case of Teflon®, even exposure to the lowest radiation doses of ~140 krads and exposure times of 7 days resulted in decreased tensile strength. At the highest radiation dose of ~3.7 Mrads and 180 day exposure to the simulant at 50°C, a tensile strength change of 70% was observed. The strength of Teflon® had degraded to such a low level that loads as low as 13 lbs was enough to cause the material to fracture.

Figure 25a-d gives the average % tensile strength changes of the five liner materials exposed to four gamma radiation doses followed by exposure to the simulant waste at 60°C for 7, 14, 28, and 180 days. The results were very similar to the data obtained at 50°C. Most materials exhibited tensile strength increases of about 20% for exposure times of 28 days and lower. No clear trends in the effects of increased radiation doses and exposure times could be noted. In some materials, a small systematic increase in tensile strength was observed in samples exposed to 7, 14, and 180 days. However, when comparing these results at the different radiation doses, a general decrease in the tensile strength can be observed. After 180 days of exposure to the simulant, all materials had a dramatically lower tensile strength. For Teflon®, the strength had decreased by 80% from that of the pristine materials.

Using the material ranking scheme discussed previously, a material ranking with tensile strength change as a metric for samples exposed to gamma radiation followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 7. From these results, it can be seen that HDPE had the best response, while Teflon® had the worst.



(a)



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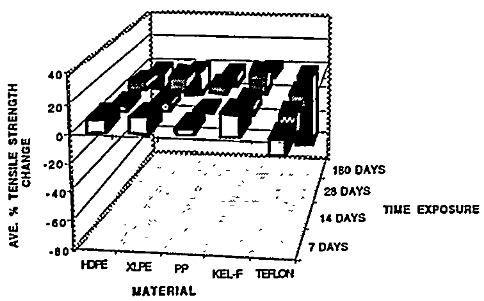

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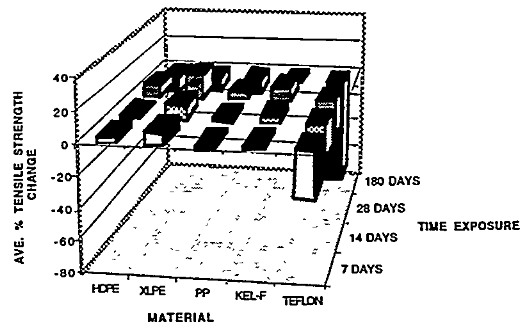


(d)

Figure 24. Tensile strength results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 50°C.

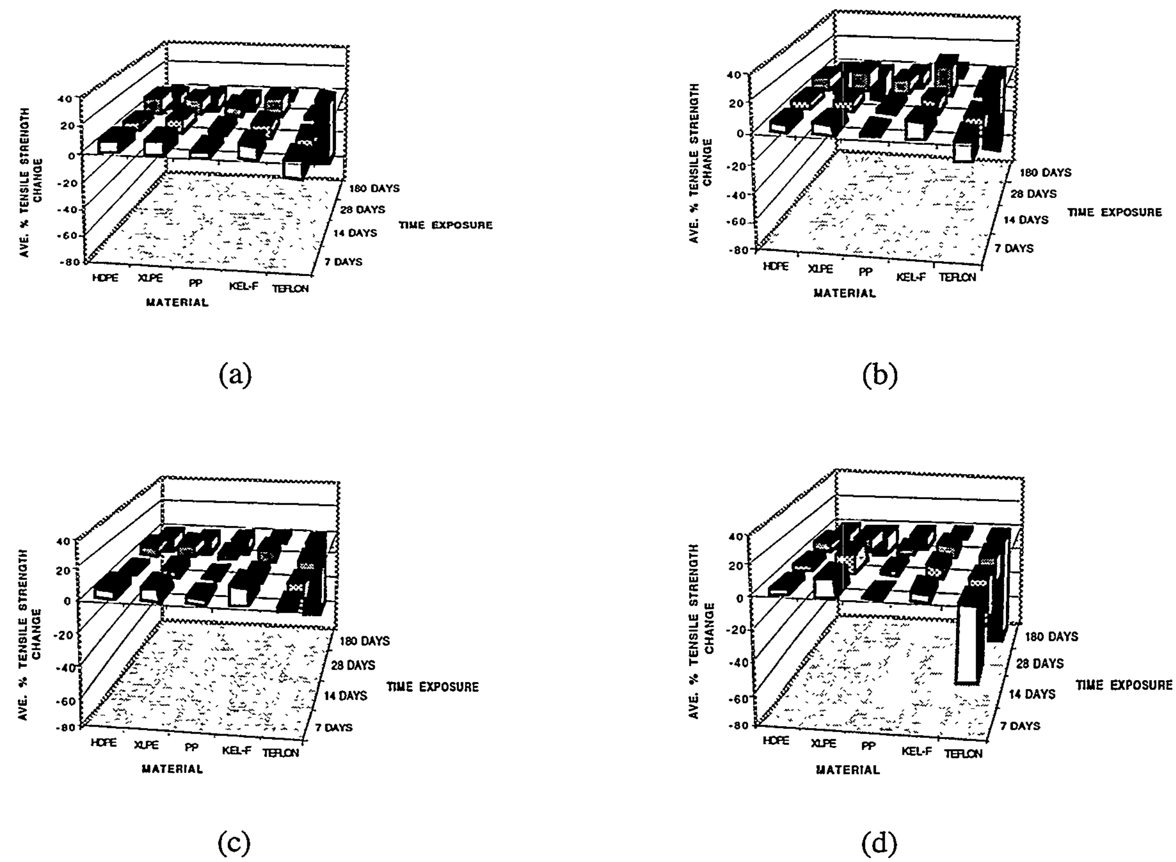


Figure 25. Tensile strength results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 60°C.

Table 7. Material Ranking Based on Tensile Strength Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	7	9	10	8	17
50°C	8	12	11	9	20
60°C	6	11	5	14	18
Total	**21**	**32**	**26**	**31**	**55**

Since these results were identical to those observed for the materials exposed only to the simulant (Table 5), it seems reasonable to assume that the chemical effects are dominating the response of these materials when tensile strength changes are used as a metric for ranking.

Elongation at Yield

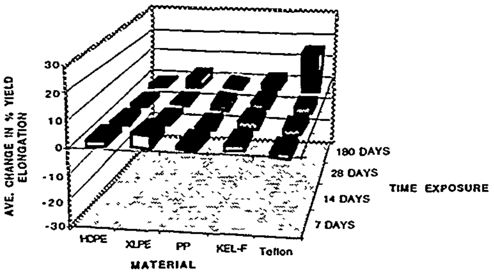
As was discussed previously, the stress-strain diagrams of linear polymers exhibit an initial maximum stress value. This maximum stress value occurs at the yield point of the material. At this point deformation starts to localize in the material, forming a "neck," and the material is said to undergo necking. Necking is observed mostly in ductile materials since less ductile materials fracture before they neck. A measurement of ductility is the percent elongation of the material. This value is defined by Eq. 1 as

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

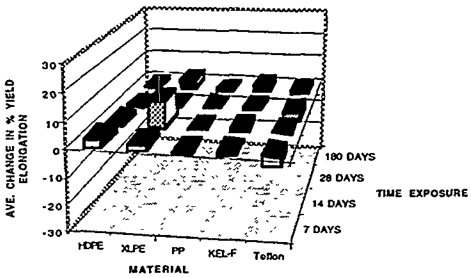
where L_o is the initial gage length (1 in. in this study), and L_f is the gage length at the yield point. It should be clear that increasing values for % elongation means increasing ductility in the material. The data presented in the following sections will describe the change in % elongation. These values are obtained by subtracting the % elongation of the pristine material from the % elongation observed in the material at the specific environmental conditions. As in previous measurements, positive and negative values for changes in % elongation are possible. If the % elongation values themselves are of interest to the reader, Appendix G should be consulted.

In Figure 26a-d, the average % elongation at yield changes of the five liner materials exposed to only the aqueous simulant at 18°C, 50°C, and 60°C for 7, 14, 28, and 180 days is shown. Similar to previous property measurements, these % changes were determined by measuring the change in elongation at yield from that of the pristine materials. Positive values of % elongation at yield changes indicate that the material's elongation at yield had increased (the material became more ductile) under the specific exposure conditions more than the pristine samples. Negative values indicate decreases in elongation at yield; i.e, the material has become less ductile than the pristine samples.

A close inspection of the results show that in general, most materials at these exposure conditions had small elongation at yield changes. At the higher temperatures, some materials, such as XLPE and Teflon®, had changes up to ~30%. These results suggest that either the simulant does not have significant effects on the material or the property of elongation at yield is not very sensitive to the effects of these environmental conditions.



(a)



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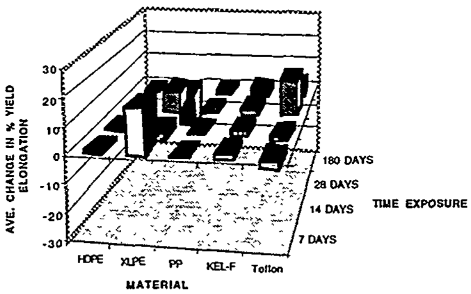


(c)

Figure 26. Elongation at yield results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

Using the material ranking scheme, the material ranking with % elongation at yield changes as the metric for samples exposed to the aqueous waste simulant at the three temperatures and four time periods was developed. This ranking is shown in Table 8. From these results, it can be seen that HDPE and PP had the best response, while XLPE and Teflon® had the worst.

Table 8. Material Ranking Based on Elongation at Yield Changes in Samples Exposed to Only the Aqueous Simulant

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	1	4	2	3	4
50°C	3	5	1	2	4
60°C	1	4	2	3	5
Total	**5**	**13**	**5**	**8**	**13**

In Figure 27a-d, the average % elongation at yield changes of the five liner materials exposed to four gamma radiation doses followed by exposure at 18°C for 7, 14, 28, and 180 days is given. All materials, except Teflon®, had elongation at yield changes below 10% for all environmental conditions. Teflon®, even at the lowest gamma radiation dose of ~140 krads, has decreased elongation at yield values. After irradiation with ~3.7 Mrads of gamma radiation and exposure at 18°C for 180 days, Teflon® has lost 20% of its ductility.

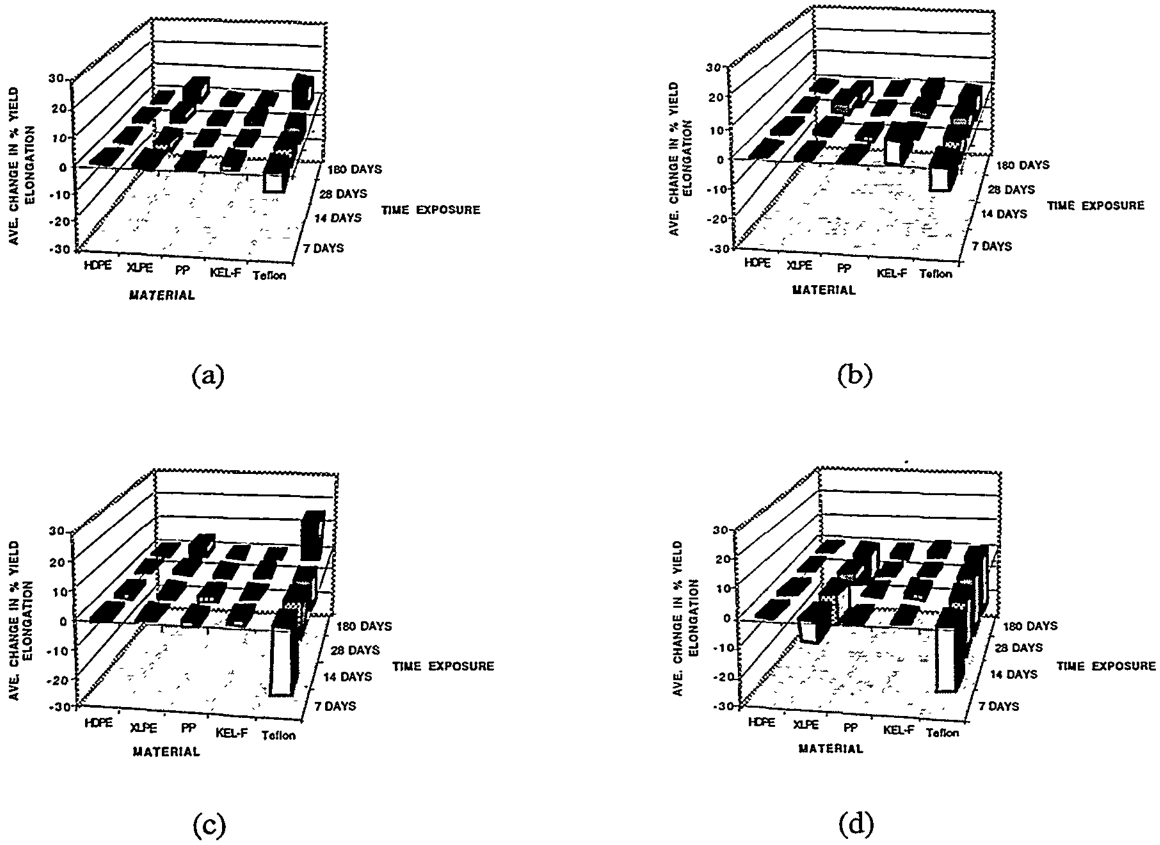


Figure 27. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 18°C.

Figure 28 shows the % elongation at yield changes of five liner materials exposed to four gamma radiation doses followed by exposure at 50°C for 7, 14, 28, and 180 days. Similar to the 18°C data, only in Teflon® does one see significant decreases in elongation at yield. A close inspection of the data also revealed that a trend of progressively decreasing elongation at yield appears to occur after exposure to ~140, 290, 570, and 3,670 krads gamma radiation exposures. This again supports the notion that exposure to these doses of gamma radiation leads to some cross-linking in the polymer that exhibits lower elongation at yield. It should also be noted that at 50°C, most materials became less ductile, i.e., mainly negative elongation at yield values were observed. At the highest gamma radiation dose, both XLPE and Teflon® had elongation at yield changes exceeding 10%. In fact, Teflon® exhibited values greater than 20%.

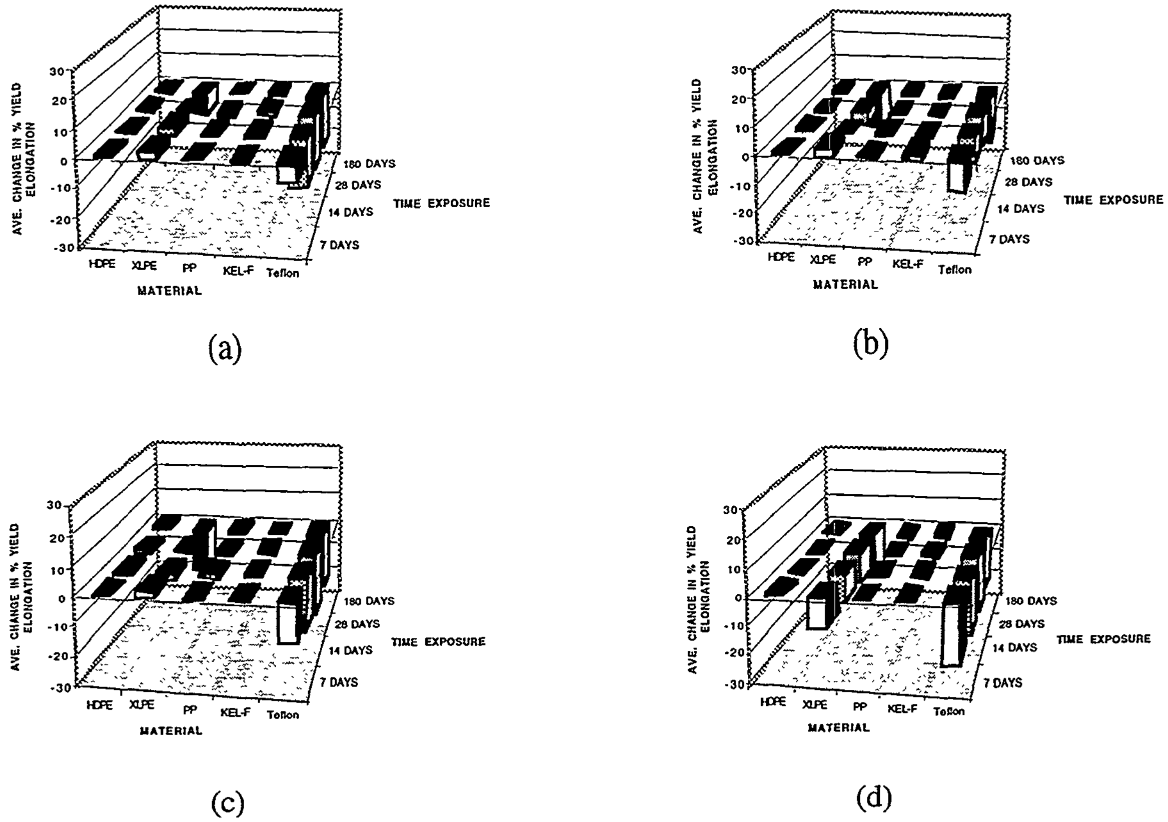


Figure 28. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 50°C.

The results of exposure of the five materials to the four radiation doses followed by exposure at 60°C for 7, 14, 28, and 180 days are given in Figure 29. The trend discussed previously for the 50°C data has continued. All materials, except XLPE and Teflon®, exhibit small increases in elongation at yield. Teflon® at all radiation doses exhibited the largest decreases in elongation at yields. At the highest radiation dose, Teflon® lost more than 20% of its ductility. These results are consistent with the observation that Teflon® becomes extremely brittle when exposed to gamma radiation.

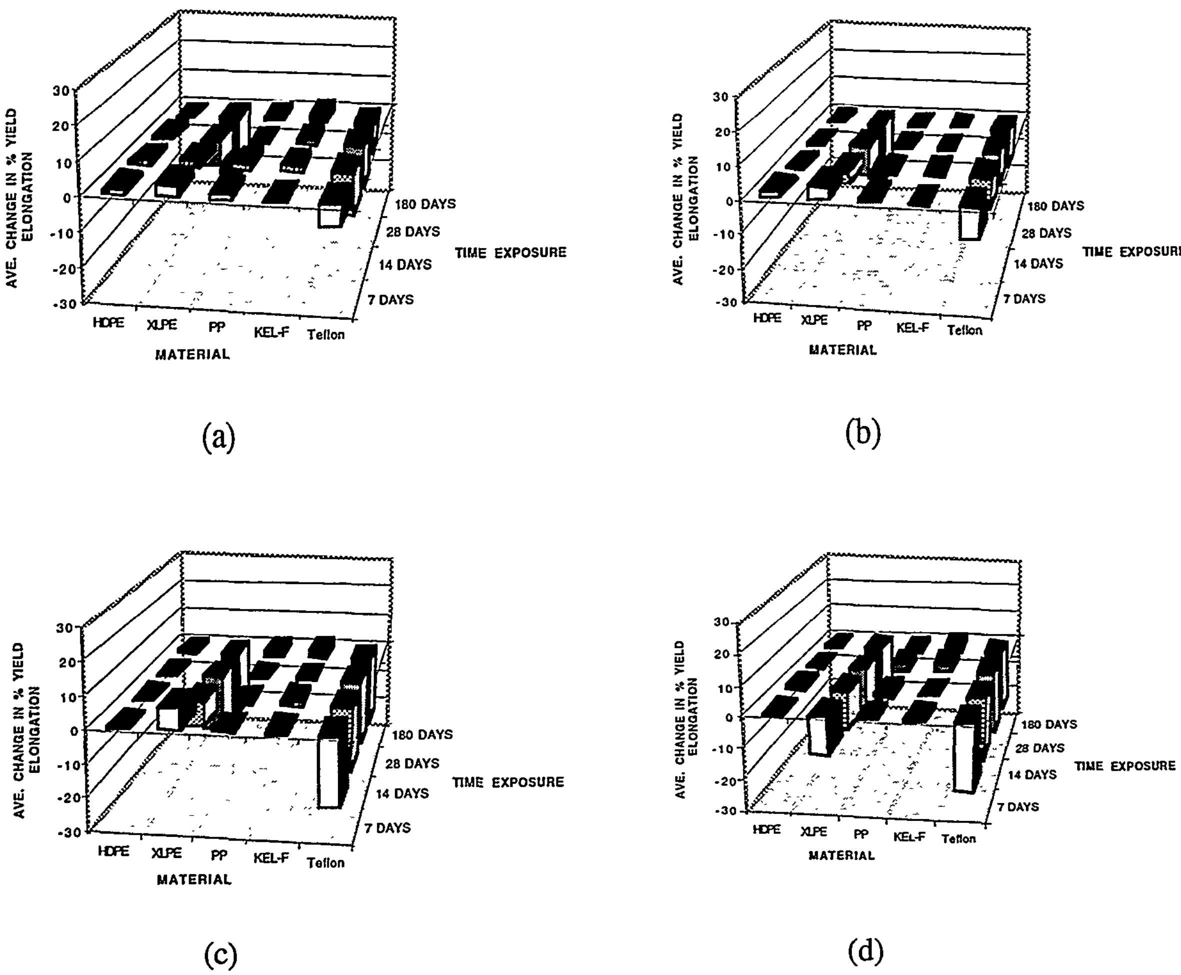


Figure 29. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 60°C.

Using the material ranking scheme discussed previously, a material ranking with elongation at yield change as a metric for samples exposed to gamma radiation followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 9. From these results, it can be seen that HDPE had the best response, while Teflon® had the worst. It should be noted that while HDPE had the best performance under these conditions, PP performed nearly as well as HDPE. Teflon® stands out in that it performs poorly under all the conditions evaluated.

Table 9. Material Ranking Based on Elongation at Yield Changes in Samples Exposed to Gamma Radiation

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	6	13	10	11	20
50°C	7	16	7	10	20
60°C	8	16	6	10	20
Total	**21**	**45**	**23**	**31**	**60**

Now that the effects of the simulant alone and the effects of radiation alone on the elongation at yield have been presented, we can compare these results with the effects of a combination of radiation and simulant on these materials. Figure 30 shows the % elongation at yield changes of five liner materials exposed to four gamma radiation doses and followed by exposure to the aqueous simulant at 18°C for 7, 14, 28, and 180 days. Similar to the radiation-alone data (Figure 27) and the simulant-alone data (Figure 26), Teflon® exhibited decreases in ductility. As can be seen in Figure 30a-d, HDPE, PP, and Kel-F™ exposed to the four radiation doses and the simulant, exhibited slight decreases (~1%) in elongation at yield. Teflon® at these conditions decreased in elongation at yield by more than 20%. XLPE, on the other hand, first increases in ductility, and then decreases. This decrease is most pronounced at 3,670 krads (Figure 30d).

In Figure 31a -d, the average % elongation at yield changes of the five liner materials exposed to four gamma radiation doses and followed by exposure to the simulant waste at 50°C for 7, 14, 28, and 180 days is given. As was seen in the 18°C data, all materials, with the exception of Teflon®, had slight increases (~2%) in elongation at yield. Teflon® at these conditions decreased in elongation at yield by more than 20%. XLPE first increases in ductility and then decreases. This decrease is most pronounced at 3,670 krads (Figure 31d).

Figure 32a-d gives the average % elongation at yield changes of the five liner materials exposed to four gamma radiation doses and followed by exposure to the simulant waste at 60°C for 7, 14, 28, and 180 days. The results were very similar to the data obtained at 50°C. Most materials exhibited elongation at yield increases of about 2%. Teflon® exhibited decreasing ductility as the radiation doses were increased. At the highest dose of 3.7 Mrads, Teflon® had decreases in elongation at yield above 20%. These results suggest elongation at yield for HDPE, PP, and Kel-F™ is not strongly affected by temperature. In fact, when the results of radiation alone (Figures 27 through 29) are considered, elongation at yield appears also to be independent of radiation dose for HDPE, PP, and Kel-F™. It will be interesting to see whether the property of elongation at break is similarly affected.

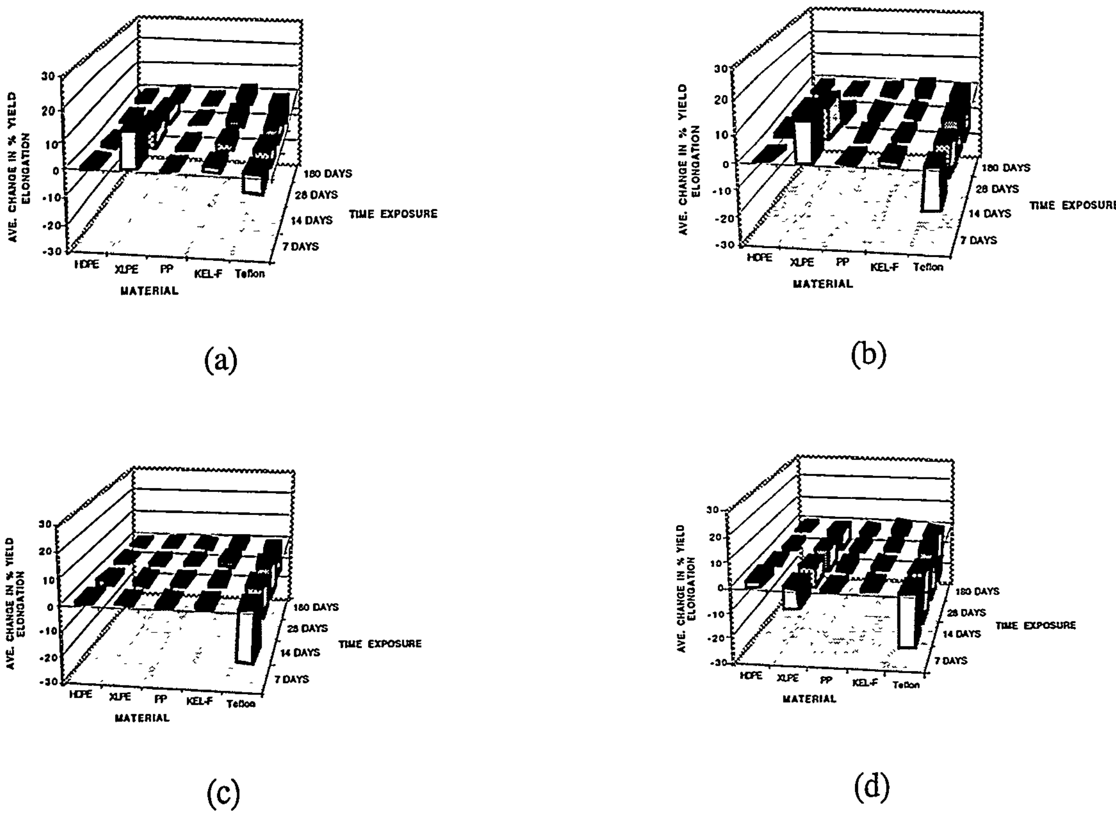


Figure 30. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 18°C.

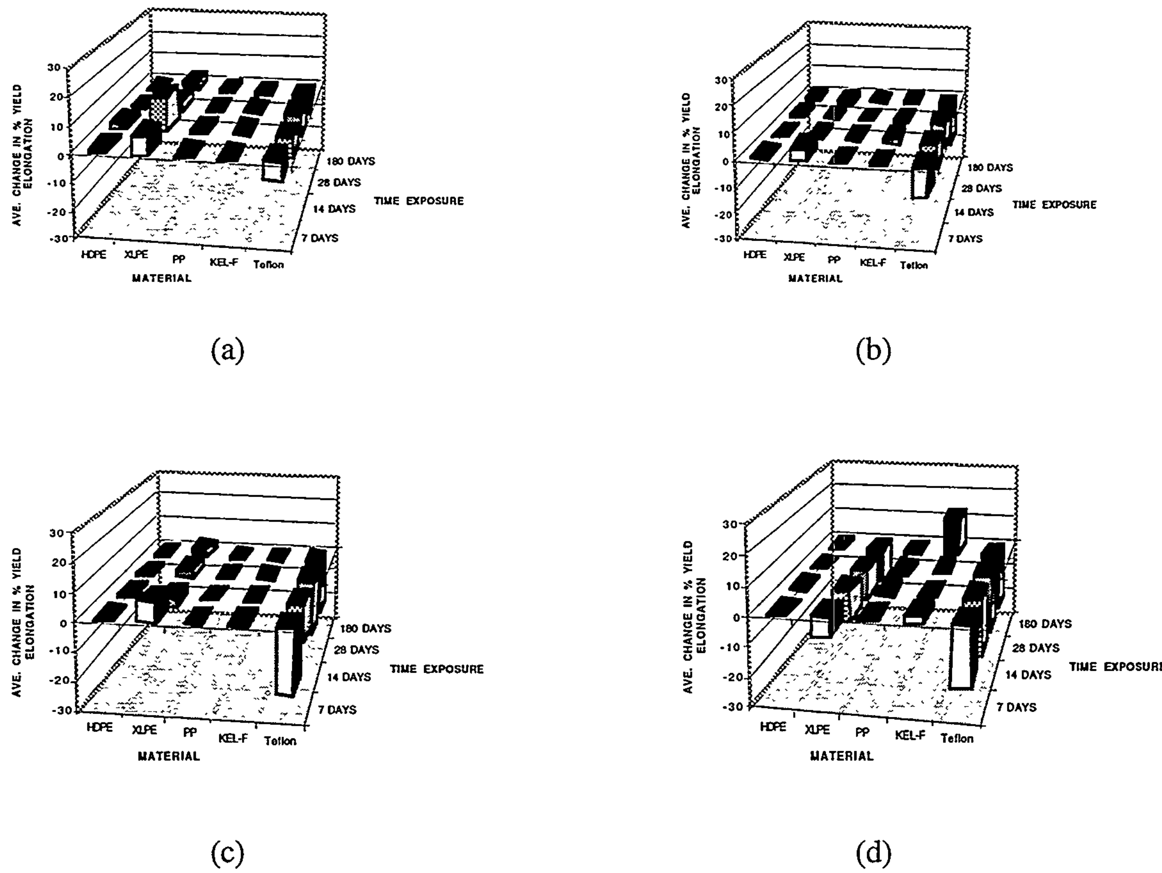


Figure 31. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 50°C.

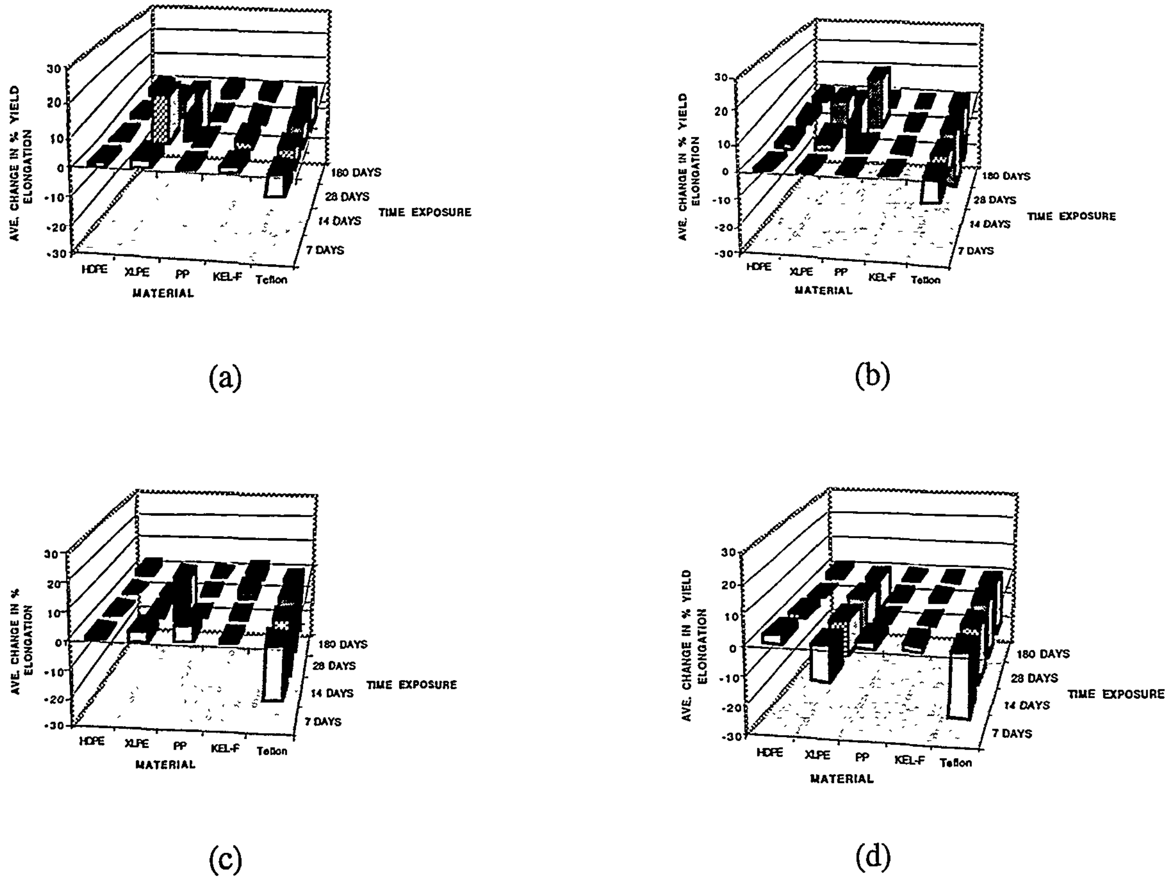


Figure 32. Elongation at yield results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,700 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 60°C.

Using the material ranking scheme discussed previously, a material ranking with elongation at yield change as a metric for samples exposed to gamma radiation and followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 10. From these results, it can be seen that HDPE had the best response, while Teflon® had the worst.

Table 10. Material Ranking Based on Elongation at Yield Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	5	15	8	12	20
50°C	8	15	6	11	20
60°C	7	15	10	8	20
Total	**20**	**45**	**24**	**31**	**60**

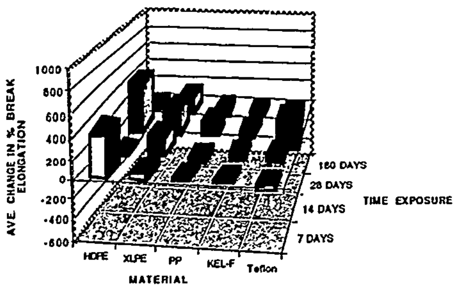
Elongation at Break

The amount of elongation that a material experienced under stress before it fractured is referred to as elongation at break. Similar to the discussions in the previous section, this measurement provides a measure of the material's ductility. Its value is defined identically to that previously given in Eq. 1 except that L_f is now the gage length at fracture. For low ductility materials, i.e., materials that are or have become brittle, % elongation at yield and % elongation at break values may be very similar. In this section, positive values for changes in % elongation indicate that the material was more ductile than the pristine material. Negative values for changes in % elongation indicate that the material was less ductile than the pristine material. We now proceed to describe the results of changes in % elongation at break for the five liner materials exposed to the environmental conditions described above. Appendix H provides the actual % elongation at break values of the five materials under the different environmental conditions.

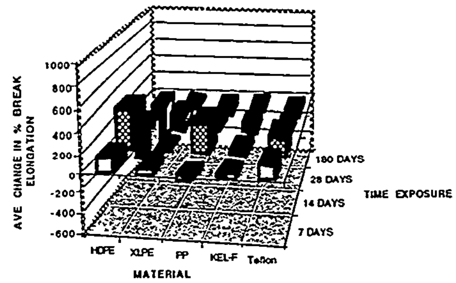
In Figure 33a-c, the average % elongation at break of the five liner materials exposed to only the aqueous simulant at 18°C, 50°C, and 60°C for 7, 14, 28, and 180 days is shown. It should be mentioned that the scale for % elongation at break changes is considerably larger than shown in previous figures. In this section, the scale ranges from -600% to 1000%. This larger scale is attributed in part to the generally greater ductility of plastics than is found in other materials such as metals and ceramics.

The data show relatively small changes (~30 to 60%) for materials such as XLPE, Kel-F™, and Teflon®. HDPE stands out because of the higher values (up to 500%). Since HDPE begins to neck at the yield point, the pristine material exhibits considerable elongation, i.e., more than 800% before breaking. At 18°C (Figure 33a), larger increases in elongation were observed for HDPE and XLPE. These results suggest that exposure to the simulant has increased the materials ductility; i.e., the simulant acted as a plasticizing agent. At higher temperatures and longer exposure times, decreases in elongation were observed for most materials. This appears to indicate that exposure to the simulant at these exposure conditions affects the material's ductility. This was especially true for HDPE.

Using the material ranking process, a material ranking with elongation at yield as the metric for samples exposed to the aqueous waste simulant at the three temperatures and four time periods was developed. This ranking is shown in Table 11. From these results, it can be seen that HDPE and PP had the best response, while XLPE and Teflon® had the worst.



(a)



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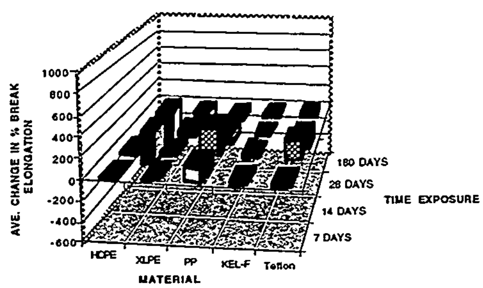


(c)

Figure 33. Elongation at break results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

Table 11. Material Ranking Based on Elongation at Break Changes in Samples Exposed to Only the Aqueous Simulant

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	1	4	2	3	4
50°C	3	5	1	2	4
60°C	1	4	2	3	5
Total	**5**	**13**	**5**	**8**	**13**

In Figure 34a-d, the average changes in % elongation at break of the five liner materials exposed to four gamma radiation doses and followed by exposure at 18°C for 7, 14, 28, and 180 days are given.

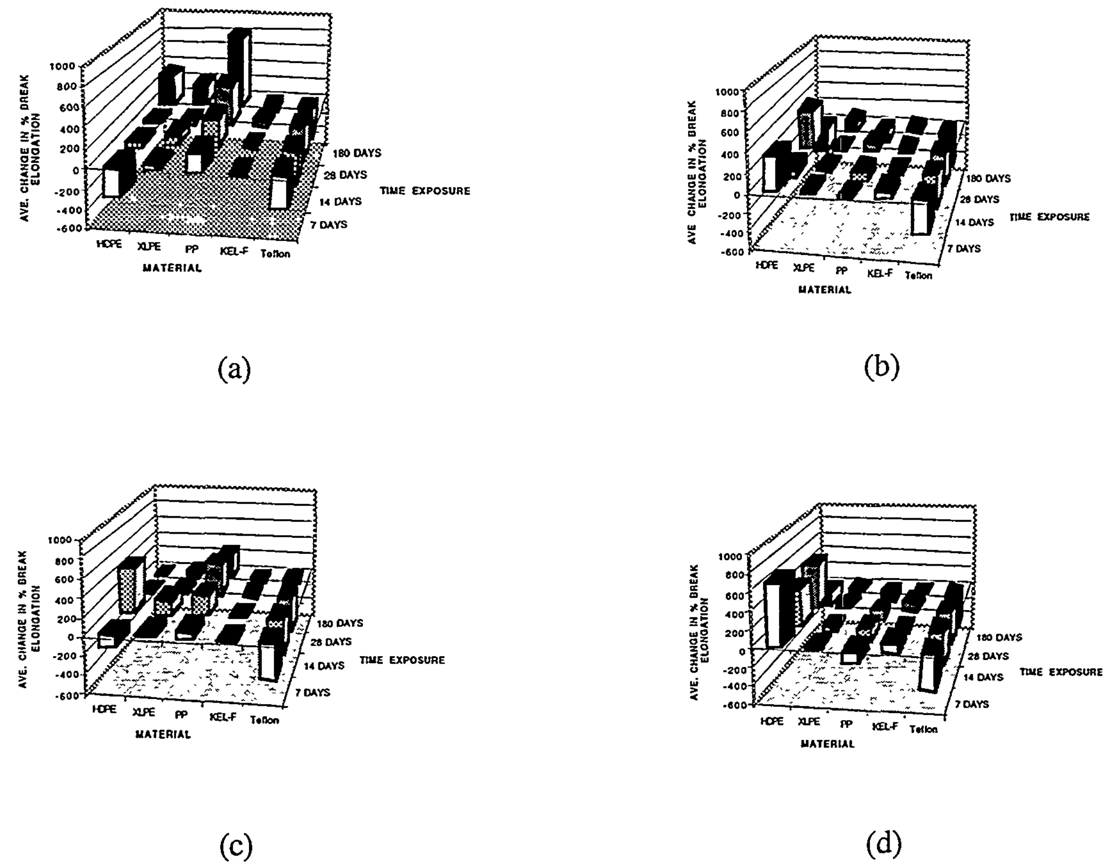
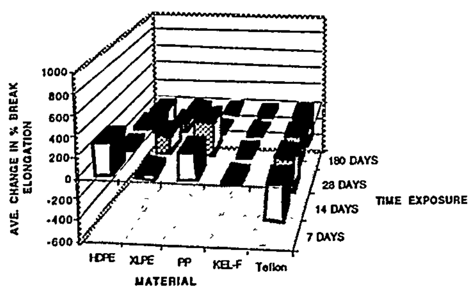


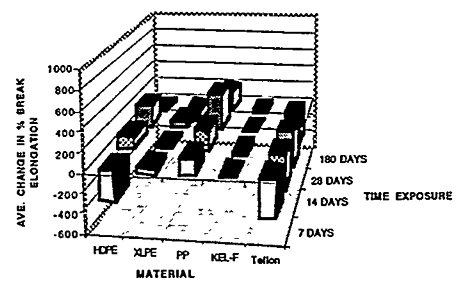
Figure 34. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 18°C.

At these conditions, two observations can be made. The first of these is that HDPE, PP, and Teflon® show the greatest response when exposed to gamma radiation. This behavior is not understood since increased cross-linking in the polymer structure would be expected to cause a decrease in elongation by virtue of an increased rigidity of the polymer network. While HDPE and PP appear to show increases in elongation, Teflon® exhibits decreased ductility. At the highest radiation dose, Teflon® has an almost 400% decrease in elongation. These results are consistent with an increased brittleness of the material.

Figure 35 shows the changes in % elongation at break of five liner materials exposed to four gamma radiation doses and followed by exposure at 50°C for 7, 14, 28, and 180 days. Similar to the 18°C data, only in Teflon® does one see significant decreases in elongation at break. An inspection of the data also revealed that a general trend of progressively decreasing elongation at break occurring after exposure to increasing gamma radiation. This again supports the notion that exposure to these doses of gamma radiation leads to some cross-linking in the polymer that exhibits lower elongation at break. At the highest gamma radiation dose, most of the materials had negative changes in % elongation; i.e., their ductility was below that of the pristine material. Teflon® had elongation at break changes exceeding -380%.



(a)



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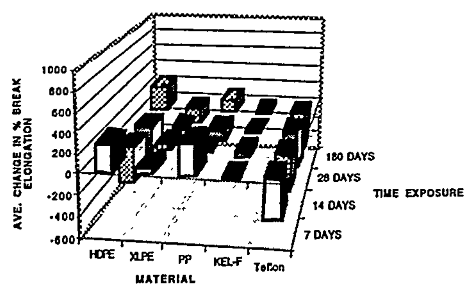

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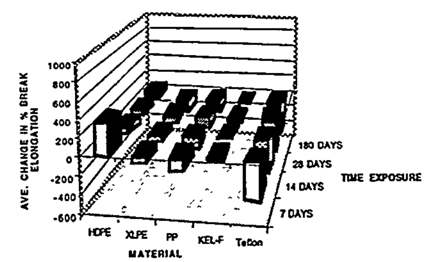
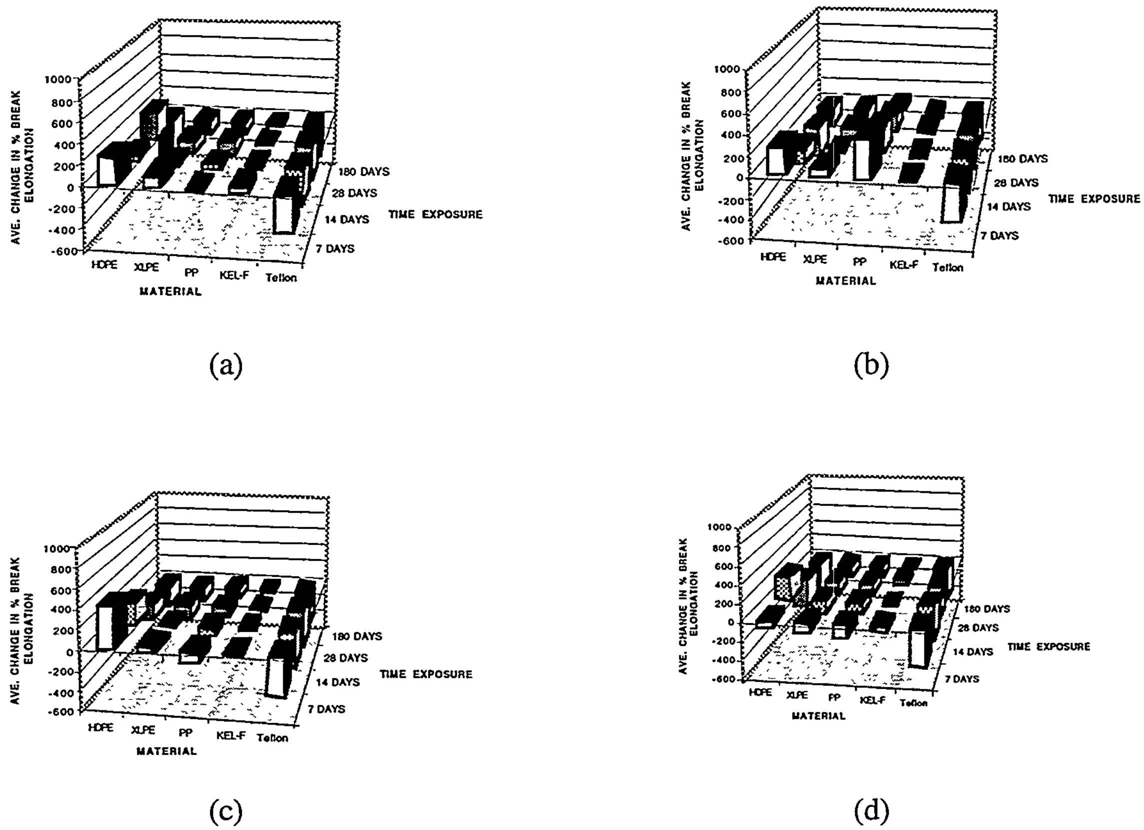


(d)

Figure 35. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 50°C.

The results of exposure of the five materials to the four radiation doses and followed by exposure at 60°C for 7, 14, 28, and 180 days are given in Figure 36. The trend discussed previously for the 50°C data has continued. Most materials, except HDPE and Teflon®, exhibit relatively small (30%) changes in elongation at break. Teflon® at all radiation doses exhibited the largest decreases in elongation at break. At the highest radiation dose, Teflon® lost nearly 400% of its ductility. These results are consistent with the observation that Teflon® becomes extremely brittle when exposed to gamma radiation. In fact the material is so brittle that loads of as little as 10 lbs cause fracture of the tensile specimens.



(a) (b) (c) (d)

Figure 36. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 60°C.

Using the material ranking scheme discussed previously, a material ranking with elongation at break change as a metric for samples exposed to gamma radiation and followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 12. From these results, it can be seen that Kel-F™ had the best response, while Teflon® had the worst. These results are somewhat different from those given in Table 10, where elongation at yield was used as the metric for ranking. However, since the former (Table 10) measurement probes the elastic regime of the material, while elongation at break probes the inelastic regime, a direct correspondence is not expected.

Table 12. Material Ranking Based on Elongation at Break Changes in Samples Exposed to Gamma Radiation

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	12	7	14	5	18
50°C	11	8	15	6	20
60°C	10	10	13	4	19
Total	**33**	**25**	**42**	**15**	**57**

Now that the effects of the simulant alone and the effects of radiation alone on the elongation at break have been presented, we can compare these results with the effects of a combination of radiation and simulant on these materials. Figure 37 shows the changes in % elongation at break of five liner materials exposed to four gamma radiation doses and followed by exposure to the aqueous simulant at 18°C for 7, 14, 28, and 180 days. Similar to the radiation only data (Figure 34), Teflon® exhibited decreases in elongation at even the lowest radiation dose. In fact, the magnitude of changes in % elongation (~400% decrease) appears to be independent of the dose. As can be seen in Figure 37a-d, HDPE exposed to the four radiation doses and the simulant, exhibited variable changes in elongation. Only at the highest radiation dose, is a smooth progression of decreasing changes in % elongation observed.

In Figure 38a-d, the average change in % elongation at break of the five liner materials exposed to four gamma radiation doses and followed by exposure to the simulant waste at 50°C for 7, 14, 28, and 180 days is given. As was seen in the 18°C data, XLPE and Kel-F™ had the smallest changes in % elongation. However, the magnitude of the changes for all of the materials was greater. These results are to be expected at the higher temperatures. Similar to the 18°C data, Teflon® had large (~400%) decreases in elongation at break, and these changes were nearly independent of dose and exposure duration. At the highest gamma radiation dose, almost all of the materials exhibited decreased ductility when compared to the pristine material.

Figure 39a-d gives the average % elongation at yield changes of the five liner materials exposed to four gamma radiation doses and followed by exposure to the simulant waste at 60°C for 7, 14, 28, and 180 days. The results were somewhat different from the data obtained at 50°C. At 60°C, most materials exhibited decreased changes in % elongation at break. While these changes were relatively small (~-10 to -60%) for several materials, HDPE and PP stood out by exhibiting significantly larger changes, i.e., ~100% decreased changes in % elongation. Teflon® exhibited decreasing ductility as the radiation doses were increased. At the highest dose of ~3.7 Mrads, Teflon® had decreases in elongation at break of nearly 400%. These results suggest elongation at break is almost independent of the temperature. In fact, when the results of radiation alone (Figures 34 through 36) are considered, elongation at break appears also to be nearly independent of radiation dose. This behavior is similar to that observed in the elongation at yield data.

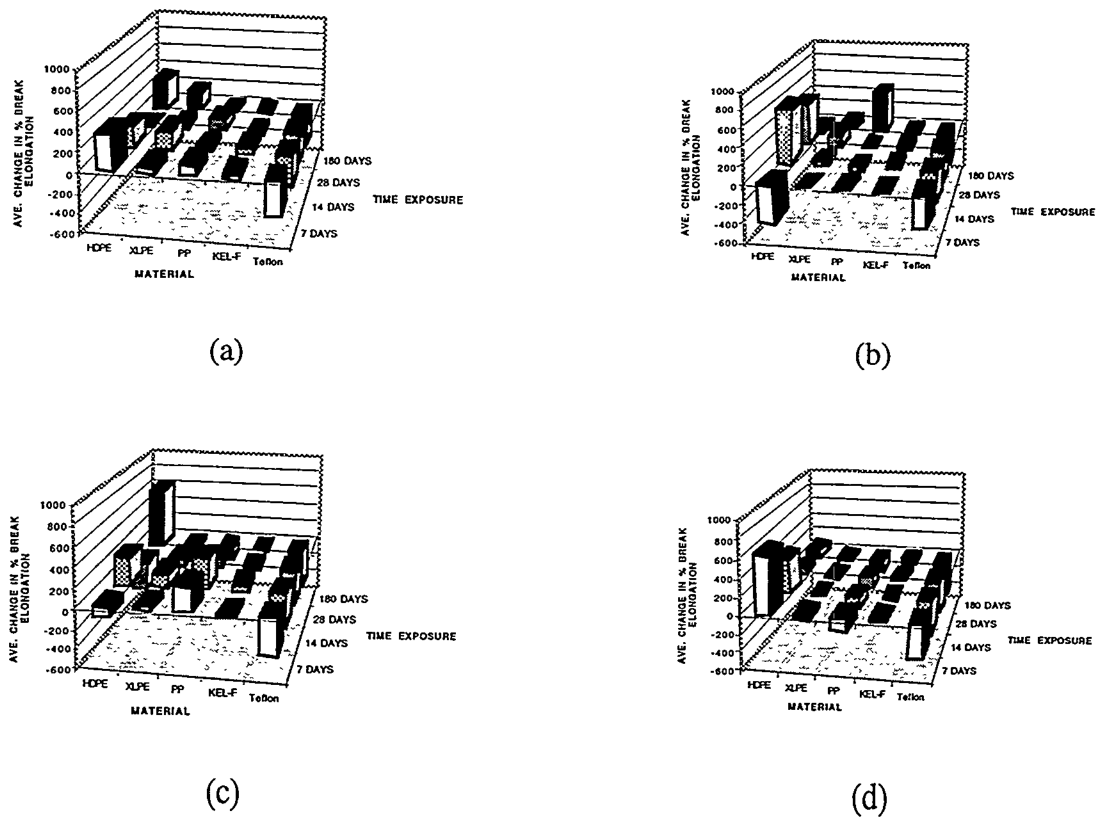
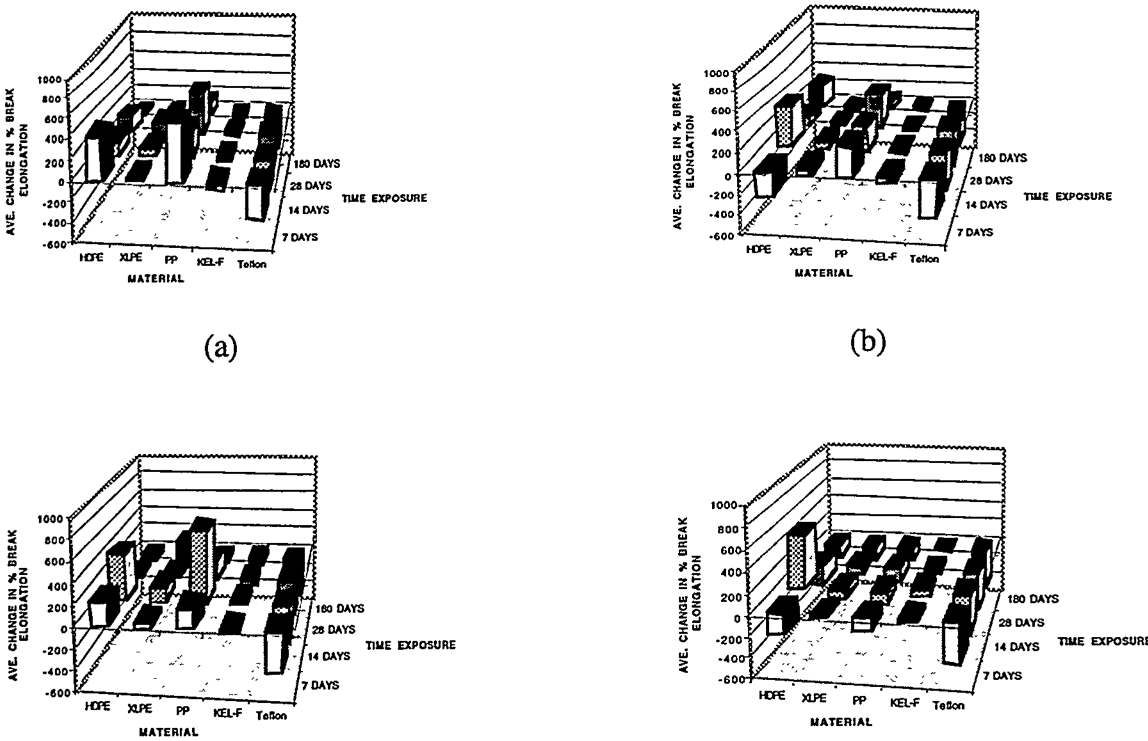


Figure 37. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 18°C.



(a) (b)

(c) (d)

Figure 38. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,700 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 50°C.

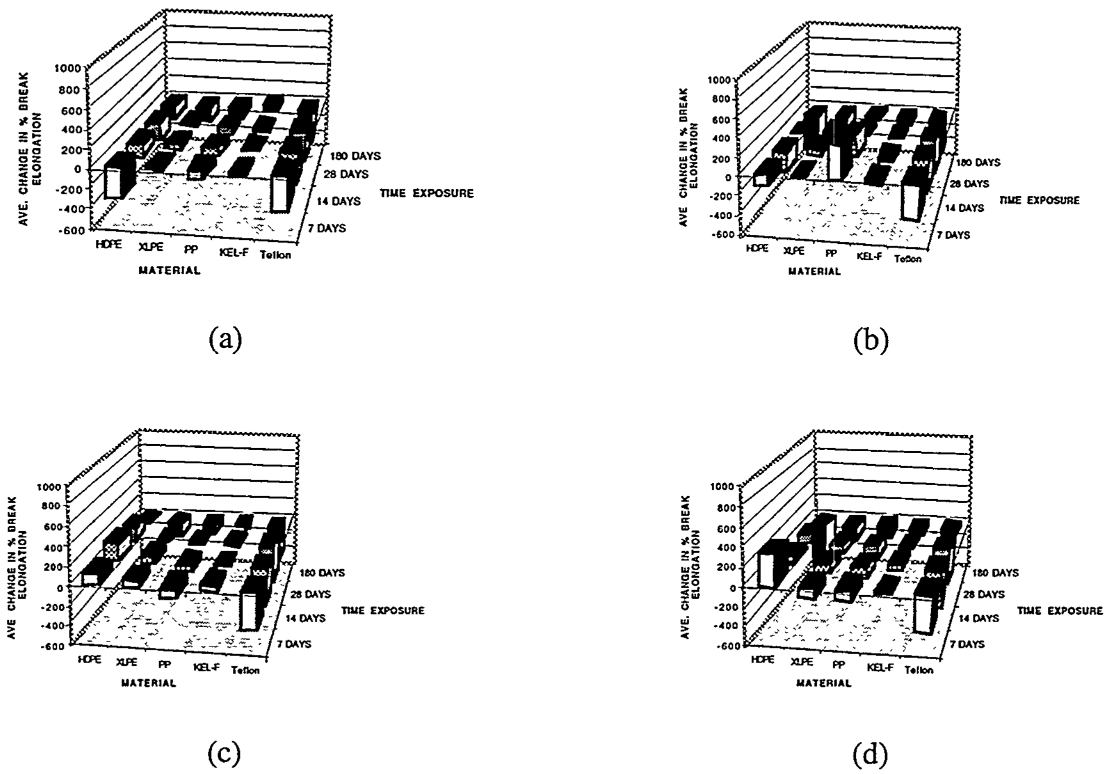


Figure 39. Elongation at break results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,700 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 60°C.

Using the material ranking scheme discussed in the previously, a material ranking with elongation at yield change as a metric for samples exposed to gamma radiation and followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 13. From these results, it can be seen that Kel-F™ had the best response, while Teflon® had the worst.

Table 13. Material Ranking Based on Elongation at Break Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	16	9	11	4	20
50°C	11	9	17	4	19
60°C	13	7	13	7	20
Total	**40**	**25**	**41**	**15**	**59**

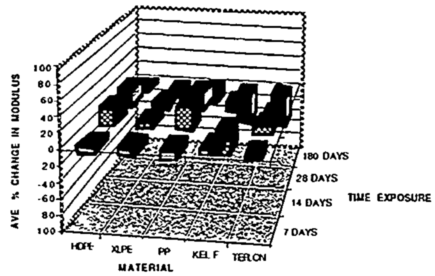
Modulus of Elasticity

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 (E), 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 strength of the bonding 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 of elasticity has the same units as stress (psi). However, since we are interested in measuring changes in the modulus of the exposed material to that of the unexposed or pristine material, we will discuss the % change in modulus of elasticity of the materials. This is calculated from the relationship given in Eq. 2:

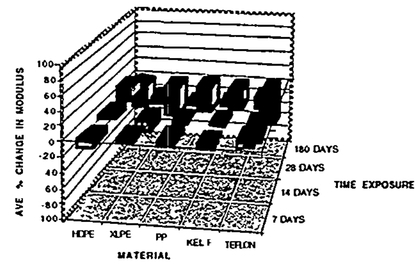
$$\% \text{ Change in Modulus of Elasticity} = (E_f - E_0)/E_0 \times 100 \qquad \text{Eq. 2}$$

where E_f is the measured modulus under the specific environmental conditions and E_0 is the modulus of the pristine material. The modulus changes can be positive or negative in value depending on the magnitude of either E_f or E_0. Positive changes in % modulus indicate that the material of interest has a greater modulus than the pristine material. Negative values indicate that the material of interest has a lower modulus than the pristine material. Appendix I provides the actual moduli of the five materials under the different environmental conditions along with the % modulus change.

In Figure 40a-c, the average % change in modulus of the five liner materials exposed to only the aqueous simulant at 18°C, 50°C, and 60°C for 7, 14, 28, and 180 days is shown. The data show that most materials exhibit modulus changes in the range of 10 to 30%. For XLPE exposed to the simulant waste at 60°C for 180 days, a ~70% change was observed (Figure 40c). In the case of Teflon®, the largest changes in modulus were also seen at the higher temperatures. However, no systematic trends could be detected in the data on increased temperatures and increased exposure times.



(a)



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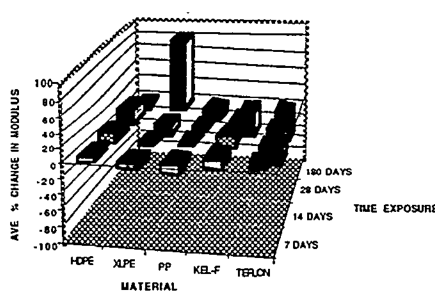


(c)

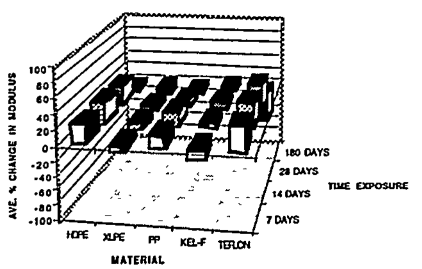
Figure 40. Modulus change results of five liner materials after exposure for 7, 14, 28, and 180 days to the aqueous simulant waste at 18°C (a), 50°C (b), and 60°C (c).

Using the material ranking scheme, the material ranking with modulus of elasticity as the metric for samples exposed to only the aqueous waste simulant at the three temperatures and four time periods was developed. This ranking is shown in Table 14. From these results, it can be seen that HDPE, PP, and Kel-F™ had the best response, while Teflon® had the worst.

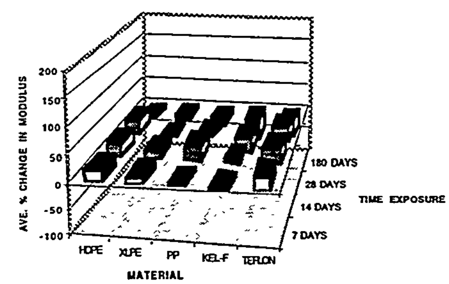
Table 14. Material Ranking Based on Modulus Changes in Samples Exposed to Only the Aqueous Simulant

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	3	1	2	4	5
50°C	1	4	3	2	5
60°C	3	4	2	1	5
Total	**7**	**9**	**7**	**7**	**15**

In Figure 41a-d, the average % change in modulus of elasticity of the five liner materials exposed to the four gamma radiation doses and followed by exposure at 18°C for 7, 14, 28, and 180 days are given. As can be seen from this data, when the gamma radiation dose was increased from ~290 krads to ~570 krads, there is a noticeable increase in the modulus (Figure 41b and c). The most pronounced modulus increase can be seen for Teflon®. Its modulus changes from an average value of ~10% to more than 80%. At the highest gamma radiation doses, all materials exhibited the largest increases in moduli (Figure 41d). Teflon®, under these conditions, changed nearly 300%. Since most of the changes are positive at these elevated radiation dose levels, these results are generally consistent with increased bonding, i.e., cross-linking of polymer chains. The latter observation is in agreement with an increasing brittleness in the material that has been confirmed by decreases in tensile strength (Figure 20d), elongation at yield (Figure 27d), and elongation at break (Figure 34d).



(a)



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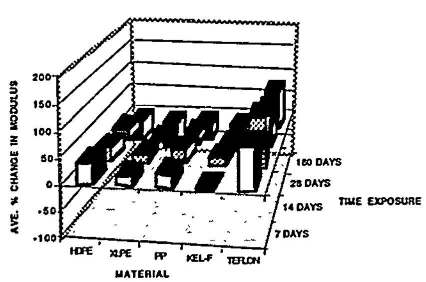

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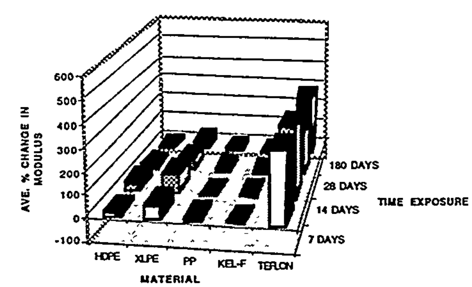
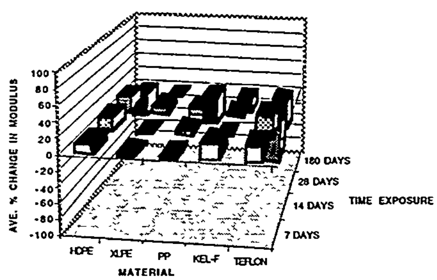


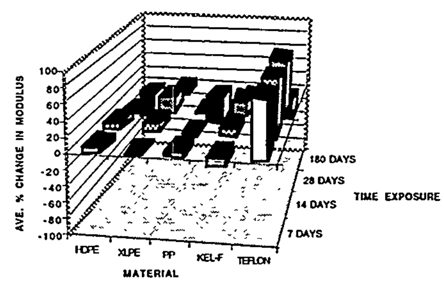
(d)

Figure 41. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 18°C. *Note: There is a scale change for graphs (b), (c), and (d).*

Figure 42 shows the average % change in modulus of five liner materials exposed to the four gamma radiation doses and followed by exposure at 50°C for 7, 14, 28, and 180 days. Similar to the 18°C data, only for Teflon® does one see significant increases in modulus. A close inspection of the data further reveals that even at the lowest gamma dose of ~140 krads, Teflon® begins to show significantly larger changes in its modulus. Starting with exposure to ~290 krads of gamma radiation, Teflon® exhibited more than 50% modulus changes and increased to more than 500% after ~3.7 Mrads of exposure. At the higher radiation doses, XLPE also had increases in modulus changes of more than 100%. These observations again support the notion that exposure to these doses of gamma radiation leads to cross-linking in the polymers that then exhibit higher moduli.



(a)



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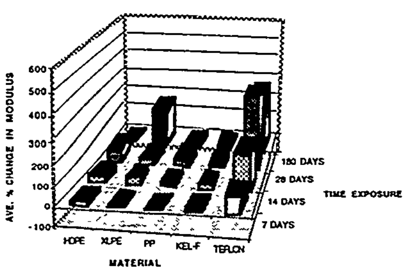

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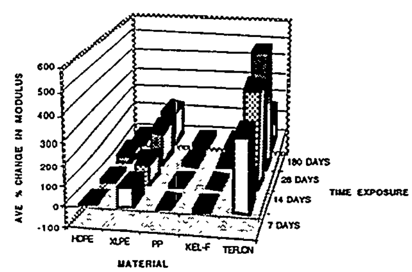


(d)

Figure 42. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 50°C. *Note: There is a scale change for graphs (c) and (d).*

The results of exposure of the five materials to the four radiation doses and followed by exposure at 60°C for 7, 14, 28, and 180 days are given in Figure 43. The trend discussed previously for the 50°C data has continued. All materials, except XLPE and Teflon®, exhibited relatively small increases in modulus changes. Teflon® at all of the radiation doses exhibited the largest increases in % modulus change. At the highest radiation dose, Teflon® had increases in moduli by more than 300%. These results are consistent with the observation that Teflon® becomes extremely brittle when exposed to gamma radiation. While XLPE does not appear to appear to embrittle on exposure to gamma radiation, the modulus was found to increase at progressively larger radiation doses. In fact at the highest radiation dose, the modulus of XLPE has increased by more than 250%.

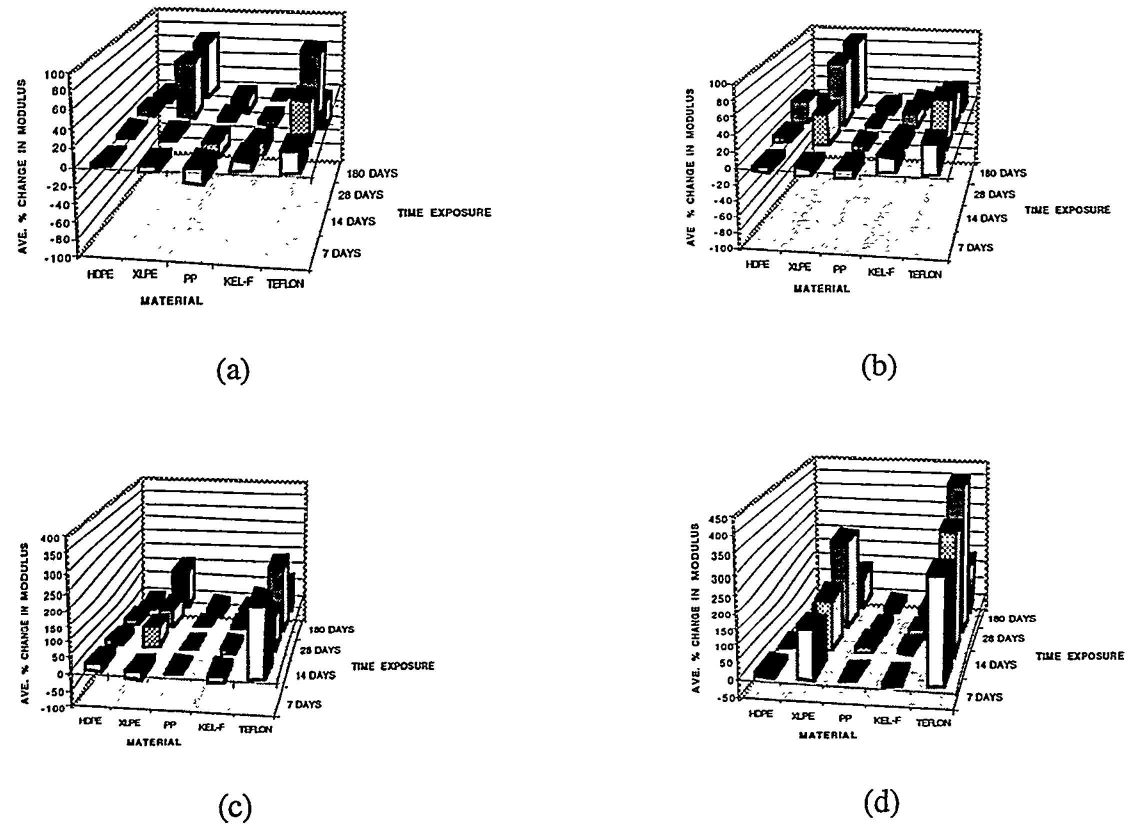


Figure 43. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure for 7, 14, 28, and 180 days at 60°C. *Note: There is a scale change for graphs (c) and (d).*

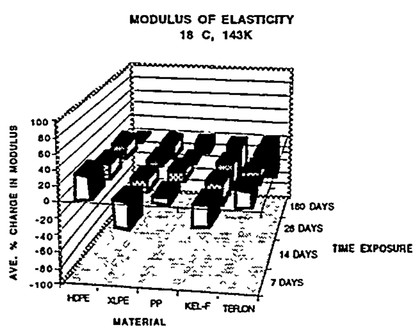
Using the material ranking scheme discussed previously, a material ranking with % modulus change as a metric for samples exposed to gamma radiation and followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 15. From these results, it can be seen that Kel-F™ had the best response, while Teflon® had the worst. It should be noted that, while Kel-F™ had the best performance under these conditions, PP performed nearly as well. Teflon® stands out in that it performs poorly under all the conditions evaluated.

Now that the effects of the simulant alone and the effects of radiation alone on the modulus change have been presented, we can compare these results with the effects of a combination of radiation and simulant on these materials. Figure 44 shows the % modulus changes of the five liner materials exposed to the four gamma radiation doses followed by exposure to the aqueous simulant at 18°C for 7, 14, 28, and 180 days. Similar to the radiation-alone data (Figures 41 through 43) and the simulant-alone data (Figure 40), only at the highest exposure doses does one see increases in moduli in XLPE and in Teflon®. As can be seen in Figure 44a-d, HDPE, PP, and Kel-F™, exposed to the four radiation doses and the simulant, exhibited slight increases

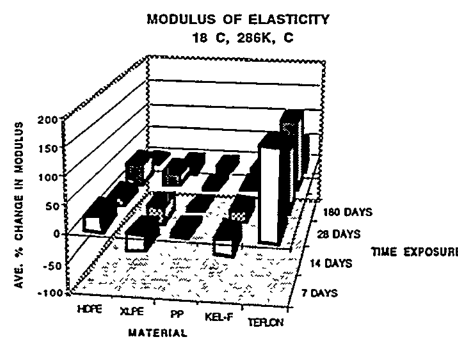
(~20%) in moduli. Teflon® at these conditions increased in moduli changes by more than 370%. Similarly, XLPE increased in modulus changes by nearly 70%. This increase was most pronounced at 3,670 krads (Figure 44d).

Table 15. Material Ranking Based on Modulus Changes in Samples Exposed to Gamma Radiation

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	16	9	10	8	17
50°C	11	14	9	6	18
60°C	6	18	7	8	18
Total	**33**	**41**	**26**	**22**	**53**



(a)



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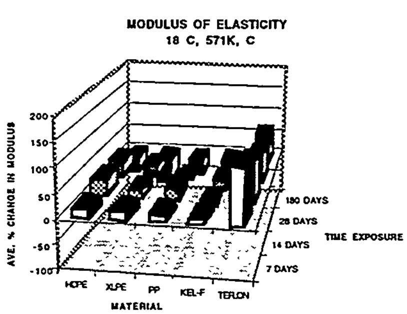

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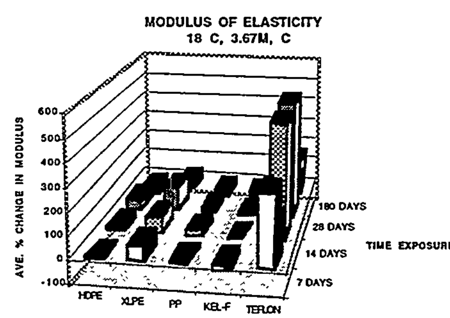
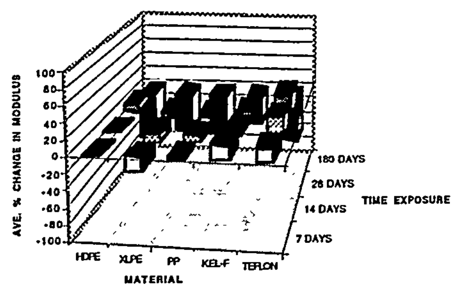


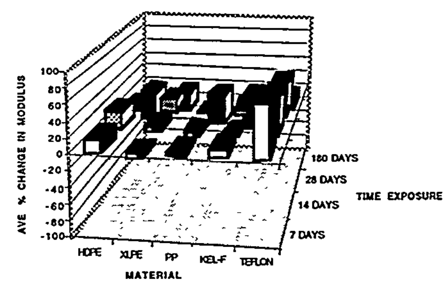
(d)

Figure 44. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 18°C. *Note: There is a scale change for graphs (b), (c) and (d).*

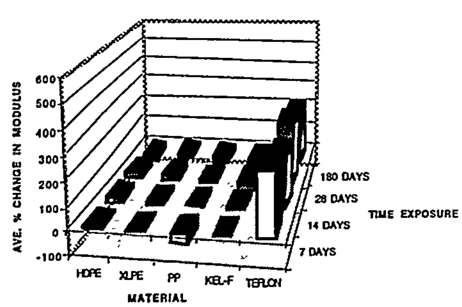
In Figure 45a-d, the average % modulus changes of the five liner materials exposed to the four gamma radiation doses and followed by exposure to the simulant waste at 50°C for 7, 14, 28, and 180 days are given. As was seen in the 18°C data, all materials, with the exception of XLPE and Teflon®, had slight changes in modulus (10 to 30%). Teflon® at these conditions had increases in modulus changes by more than 300%. Similarly XLPE had increases in % modulus changes. This increase is most pronounced at 3,670 krads (Figure 45d), where it was nearly 100%.



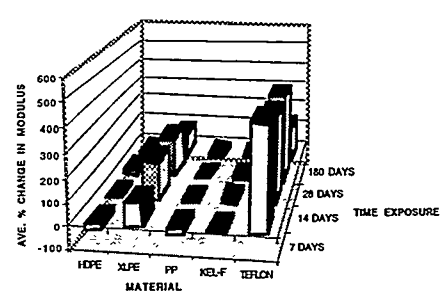
(a)



(b)



(c)



(d)

Figure 45. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,670 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 50°C. *Note: There is a scale change for graphs (c) and (d).*

Figure 46a-d gives the average % modulus changes of the five liner materials exposed to the four gamma radiation doses and followed by exposure to the simulant waste at 60°C for 7, 14, 28, and 180 days. The results were very similar to the data obtained at 50°C. Most materials exhibited moduli changes of about 10 to 20%. XLPE and Teflon® exhibited increased moduli as the radiation doses were increased. At the highest dose of ~3.7 Mrads, Teflon® had modulus changes above 430%.

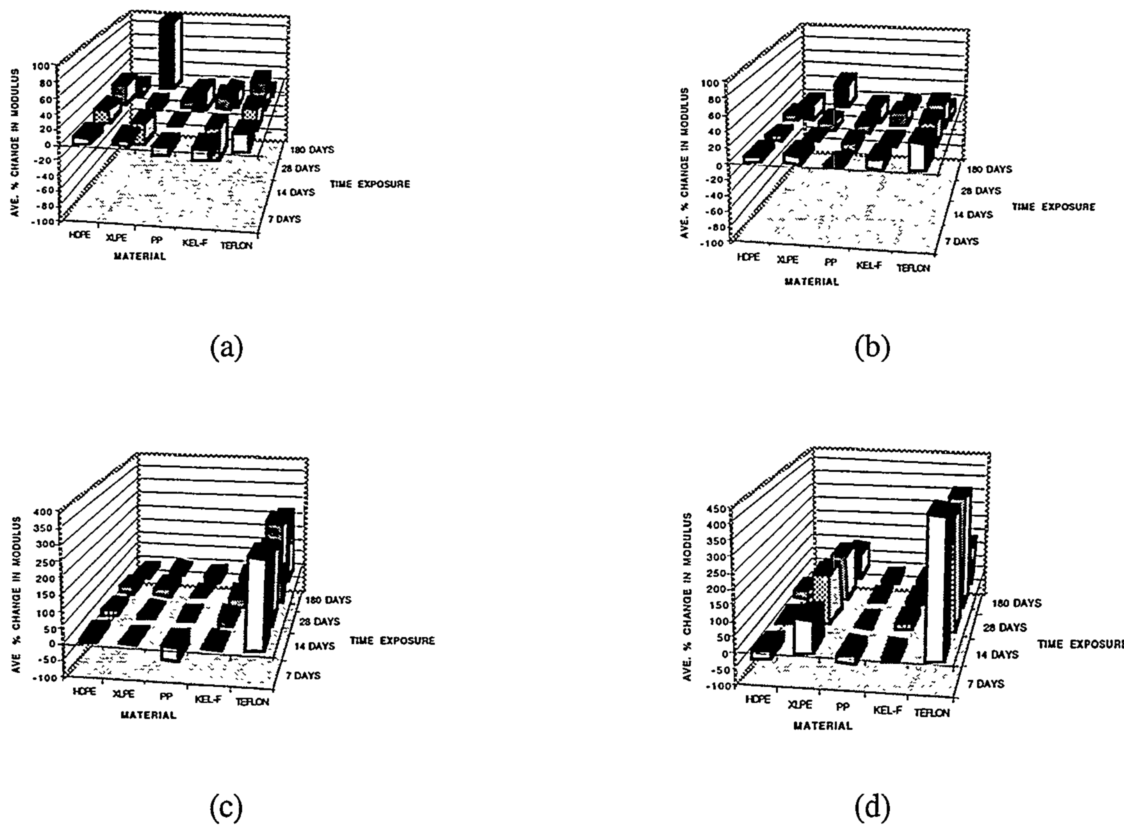


Figure 46. Modulus change results of five liner materials after exposure to ~140 (a), 290 (b), 570 (c), and 3,700 krads (d) of gamma radiation followed by exposure to the aqueous simulant for 7, 14, 28, and 180 days at 60°C. *Note: There is a scale change for graphs (c) and (d).*

These results suggest modulus changes are somewhat independent of the temperature, especially at the lowest radiation dose of ~140 krads. In fact when the results of radiation-alone measurements at the three temperatures (Figures 41 through 43) are compared to the results in Figures 44 through 46, the modulus changes appear to be more strongly dominated by a combination of radiation and chemical effects than by radiation effects alone. The results in Figures 44 through 46 show a general decrease in modulus of elasticity with increasing temperature. These effects are least pronounced at 18°C. It should be mentioned that these results are general. Instances can be found in the data that are opposite to these general trends.

Using the material ranking scheme discussed earlier, a material ranking with modulus change as a metric for samples exposed to gamma radiation and followed by exposure at the three temperatures and four time periods was developed. This ranking is shown in Table 16. From these results it can be seen that HDPE had the best response, while Teflon® had the worst.

Table 16. Material Ranking Based on Modulus Changes for Radiation and Simulant Exposures

Temperature	HDPE	XLPE	PP	Kel-F™	Teflon®
18°C	10	10	6	14	16
50°C	10	12	12	8	16
60°C	5	11	10	11	19
Total	**25**	**33**	**28**	**33**	**51**

Because tensile strength, elongation at yield, elongation at break, and modulus of elasticity are a subset of a more general property, namely the material's tensile property, we believe it is useful to determine a material ranking based on these four measurements. This ranking is shown in Table 17.

Table 17. Material Ranking Based on Tensile Strength, Elongation at Yield, Elongation at Break, and Modulus of Elasticity Changes

Tensile Property	HDPE	XLPE	PP	Kel-F™	Teflon®
Tensile Strength	21	32	26	31	55
Elongation at Yield	20	45	24	31	60
Elongation at Break	40	25	41	15	59
Modulus of Elasticity	25	33	28	33	51
Total	**106**	**135**	**119**	**110**	**225**

From the results given in Table 17, the material that had the best response based on its tensile properties was HDPE. Teflon® had the worst response when tensile property was used as the metric.

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DISCUSSIONS

The purpose of the Chemical Compatibility Program is to provide a scientifically defensible methodology for measuring the chemical compatibility of polymeric liner and seal materials with hazardous wastes. These polymeric materials may be used throughout the DOE complex in current and future container designs for the transportation of hazardous and mixed wastes and other materials. The purpose of this testing program was to assess the current state of chemical compatibility testing technology and provide comprehensive and reliable chemical compatibility for decision-making.

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 when exposed to the simulant Hanford tank taste, ten materials needed to be subjected to the test matrix. This results in an extremely large sample set, and the comprehensive testing phase of the program was further subdivided into the testing of liner materials and seal materials. The results of liner testing has been the subject of this report and involved the evaluation of five liner materials.

Based on the results presented here, it is worthwhile to attempt to identify one material that displayed the greatest chemical compatibility with the simulant mixed waste under test conditions. A ranking scheme was developed that evaluated the performance of the test materials based on five measurements. Such a ranking scheme makes use of the final results presented in the previous sections for each measurement type, i.e., Tables 1, 3, 4, 17. Accordingly, we simply added the rankings obtained for each measurement to derive an overall ranking value. The material that was calculated to have the lowest value, i.e., changed the least based on all four properties, was judged to have the greatest compatibility towards the simulant mixed waste. Since the fifth property, stress-cracking measurements, pertains only to ethylenic polymers, its inclusion in the ranking process is inappropriate. However, as will be discussed later, the results of stress cracking can be used when specific properties are chosen rather than overall performance. The overall ranking scheme developed for this process is shown in Table 18. As can be seen, this very simplistic approach has identified the chlorofluorocarbon Kel-F™ as the material that is most compatible with the simulant mixed waste. The well-known engineering plastic, HDPE, is very compatible specific gravity and tensile properties are used as the metric. The data in Table 18 therefore can be used by packaging designers to assess the properties pertinent to their design requirements.

Since HDPE might be selected on the ranking from the tensile data, it is worthwhile to discuss the issue of stress cracking. Stress cracking is a form of chemical attack in which a chemical, which does not appreciably attack or dissolve a polymer in an unstressed state, will cause catastrophic failure when the polymer is stressed in its presence.

As was established previously in the stress-cracking section of this report, XLPE is the best material choice when stress cracking might be an issue, when there is higher radiation doses, higher temperatures, and longer transportation/storage times. While Kel-F™ was the best overall material choice, nontechnical issues such as material cost might drive a designer's selection choice. If cost considerations prove to be important, PP might prove to be a good compromise material. A description of the material cost aspect can be found in Appendix A.

Table 18. Material Ranking Based on Four Property Evaluations

Property	HDPE	XLPE	PP	Kel-F™	TEFLON®
Specific Gravity Changes	26	31	32	31	60
Dimensional Changes	43	46	32	29	31
Hardness Changes	39	22	37	22	60
Tensile Changes	106	135	119	110	252
Total	**214**	**234**	**220**	**192**	**376**

CONCLUSIONS

We have developed a chemical compatibility program for the evaluation of plastic packaging components that may be incorporated in packaging mixed-waste forms. Consistent with the methodology outlined in this report, we have performed the second phase of this experimental program to determine the effects of simulant Hanford Tank mixed wastes on packaging liner materials. This effort involved the comprehensive testing of five plastic liner materials in the aqueous mixed-waste simulant. The testing protocol involved exposing the respective materials to ~140, 290, 570, and 3,670 krads of gamma radiation and followed by 7, 14, 28, 180 day exposures to the waste simulant at 18, 50, and 60°C. From the data analyses performed, we have identified the fluorocarbon Kel-F™ as having the greatest chemical durability after having been exposed to gamma radiation and followed by exposure to the Hanford tank simulant mixed waste. The most striking observation from this study was the extremely poor performance of Teflon® under these conditions.

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APPENDIX A

MATERIAL INFORMATION

Liner Materials

Material	Supplier	Identification.
Crosslinked Polyethylene (XLPE)[a]	Regal Plastics 3455 Princeton NE Albuquerque, NM 87107 (505) 884-2651	TIVAR® 88
High Density Polyethylene (HDPE)[b]	Regal Plastics	PLA 11785 Code No. JH I 12 E
Fluorocarbon (Kel-F™)[c]	Regal Plastics	5055 Kel-F™ 81 PCTFE
Polypropylene (PP)[d]	Regal Plastics	PLA 3801 Code No. TB J 22 E
Polytetrafluoroethylene (Teflon®)[e]	Regal Plastics	PLA 7625

a. Manufactured by POLY-HI SOLIDUR, Menasha Corp., Scranton, PA (717) 348-6800 This material was only available in 0.25" thick sheet stock. The material was machined at SNL to a thickness of 0.125" as required by the test method. **Cost: $5.50/sq.ft.**

b. Manufactured by POLY-HI SOLIDUR, ibid. This material was available in 0.125" sheet stock from supplier. **Cost: $0.74/sq.ft.**

c. Tradename assigned to 3 M Corp., St. Paul, MN. Kel-F™ is a thermoplastic homopolymer of chlorotrifluoroethlene (CTFE). This material was available in 0.125" sheet stock from supplier. **Cost: $166/sq.ft.**

d. Manufactured by POLY-HI SOLIDUR, ibid. This material was available in 0.125" sheet stock from supplier. **Cost: ~$0.68/sq.ft.**

e. Registered trademark of DuPont. Manufactured by INTERPLAST, 1 Connecticut Dr., Burlington, NJ . This material was available in 0.125" sheet stock from supplier. **Cost: ~$14/sq.ft.**

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APPENDIX B
Specific Gravity Data

AVERAGE SPECIFIC GRAVITY AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9525	1.68	0.9443	0.22	0.9546	-0.46	0.9547	-0.33
XLPE	0.9334	1.12	0.9272	-1.05	0.9315	-0.62	0.9332	-0.39
PP	0.9046	2.29	0.8962	0.81	0.9018	-0.89	0.9062	-0.33
KEL-F	2.1142	0.43	2.1038	-1.10	2.1206	-0.31	2.1187	-0.34
TEFLON	2.1836	1.54	2.1748	0.77	2.1808	-0.64	2.1717	-0.73
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9491	-0.63	0.9571	0.27	0.9551	-0.44	0.9562	-0.11
XLPE	0.9294	-0.66	0.9328	0.06	0.9340	-0.06	0.9324	-0.17
PP	0.9005	-0.26	0.9036	-0.35	0.9073	0.75	0.9048	-0.09
KEL-F	2.1099	-0.70	2.1254	0.46	2.1209	-0.08	2.1176	-0.24
TEFLON	2.1690	-0.42	2.1811	0.15	2.1812	0.11	2.1857	0.00
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9536	-0.55	0.9453	-1.47	0.9508	-0.67	0.9506	-0.80
XLPE	0.9295	-0.75	0.9253	-1.29	0.9324	-0.61	0.9319	-0.47
PP	0.9084	-0.24	0.8943	-1.15	0.9054	-0.51	0.9067	-0.30
KEL-F	2.1199	-0.47	2.1035	-1.14	2.1255	-0.21	2.1239	-0.22
TEFLON	2.1832	-0.30	2.1649	-1.14	2.1816	-0.36	2.1840	0.05
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9556	0.02	0.9557	0.04	0.9586	0.34	0.9546	-0.08
XLPE	0.9337	-0.06	0.9344	0.01	0.9358	0.16	0.9378	0.37
PP	0.9041	0.18	0.9059	0.37	0.9101	0.84	0.9058	0.36
KEL-F	2.1152	-0.13	2.1225	0.22	2.1204	0.12	2.1210	0.15
TEFLON	2.1887	0.46	2.1902	0.53	2.1992	0.94	2.1940	0.71
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9541	-0.34	0.9561	-0.13	0.9561	-0.12	0.9561	-0.13
XLPE	0.9307	-0.46	0.9310	-0.42	0.9251	-1.06	0.9322	-0.30
PP	0.9025	0.01	0.9040	0.18	0.9052	0.30	0.9058	0.37
KEL-F	2.1180	-0.16	2.1237	0.11	2.1029	-0.87	2.1233	0.09
TEFLON	2.1980	0.86	2.1993	0.92	2.1985	0.88	2.2010	1.00
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9564	0.06	0.9561	0.03	0.9543	-0.16	0.9545	-0.14
XLPE	0.9343	0.10	0.9333	0.00	0.9306	-0.29	0.9304	-0.31
PP	0.9043	-0.35	0.9014	-0.67	0.9068	-0.07	0.9022	-0.58
KEL-F	2.1189	-0.31	2.1204	-0.24	2.1198	-0.27	2.1196	-0.27
TEFLON	2.2050	1.20	2.2036	1.14	2.1912	0.57	2.2037	1.14
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9567	-0.66	0.9599	0.01	0.9602	0.32	0.9546	-0.22
XLPE	0.9316	-0.58	0.9348	0.05	0.9372	0.53	0.9436	0.79
PP	0.9025	-0.78	0.9033	-0.65	0.9044	-0.57	0.9088	0.14
KEL-F	2.1142	-0.64	2.1265	-0.20	2.1230	-0.27	2.1214	-0.38
TEFLON	2.2191	1.11	2.2258	1.06	2.2213	1.30	2.2269	1.80
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9531	-0.44	0.9567	-0.06	0.9586	0.14	0.9583	0.11
XLPE	0.9316	-0.38	0.9325	-0.29	0.9349	-0.03	0.9365	0.14
PP	0.9013	-0.30	0.9053	0.15	0.9087	0.53	0.9089	0.55
KEL-F	2.1200	-0.11	2.1213	-0.05	2.1285	0.29	2.1234	0.06
TEFLON	2.1978	1.13	2.2011	1.28	2.2049	1.46	2.2088	1.63

Specific Gravity Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9545	-0.43	0.9512	-0.79	0.9483	-1.08	0.9527	-0.63
XLPE	0.9305	-0.61	0.9280	-0.87	0.9330	-0.34	0.9389	0.29
PP	0.9026	-0.31	0.9051	-0.04	0.8994	-0.67	0.9051	-0.04
KEL-F	2.1182	-0.15	2.1173	-0.19	2.0781	-2.04	2.1269	0.26
TEFLON	2.2075	1.45	2.2066	1.41	2.1727	-0.15	2.2088	1.51
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9522	-0.36	0.9520	-0.38	0.9560	0.04	0.9548	-0.08
XLPE	0.9321	0.10	0.9301	-0.12	0.9354	0.45	0.9345	0.36
PP	0.9020	-0.47	0.9033	-0.33	0.9058	-0.06	0.9057	-0.07
KEL-F	2.1244	0.21	2.1155	-0.21	2.1272	0.34	2.1262	0.29
TEFLON	2.2134	1.43	2.2021	0.91	2.2204	1.75	2.2160	1.55
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9510	-0.16	0.9549	0.27	0.9528	-0.44	0.9561	0.09
XLPE	0.9356	0.30	0.9393	0.73	0.9387	0.58	0.9420	0.84
PP	0.9035	0.00	0.9049	0.19	0.9000	-0.51	0.9073	0.35
KEL-F	2.1217	0.02	2.1215	0.08	2.1239	0.38	2.1221	-0.05
TEFLON	2.2340	2.64	2.2304	2.71	2.2261	2.09	2.2302	2.54
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9556	0.03	0.9546	-0.08	0.9588	0.36	0.9574	0.21
XLPE	0.9326	-0.15	0.9301	-0.41	0.9345	0.06	0.9398	0.63
PP	0.9050	-0.03	0.9024	-0.33	0.9064	0.12	0.9066	0.13
KEL-F	2.1242	0.34	2.1230	0.29	2.1252	0.39	2.1272	0.48
TEFLON	2.1963	0.82	2.2031	1.13	2.2075	1.33	2.2089	1.40
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9549	-0.32	0.9535	-0.46	0.9390	-1.97	0.9492	-0.90
XLPE	0.9371	0.00	0.9295	-0.81	0.9295	-0.80	0.9359	-0.13
PP	0.9015	-0.45	0.9022	-0.37	0.8920	-1.50	0.9024	-0.34
KEL-F	2.1178	-0.30	2.1183	-0.27	2.0953	-1.36	2.1230	-0.05
TEFLON	2.2067	1.52	2.1972	1.09	2.1636	1.66	2.2040	1.40
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9519	-0.28	0.9521	-0.26	0.9591	0.47	0.9524	-0.24
XLPE	0.9338	0.02	0.9330	-0.07	0.9377	0.44	0.9406	0.74
PP	0.9063	0.11	0.9029	-0.27	0.9082	0.32	0.9051	-0.02
KEL-F	2.1213	0.04	2.1215	0.05	2.1308	0.49	2.1227	0.10
TEFLON	2.2090	1.34	2.2086	1.32	2.2217	1.92	2.2149	1.61
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE	SPECIFIC GRAVITY	% CHANGE
HDPE	0.9454	-1.27	0.9470	-1.26	0.9549	-0.21	0.9538	-0.50
XLPE	0.9243	-1.38	0.9389	0.26	0.9387	0.18	0.9452	1.01
PP	0.9046	-0.58	0.8982	-1.16	0.9054	-0.53	0.9049	-0.45
KEL-F	2.1014	-1.28	2.1240	-0.23	2.1216	-0.24	2.1235	-0.24
TEFLON	2.2108	0.98	2.2253	1.82	2.2401	2.40	2.2378	2.38

APPENDIX C-1

Mass Data

AVERAGE WEIGHT (g) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.683	0.03	5.683	0.02	5.683	0.03	5.684	0.04
XLPE	5.837	0.01	5.838	0.01	5.837	0.01	5.838	0.02
PP	5.615	0.01	5.616	0.02	5.616	0.02	5.616	0.02
KEL-F	14.730	0.02	14.728	0.00	14.728	0.00	14.728	0.01
TEFLON	13.964	0.00	13.965	0.01	13.965	0.01	13.965	0.01
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.699	0.02	5.699	0.02	5.699	0.02	5.698	0.01
XLPE	5.836	0.06	5.833	0.01	5.833	0.01	5.834	0.03
PP	5.636	0.02	5.636	0.02	5.636	0.01	5.636	0.01
KEL-F	14.716	0.01	14.716	0.01	14.715	0.00	14.716	0.01
TEFLON	13.976	0.03	13.973	0.00	13.973	0.00	13.974	0.01
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.698	0.01	5.698	0.01	5.698	0.00	5.695	-0.04
XLPE	5.849	0.00	5.849	0.00	5.849	0.00	5.851	0.04
PP	5.643	0.00	5.643	-0.01	5.644	0.00	5.642	-0.02
KEL-F	14.653	0.00	14.653	0.00	14.653	0.00	14.655	0.02
TEFLON	13.944	-0.01	13.944	-0.01	13.945	-0.01	13.948	0.02
18 C,143K *	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.670	-0.56	5.671	-0.54	5.670	-0.55	5.671	-0.54
XLPE	5.834	1.78	5.834	1.78	5.834	1.78	5.834	1.78
PP	5.640	4.82	5.641	4.83	5.639	4.81	5.640	4.82
KEL-F	14.683	5.00	14.683	5.00	14.684	5.01	14.683	5.00
TEFLON	13.189	0.82	13.189	0.81	13.189	0.82	13.189	0.82
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.678	0.02	5.678	0.03	5.678	0.02	5.679	0.03
XLPE	5.830	0.01	5.830	0.02	5.830	0.02	5.830	0.02
PP	5.634	0.02	5.634	0.03	5.634	0.03	5.635	0.04
KEL-F	14.570	0.00	14.571	0.00	14.572	0.01	14.570	0.00
TEFLON	13.281	0.00	13.281	0.01	13.281	0.01	13.281	0.01
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.678	0.02	5.679	0.02	5.679	0.03	5.680	0.04
XLPE	5.825	0.03	5.825	0.02	5.825	0.03	5.826	0.04
PP	5.643	0.02	5.643	0.03	5.643	0.03	5.644	0.04
KEL-F	14.612	0.00	14.612	0.00	14.612	0.00	14.612	0.00
TEFLON	13.171	0.00	13.171	0.01	13.171	0.01	13.172	0.01
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.685	0.03	5.685	0.02	5.685	0.03	5.687	0.06
XLPE	5.748	0.04	5.748	0.04	5.749	0.05	5.750	0.08
PP	5.406	0.05	5.405	0.04	5.405	0.04	5.406	0.06
KEL-F	14.207	0.03	14.204	0.01	14.203	0.00	14.203	0.00
TEFLON	13.099	0.00	13.099	0.00	13.098	-0.01	13.098	-0.01
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.693	0.02	5.694	0.03	5.693	0.02	5.691	-0.01
XLPE	5.825	0.01	5.825	0.02	5.828	0.06	5.825	0.02
PP	5.647	0.07	5.645	0.04	5.645	0.03	5.644	0.01
KEL-F	15.286	0.01	15.285	0.00	15.285	0.00	15.285	0.00
TEFLON	13.888	0.00	13.888	0.00	13.888	0.00	13.888	0.00

Mass Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.703	0.02	5.703	0.01	5.702	0.00	5.702	-0.01
XLPE	5.733	0.01	5.733	0.02	5.733	0.01	5.733	0.02
PP	5.383	0.03	5.383	0.03	5.382	0.02	5.382	0.01
KEL-F	13.986	0.00	13.986	0.00	13.985	0.00	13.985	0.00
TEFLON	13.084	0.01	13.083	0.00	13.083	0.00	13.084	0.01
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.694	0.07	5.692	0.04	5.691	0.03	5.690	0.00
XLPE	5.824	0.02	5.824	0.02	5.824	0.02	5.824	0.01
PP	5.632	0.06	5.631	0.04	5.631	0.04	5.630	0.03
KEL-F	15.022	0.01	15.021	0.01	15.021	0.01	15.021	0.01
TEFLON	13.207	0.01	13.207	0.01	13.206	0.01	13.207	0.01
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.709	0.06	5.708	0.05	5.709	0.05	5.708	0.04
XLPE	5.742	0.08	5.742	0.08	5.742	0.09	5.744	0.12
PP	5.396	0.06	5.397	0.07	5.396	0.05	5.395	0.04
KEL-F	14.177	0.02	14.175	0.00	14.176	0.00	14.175	0.00
TEFLON	13.128	0.00	13.129	0.00	13.128	-0.01	13.128	-0.01
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.692	0.04	5.692	0.03	5.692	0.03	5.689	-0.02
XLPE	5.830	0.01	5.830	0.02	5.831	0.03	5.835	0.10
PP	5.630	0.03	5.630	0.03	5.630	0.03	5.627	-0.01
KEL-F	14.786	0.01	14.788	0.02	14.785	0.01	14.786	0.01
TEFLON	13.887	0.01	13.886	0.00	13.886	0.00	13.886	0.00
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.683	0.05	5.683	0.04	5.682	0.03	5.679	-0.02
XLPE	5.819	0.01	5.818	0.01	5.819	0.02	5.822	0.08
PP	5.623	0.03	5.622	0.01	5.622	0.01	5.621	-0.01
KEL-F	15.052	0.01	15.053	0.01	15.052	0.01	15.052	0.01
TEFLON	13.882	0.00	13.883	0.01	13.882	0.00	13.883	0.00
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.684	0.02	5.683	0.01	5.683	0.01	5.679	-0.05
XLPE	5.882	0.02	5.882	0.01	5.883	0.02	5.884	0.04
PP	5.623	0.03	5.622	0.03	5.623	0.03	5.621	0.00
KEL-F	15.129	0.00	15.129	0.01	15.129	0.00	15.130	0.01
TEFLON	13.982	0.01	13.981	0.00	13.981	0.00	13.981	0.00
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE	WEIGHT	% CHANGE
HDPE	5.707	0.05	5.706	0.03	5.706	0.04	5.704	0.01
XLPE	5.754	0.11	5.755	0.12	5.756	0.14	5.760	0.21
PP	5.385	0.05	5.385	0.05	5.385	0.05	5.385	0.05
KEL-F	14.295	0.00	14.295	0.01	14.296	0.01	14.296	0.01
TEFLON	13.086	-0.01	13.086	-0.01	13.086	-0.01	13.089	-0.02
* Measurement Error								

APPENDIX C
Dimensional Data

AVERAGE VOLUME (mm^3) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6010	1.34	6030	1.78	6060	2.29	6070	2.36
XLPE	6340	1.37	6340	1.50	6380	2.01	6390	2.31
PP	6260	0.41	6260	0.40	6290	0.86	6290	0.95
KEL-F	7040	0.35	7050	0.54	7070	0.81	7070	0.72
TEFLON	6470	0.33	6490	0.61	6510	0.93	6530	1.21
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6080	1.90	6070	1.73	6120	2.57	6140	2.89
XLPE	6320	0.93	6320	0.96	6370	1.81	6370	1.77
PP	6310	0.69	6310	0.02	6330	1.08	6340	1.16
KEL-F	7010	0.72	7020	0.88	7050	1.28	7070	1.47
TEFLON	6460	0.45	6460	0.41	6520	1.34	6560	2.01
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6090	1.82	6110	2.21	6140	2.61	6100	1.99
XLPE	6350	1.63	6330	1.24	6390	2.18	6360	1.83
PP	6320	1.05	6290	0.69	6340	1.46	6340	1.36
KEL-F	7030	1.33	7020	1.24	7040	1.53	7060	1.75
TEFLON	6460	1.23	6460	1.29	6510	1.98	6530	2.41
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6020	0.57	6030	0.73	6040	0.93	6050	1.08
XLPE	6340	0.37	6360	0.65	6380	1.00	6370	0.88
PP	6310	0.32	6310	0.36	6330	0.69	6320	0.41
KEL-F	7020	0.76	7050	1.14	7010	0.57	7040	0.95
TEFLON	6060	0.09	6060	0.24	6060	0.10	6070	0.28
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6030	0.63	6040	0.73	6070	1.19	6070	1.18
XLPE	6330	0.58	6340	0.71	6350	0.85	6360	1.00
PP	6300	0.24	6320	0.53	6320	0.44	6330	0.67
KEL-F	6990	0.53	7000	0.67	7010	0.87	6980	0.47
TEFLON	6100	-0.35	6090	-0.44	6130	0.14	6110	-0.22
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6010	0.24	6020	0.34	6040	0.67	6060	0.97
XLPE	6340	0.56	6340	0.59	6340	0.55	6380	1.22
PP	6270	-0.31	6310	0.19	6290	0.01	6330	0.56
KEL-F	6990	0.31	7010	0.51	7000	0.39	7030	0.81
TEFLON	5990	-1.19	6030	-0.57	6030	-0.51	6050	-0.30
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	5980	-0.26	6020	0.33	6010	0.26	6030	0.59
XLPE	6200	0.69	6240	1.41	6230	1.32	6260	1.70
PP	6120	1.07	6130	1.26	6140	1.40	6170	1.89
KEL-F	6770	0.23	6810	0.75	6800	0.68	6800	0.63
TEFLON	5930	0.38	5960	0.87	5970	1.00	5970	0.97
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6060	1.05	6080	1.27	6100	1.61	6100	1.63
XLPE	6340	0.61	6360	0.81	6370	1.03	6360	0.90
PP	6320	0.43	6320	0.43	6340	0.76	6320	0.49
KEL-F	7310	0.35	7320	0.55	7300	0.28	7310	0.34
TEFLON	6420	-0.05	6440	0.20	6450	0.46	6480	0.93

Dimensional Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6030	0.25	6040	0.29	6040	0.38	6050	0.53
XLPE	6330	1.29	6356	1.66	6350	1.60	6370	1.91
PP	6100	0.37	6120	0.65	6110	0.46	6160	1.28
KEL-F	6660	0.45	6680	0.74	6650	0.34	6660	0.53
TEFLON	5990	-0.55	6000	-0.32	5990	-0.46	6000	-0.23
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6090	1.28	6090	1.34	6080	1.09	6070	0.99
XLPE	6660	0.45	6680	0.74	6650	0.34	6660	0.53
PP	6330	0.14	6330	0.14	6330	0.24	6360	0.62
KEL-F	7180	0.31	7170	0.27	7180	0.42	7170	0.25
TEFLON	6020	-1.29	6030	-0.99	6040	-0.84	6030	-1.00
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6030	0.15	6070	0.82	6050	0.53	6070	0.84
XLPE	6210	0.05	6250	0.75	6250	0.66	6240	0.56
PP	6140	0.64	6170	1.09	6160	0.88	6160	1.00
KEL-F	6720	-0.29	6750	0.19	6750	0.05	6770	0.37
TEFLON	5900	-2.29	5940	-1.75	5940	-1.76	5950	-1.52
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6090	1.51	6090	1.62	6100	1.70	6100	1.70
XLPE	6360	0.89	6350	0.81	6350	0.87	6340	0.70
PP	6290	0.32	6310	0.63	6310	0.63	6320	0.86
KEL-F	7190	0.40	7190	0.49	7220	0.85	7240	1.10
TEFLON	6400	-0.29	6410	-0.13	6400	0.08	6460	0.73
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6110	1.77	6130	2.17	6190	3.19	6130	2.16
XLPE	6380	1.11	6360	0.82	6370	1.02	6330	0.36
PP	6330	0.88	6310	0.53	6340	0.99	6330	0.87
KEL-F	7080	0.69	7090	0.90	7080	0.65	7100	0.92
TEFLON	6440	0.67	6420	0.42	6400	0.08	6440	0.64
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6040	0.55	6050	0.70	6090	1.25	6120	1.85
XLPE	6460	0.88	6480	1.18	6500	1.59	6510	1.68
PP	6280	0.32	6300	0.53	6310	0.73	6310	0.73
KEL-F	7240	0.38	7260	0.74	7270	0.81	7340	1.79
TEFLON	6410	-0.67	6420	-0.49	6440	-0.15	6450	0.01
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE	VOLUME	% CHANGE
HDPE	6020	-0.04	6040	0.20	6040	0.29	6050	0.47
XLPE	6320	1.57	6330	1.82	6340	1.97	6330	1.80
PP	6190	1.69	6190	1.68	6210	2.09	6170	1.40
KEL-F	6800	0.11	6830	0.51	6840	0.72	6830	0.50
TEFLON	5890	-2.30	5920	-1.85	5930	-1.77	5930	-1.75

Dimensional Data (cont.)

AVERAGE LENGTH (mm) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.01	0.03	76.03	0.06	76.06	0.09	76.10	0.14
XLPE	75.87	0.03	75.88	0.03	75.92	0.09	75.95	0.12
PP	76.02	0.01	76.02	0.00	76.04	0.04	76.07	0.07
KEL-F	76.10	-0.01	76.10	0.00	76.12	0.02	76.13	0.04
TEFLON	75.97	0.01	75.97	0.02	76.01	0.07	76.03	0.10
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.02	0.04	75.99	0.00	76.04	0.07	76.01	0.03
XLPE	75.91	0.00	75.88	-0.04	75.94	0.05	75.90	-0.02
PP	76.04	0.05	76.02	0.02	76.07	0.08	76.06	0.07
KEL-F	75.91	-0.18	75.90	-0.19	75.92	-0.17	75.92	-0.17
TEFLON	76.02	0.06	76.02	0.06	76.08	0.14	76.08	0.15
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	75.94	-0.05	75.91	-0.09	75.95	-0.04	75.90	-0.10
XLPE	75.87	-0.11	75.83	-0.16	75.87	-0.10	75.80	-0.21
PP	76.03	0.04	76.01	0.01	76.06	0.08	76.03	0.04
KEL-F	75.78	-0.37	75.78	-0.37	75.77	-0.38	75.77	-0.38
TEFLON	76.03	0.11	76.01	0.07	76.07	0.15	76.11	0.20
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.07	0.04	76.07	0.03	76.09	0.06	76.05	0.01
XLPE	75.94	0.02	75.92	-0.01	76.00	0.09	75.91	-0.03
PP	76.13	0.03	76.12	0.01	76.15	0.05	76.11	0.00
KEL-F	76.00	0.05	76.00	0.04	76.00	0.05	75.98	0.02
TEFLON	75.93	-0.09	75.90	-0.13	75.88	-0.17	75.84	-0.21
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.06	0.04	76.03	0.00	76.10	0.09	76.03	-0.01
XLPE	75.94	-0.01	75.90	-0.06	75.98	0.04	75.93	-0.03
PP	76.00	-0.13	76.10	0.00	76.12	0.02	76.09	-0.01
KEL-F	76.04	0.06	76.02	0.03	76.04	0.05	76.00	0.01
TEFLON	75.88	-0.14	75.85	-0.18	75.81	-0.22	75.80	-0.25
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.05	0.03	76.05	0.02	76.28	0.32	76.10	0.09
XLPE	75.93	0.04	75.95	0.07	75.92	0.03	75.96	0.08
PP	76.06	-0.01	76.08	0.02	76.07	0.01	76.10	0.05
KEL-F	76.06	0.04	76.06	0.04	76.06	0.04	76.08	0.06
TEFLON	75.79	-0.27	75.79	-0.26	75.76	-0.31	75.78	-0.27
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.09	0.02	76.10	0.04	76.09	0.02	76.12	0.07
XLPE	76.04	-0.12	76.08	-0.07	76.07	-0.09	76.06	-0.09
PP	76.17	0.05	76.18	0.07	76.18	0.07	76.19	0.09
KEL-F	76.07	-0.01	76.10	0.02	76.09	0.01	76.10	0.02
TEFLON	75.58	-0.54	75.60	-0.52	75.58	-0.55	75.58	-0.55
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.04	0.00	76.00	-0.05	76.02	-0.03	75.93	-0.14
XLPE	76.03	-0.01	76.00	-0.05	76.00	-0.05	75.93	-0.13
PP	76.08	0.06	76.05	0.02	76.06	0.03	76.01	-0.03
KEL-F	75.87	-0.18	75.86	-0.19	75.86	-0.19	75.82	-0.24
TEFLON	75.87	-0.20	75.85	-0.23	75.88	-0.19	75.83	-0.25

Dimensional Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.19	0.05	76.20	0.07	76.22	0.08	76.24	0.11
XLPE	75.97	-0.18	76.00	-0.13	76.05	-0.07	76.01	-0.12
PP	76.20	0.04	76.21	0.06	76.22	0.07	76.22	0.07
KEL-F	75.97	-0.17	75.97	-0.17	75.96	-0.18	75.96	-0.18
TEFLON	75.76	-0.39	75.77	-0.37	75.78	-0.36	75.78	-0.37
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.07	0.03	76.05	0.01	76.05	0.00	76.02	-0.04
XLPE	75.95	-0.06	75.96	-0.06	75.97	-0.04	75.93	-0.10
PP	76.17	0.02	76.18	0.04	76.19	0.05	76.15	0.00
KEL-F	75.88	-0.21	75.88	-0.19	75.88	-0.20	75.88	-0.21
TEFLON	75.59	-0.55	75.61	-0.53	75.62	-0.51	75.61	-0.53
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.17	0.10	76.20	0.14	76.19	0.13	76.21	0.15
XLPE	75.91	-0.28	75.94	-0.24	75.92	-0.27	75.86	-0.35
PP	76.18	0.02	76.21	0.07	76.20	0.05	76.20	0.06
KEL-F	75.87	-0.25	75.89	-0.22	75.88	-0.24	75.88	-0.24
TEFLON	75.43	-0.81	75.47	-0.76	75.45	-0.78	75.47	-0.76
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.06	0.04	76.00	-0.04	75.97	-0.07	75.82	-0.27
XLPE	75.97	0.05	75.86	-0.09	75.84	-0.12	75.63	-0.40
PP	76.11	0.07	76.08	0.03	76.08	0.04	76.02	-0.04
KEL-F	75.81	-0.27	75.72	-0.39	75.80	-0.27	75.55	-0.61
TEFLON	75.82	-0.26	75.80	-0.29	75.73	-0.38	75.79	-0.30
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.02	0.02	75.96	-0.06	75.96	-0.07	75.86	-0.20
XLPE	75.86	-0.09	75.81	-0.15	75.79	-0.18	75.65	-0.36
PP	76.09	0.04	76.06	0.00	76.07	0.01	76.04	-0.03
KEL-F	75.67	-0.44	75.64	-0.48	75.65	-0.47	75.57	-0.57
TEFLON	75.79	-0.28	75.77	-0.30	75.77	-0.30	75.74	-0.33
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	75.98	-0.06	75.98	-0.05	75.91	-0.14	75.89	-0.17
XLPE	75.78	-0.15	75.83	-0.08	75.75	-0.20	75.71	-0.25
PP	76.03	-0.01	76.03	0.00	76.01	-0.04	76.01	-0.03
KEL-F	75.73	-0.45	75.72	-0.46	75.71	-0.48	75.64	-0.57
TEFLON	75.58	-0.48	75.60	-0.46	75.57	-0.49	75.60	-0.45
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE	LENGTH	% CHANGE
HDPE	76.23	0.12	76.24	0.13	76.25	0.15	76.26	0.15
XLPE	75.86	-0.33	75.84	-0.35	75.79	-0.42	75.62	-0.65
PP	76.21	0.08	76.21	0.08	76.22	0.08	76.21	0.08
KEL-F	75.67	-0.58	75.67	-0.57	75.69	-0.55	75.73	-0.49
TEFLON	75.36	-0.93	75.37	-0.91	75.36	-0.92	75.36	-0.91

Dimensional Data (cont.)

AVERAGE WIDTH (mm) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.45	0.18	25.45	0.17	25.48	0.28	25.51	0.40
XLPE	25.40	0.24	25.42	0.30	25.43	0.34	25.45	0.43
PP	25.41	0.09	25.43	0.16	25.42	0.13	25.43	0.19
KEL-F	25.43	0.20	25.49	0.42	25.48	0.39	25.43	0.19
TEFLON	25.31	0.09	25.32	0.12	25.33	0.19	25.34	0.22
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.49	0.10	25.50	0.14	25.54	0.29	25.55	0.32
XLPE	25.39	0.04	25.39	0.04	25.42	0.16	25.41	0.11
PP	25.42	0.13	25.44	0.19	25.44	0.21	25.46	0.27
KEL-F	25.34	-0.04	25.35	0.00	25.36	0.01	25.37	0.07
TEFLON	25.32	0.09	25.33	0.12	25.35	0.20	25.34	0.19
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.52	0.28	25.53	0.31	25.51	0.27	25.48	0.15
XLPE	25.36	0.02	25.35	0.00	25.39	0.16	25.36	0.02
PP	25.46	0.28	25.44	0.20	25.46	0.28	25.46	0.29
KEL-F	25.33	-0.09	25.33	-0.09	25.34	-0.07	25.32	-0.14
TEFLON	25.37	0.29	25.36	0.25	25.39	0.35	25.42	0.45
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.44	0.21	25.43	0.16	25.45	0.26	25.44	0.21
XLPE	25.44	0.11	25.46	0.18	25.47	0.20	25.49	0.29
PP	25.44	0.02	25.44	0.01	25.46	0.09	25.43	-0.03
KEL-F	25.38	0.22	25.38	0.24	25.36	0.16	25.36	0.22
TEFLON	25.34	-0.11	25.34	-0.13	25.37	-0.02	25.35	-0.07
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.45	0.06	25.46	0.09	25.49	0.20	25.47	0.11
XLPE	25.43	0.01	25.45	0.10	25.47	0.19	25.44	0.07
PP	25.51	0.10	25.49	0.02	25.45	-0.13	25.50	0.07
KEL-F	25.36	-0.02	25.37	0.02	25.44	0.28	25.37	0.03
TEFLON	25.28	-0.28	25.27	-0.33	25.32	-0.12	25.31	-0.18
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.44	0.03	25.44	0.07	25.45	0.09	25.47	0.16
XLPE	25.47	0.11	25.44	0.01	25.46	0.07	25.49	0.19
PP	25.48	0.04	25.49	0.10	25.48	0.07	25.50	0.13
KEL-F	25.45	0.04	25.48	0.14	25.47	0.11	25.50	0.22
TEFLON	25.22	-0.40	25.22	-0.38	25.22	-0.38	25.24	-0.31
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.42	-0.07	25.47	0.11	25.45	0.05	25.48	0.16
XLPE	25.24	0.05	25.27	0.16	25.29	0.26	25.25	0.09
PP	25.56	0.20	25.55	0.18	25.57	0.25	25.56	0.22
KEL-F	25.38	0.14	25.39	0.19	25.39	0.19	25.39	0.16
TEFLON	25.28	-0.17	25.29	-0.13	25.29	-0.13	25.28	-0.18
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.49	0.22	25.48	0.17	25.53	0.35	25.50	0.23
XLPE	25.42	-0.06	25.42	-0.03	25.44	0.06	25.42	-0.02
PP	25.49	0.14	25.50	0.17	25.51	0.22	25.48	0.11
KEL-F	25.28	-0.18	25.28	-0.17	25.24	-0.32	25.26	-0.26
TEFLON	25.30	-0.12	25.29	-0.14	25.30	-0.11	25.29	-0.14

Dimensional Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.39	-0.02	25.41	0.04	25.40	0.01	25.39	-0.01
XLPE	25.31	0.08	25.31	0.08	25.33	0.15	25.29	0.00
PP	25.59	0.08	25.58	0.08	25.57	0.03	25.56	-0.01
KEL-F	25.29	-0.06	25.28	-0.09	25.27	-0.15	25.26	-0.18
TEFLON	25.43	-0.27	25.45	-0.20	25.43	-0.28	25.44	-0.22
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.43	0.14	25.44	0.15	25.44	0.15	25.42	0.10
XLPE	25.41	-0.06	25.43	-0.01	25.42	-0.02	25.40	-0.10
PP	25.46	0.08	25.46	0.10	25.47	0.13	25.48	0.17
KEL-F	25.32	-0.17	25.32	-0.16	25.31	-0.19	25.30	-0.23
TEFLON	25.19	-0.46	25.20	-0.42	25.20	-0.40	25.18	-0.47
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.52	0.05	25.52	0.07	25.50	0.00	25.49	-0.03
XLPE	25.23	-0.05	25.26	0.07	25.24	0.01	25.20	-0.15
PP	25.54	0.16	25.56	0.21	25.54	0.16	25.53	0.09
KEL-F	25.24	-0.29	25.26	-0.22	25.24	-0.31	25.25	-0.28
TEFLON	25.24	-0.75	25.25	-0.71	25.26	-0.67	25.26	-0.66
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.45	0.18	25.45	0.17	25.50	0.36	25.46	0.22
XLPE	25.43	-0.06	25.42	-0.11	25.46	0.05	25.36	-0.36
PP	25.48	0.22	25.46	0.16	25.49	0.29	25.47	0.20
KEL-F	25.31	-0.22	25.29	-0.32	25.27	-0.38	25.23	-0.55
TEFLON	25.30	-0.07	25.29	-0.12	25.27	-0.19	25.28	-0.16
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.50	0.24	25.49	0.21	25.52	0.33	25.50	0.25
XLPE	25.40	-0.04	25.39	-0.06	25.42	0.03	25.34	-0.26
PP	25.46	0.07	25.45	0.05	25.49	0.20	25.45	0.06
KEL-F	25.31	-0.17	25.29	-0.27	25.33	-0.11	25.28	-0.29
TEFLON	25.33	-0.01	25.31	-0.09	25.31	-0.08	25.33	-0.03
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.53	0.21	25.54	0.25	25.56	0.32	25.55	0.30
XLPE	25.49	0.03	25.48	-0.01	25.53	0.17	25.47	-0.05
PP	25.43	0.02	25.44	0.08	25.48	0.21	25.46	0.14
KEL-F	25.33	-0.23	25.33	-0.22	25.34	-0.17	25.32	-0.27
TEFLON	25.27	-0.36	25.29	-0.26	25.29	-0.28	25.29	-0.26
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE	WIDTH	% CHANGE
HDPE	25.47	-0.12	25.48	-0.08	25.43	-0.28	25.45	-0.19
XLPE	25.24	-0.16	25.24	-0.15	25.25	-0.11	25.18	-0.38
PP	25.60	0.15	25.59	0.14	25.50	-0.23	25.58	0.07
KEL-F	25.14	-0.53	25.15	-0.51	25.17	-0.45	25.11	-0.66
TEFLON	25.28	-0.53	25.27	-0.56	25.23	-0.74	25.32	-0.58

Dimensional Data (cont.)

AVERAGE THICKNESS (mm) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.11	1.12	3.12	1.56	3.13	1.92	3.13	1.81
XLPE	3.29	1.09	3.29	1.16	3.30	1.57	3.31	1.74
PP	3.24	0.31	3.24	0.24	3.25	0.69	3.25	0.69
KEL-F	3.64	0.15	3.64	0.12	3.65	0.40	3.65	0.49
TEFLON	3.37	0.23	3.37	0.46	3.38	0.66	3.39	0.89
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.14	1.77	3.13	1.59	3.15	2.20	3.16	2.52
XLPE	3.28	0.89	3.28	0.96	3.30	1.61	3.30	1.68
PP	3.26	0.51	3.26	0.51	3.27	0.79	3.27	0.82
KEL-F	3.65	0.95	3.65	1.08	3.66	1.45	3.67	1.57
TEFLON	3.36	0.30	3.35	0.23	3.38	1.00	3.40	1.66
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.14	1.58	3.15	1.98	3.17	2.37	3.15	1.94
XLPE	3.30	1.71	3.29	1.40	3.31	2.12	3.31	2.02
PP	3.26	0.72	3.26	0.48	3.28	1.10	3.27	1.03
KEL-F	3.66	1.79	3.66	1.70	3.67	1.98	3.68	2.28
TEFLON	3.35	0.84	3.35	0.97	3.37	1.47	3.38	1.74
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.11	0.32	3.12	0.54	3.12	0.61	3.13	0.86
XLPE	3.28	0.24	3.29	0.48	3.30	0.71	3.29	0.61
PP	3.26	0.27	3.26	0.34	3.27	0.55	3.26	0.44
KEL-F	3.64	0.49	3.65	0.86	3.64	0.37	3.65	0.71
TEFLON	3.15	0.28	3.15	0.24	3.15	0.28	3.16	0.57
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.12	0.54	3.12	0.65	3.13	0.90	3.13	1.07
XLPE	3.28	0.58	3.28	0.68	3.28	0.61	3.29	0.95
PP	3.25	0.27	3.26	0.51	3.26	0.55	3.26	0.62
KEL-F	3.62	0.49	3.63	0.62	3.63	0.53	3.62	0.43
TEFLON	3.18	0.07	3.18	0.07	3.19	0.49	3.18	0.21
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.11	0.14	3.11	0.25	3.11	0.25	3.13	0.72
XLPE	3.28	0.41	3.28	0.51	3.28	0.44	3.30	0.95
PP	3.24	-0.34	3.25	0.07	3.25	-0.07	3.26	0.38
KEL-F	3.61	0.22	3.62	0.34	3.61	0.25	3.62	0.52
TEFLON	3.14	-0.53	3.15	0.07	3.16	0.18	3.16	0.28
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.09	-0.22	3.11	0.18	3.11	0.18	3.11	0.36
XLPE	3.23	0.76	3.25	1.32	3.24	1.15	3.26	1.70
PP	3.15	0.82	3.15	1.00	3.15	1.08	3.17	1.57
KEL-F	3.51	0.10	3.52	0.54	3.52	0.48	3.52	0.44
TEFLON	3.11	1.10	3.12	1.54	3.12	1.68	3.12	1.71
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.13	0.82	3.14	1.15	3.14	1.29	3.15	1.54
XLPE	3.28	0.68	3.29	0.89	3.29	1.02	3.30	1.06
PP	3.26	0.24	3.26	0.24	3.27	0.51	3.27	0.41
KEL-F	3.81	0.70	3.82	0.91	3.81	0.79	3.82	0.85
TEFLON	3.35	0.27	3.36	0.57	3.36	0.77	3.38	1.33

Dimensional Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.12	0.21	3.12	0.18	3.12	0.29	3.13	0.43
XLPE	3.29	1.39	3.30	1.71	3.30	1.52	3.32	2.04
PP	3.13	0.25	3.14	0.52	3.13	0.36	3.16	1.22
KEL-F	3.47	0.68	3.48	1.00	3.47	0.68	3.47	0.90
TEFLON	3.11	0.11	3.11	0.25	3.11	0.18	3.11	0.36
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.15	1.11	3.15	1.18	3.14	0.93	3.14	0.93
XLPE	3.29	0.51	3.29	0.75	3.30	0.88	3.30	0.82
PP	3.26	0.03	3.26	0.00	3.26	0.07	3.28	0.44
KEL-F	3.74	0.69	3.73	0.63	3.74	0.81	3.74	0.69
TEFLON	3.16	-0.28	3.17	-0.03	3.17	0.07	3.17	0.00
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.10	0.00	3.12	0.61	3.11	0.39	3.12	0.72
XLPE	3.24	0.38	3.26	0.93	3.26	0.93	3.27	1.07
PP	3.16	0.46	3.17	0.81	3.16	0.67	3.17	0.85
KEL-F	3.51	0.25	3.52	0.63	3.52	0.60	3.53	0.89
TEFLON	3.10	-0.75	3.12	-0.29	3.11	-0.32	3.12	-0.11
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.15	1.54	3.17	2.04	3.20	2.90	3.18	2.22
XLPE	3.30	1.12	3.30	1.02	3.30	1.09	3.30	1.12
PP	3.27	0.58	3.26	0.34	3.27	0.65	3.27	0.72
KEL-F	3.69	1.19	3.71	1.61	3.69	1.31	3.72	2.10
TEFLON	3.36	1.00	3.35	0.84	3.34	0.65	3.36	1.10
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.14	1.25	3.15	1.47	3.15	1.43	3.15	1.65
XLPE	3.30	1.02	3.30	1.02	3.30	1.02	3.31	1.33
PP	3.25	0.21	3.26	0.58	3.25	0.41	3.27	0.82
KEL-F	3.75	1.02	3.76	1.26	3.77	1.44	3.79	1.98
TEFLON	3.33	0.00	3.34	0.27	3.36	0.80	3.37	1.10
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.12	0.39	3.12	0.50	3.14	1.07	3.16	1.72
XLPE	3.34	1.01	3.35	1.28	3.36	1.61	3.37	1.98
PP	3.25	0.31	3.26	0.45	3.26	0.55	3.26	0.62
KEL-F	3.77	1.07	3.79	1.43	3.79	1.46	3.83	2.65
TEFLON	3.36	0.17	3.36	0.23	3.37	0.63	3.38	0.73
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE	THICKNESS	% CHANGE
HDPE	3.10	-0.04	3.11	0.18	3.12	0.43	3.12	0.50
XLPE	3.30	2.06	3.31	2.34	3.31	2.51	3.32	2.85
PP	3.17	1.46	3.17	1.46	3.20	2.24	3.17	1.24
KEL-F	3.57	1.23	3.59	1.61	3.59	1.73	3.59	1.67
TEFLON	3.09	-0.85	3.11	-0.39	3.12	-0.11	3.11	-0.27

APPENDIX D
Hardness Data

AVERAGE SHORE TYPE D HARDNESS AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	68.4	1.13	68.2	0.84	68.0	0.49	67.2	-0.64
XLPE	67.5	1.10	67.2	0.70	67.3	0.80	66.6	-0.20
PP	77.0	1.72	77.0	1.72	76.6	1.23	75.7	-0.04
KEL-F	80.7	1.09	80.6	0.92	80.6	0.88	79.4	-0.58
TEFLON	60.3	2.90	59.9	2.28	59.6	1.71	58.3	-0.57
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	67.4	-1.08	67.5	-1.03	67.2	-1.47	66.0	-3.18
XLPE	66.8	0.45	66.3	-0.30	66.3	-0.30	65.7	-1.15
PP	76.4	0.53	75.7	-0.39	75.2	-1.05	74.8	-1.58
KEL-F	80.3	0.80	80.3	0.75	79.6	-0.17	78.7	-1.30
TEFLON	59.3	0.79	59.9	1.70	58.1	-1.25	58.2	-1.13
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	67.4	-1.03	67.4	-1.03	67.5	-0.93	66.1	-2.89
XLPE	66.1	-0.20	65.8	-0.60	66.2	-0.05	65.1	-1.66
PP	75.6	-0.35	75.0	-1.14	75.1	-1.01	73.9	-2.59
KEL-F	80.5	0.38	80.2	-0.08	80.0	-0.33	78.5	-2.20
TEFLON	58.9	-0.06	59.0	0.06	58.7	-0.34	57.6	-2.21
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	68.2	-0.29	68.3	-0.10	68.2	-0.29	66.8	-2.34
XLPE	67.3	-0.15	67.7	0.40	67.8	0.54	66.8	-0.84
PP	76.5	1.91	76.9	2.53	76.4	1.87	75.6	0.76
KEL-F	81.2	0.08	81.3	0.20	81.2	0.08	80.7	-0.49
TEFLON	58.5	-2.66	59.0	-1.77	58.6	-2.49	58.4	-2.77
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	67.9	-0.49	68.0	-0.39	67.9	-0.54	66.7	-2.20
XLPE	66.9	-0.25	67.2	0.10	66.9	-0.25	67.0	-0.15
PP	76.0	0.40	77.0	1.67	76.4	0.97	75.0	-0.93
KEL-F	80.8	0.46	81.0	0.75	80.8	0.42	79.9	-0.66
TEFLON	58.0	-4.60	58.3	-4.16	57.9	-4.77	57.6	-5.26
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	68.4	-0.63	65.8	-4.44	67.8	-1.50	66.5	-3.43
XLPE	67.4	0.35	65.1	-3.18	67.3	0.15	65.9	-1.88
PP	76.5	0.84	73.4	-3.30	75.9	0.00	74.3	-2.02
KEL-F	81.1	1.00	78.3	-2.47	80.8	0.58	79.0	-1.62
TEFLON	57.5	-3.84	54.0	-9.70	56.5	-5.51	54.1	-9.53
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	69.4	1.86	68.2	0.15	68.0	-0.10	66.6	-2.25
XLPE	69.0	2.94	67.7	1.00	67.9	1.35	66.1	-1.39
PP	78.1	3.95	76.9	2.40	76.6	2.04	74.9	-0.31
KEL-F	82.0	2.33	80.8	0.87	80.9	0.96	80.5	0.50
TEFLON	57.6	-3.84	55.9	-6.68	55.2	-7.74	52.5	-12.25
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE	HARDNESS	% CHANGE
HDPE	67.6	-0.69	67.3	-1.08	67.5	-0.78	67.0	-1.57
XLPE	66.7	0.10	66.5	-0.15	66.7	0.05	66.4	-0.35
PP	75.6	0.62	75.0	-0.13	74.9	-0.27	74.8	-0.44
KEL-F	80.7	0.42	80.7	0.46	79.8	-0.62	79.7	-0.78
TEFLON	58.8	-0.84	57.6	-2.87	57.5	-2.98	58.7	-0.95

Hardness Data (cont.)

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.9	-0.29	67.4	-1.03	67.2	-1.32	67.0	-1.52
XLPE	66.9	0.10	66.3	-0.70	66.4	-0.60	66.3	-0.75
PP	75.3	-0.70	75.0	-1.14	76.9	1.36	75.0	-1.10
KEL-F	80.8	0.50	80.7	0.38	81.1	0.84	79.5	-1.08
TEFLON	57.3	-2.44	57.0	-2.95	59.2	0.80	57.7	-1.70
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.9	-0.54	65.6	-3.93	67.1	-1.80	66.1	-3.27
XLPE	66.9	-0.54	64.6	-3.89	66.2	-1.59	65.6	-2.38
PP	75.7	-0.70	73.3	-3.93	74.7	-2.01	74.1	-2.88
KEL-F	81.3	0.66	79.6	-1.49	80.4	-0.45	79.4	-1.77
TEFLON	57.2	-5.40	54.7	-9.63	55.5	-8.26	53.8	-11.02
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	68.1	-0.34	68.1	-0.44	68.0	-0.54	67.0	-2.05
XLPE	67.5	0.85	67.3	0.60	67.5	0.85	66.9	0.05
PP	76.2	0.04	76.3	0.18	76.2	0.09	75.1	-1.44
KEL-F	80.6	0.12	80.5	-0.08	80.4	-0.17	79.9	-0.83
TEFLON	56.1	-7.06	54.9	-9.16	54.5	-9.71	52.5	-13.08
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.6	-0.54	67.4	-0.83	67.1	-1.32	67.0	-1.52
XLPE	66.4	0.15	66.7	0.60	66.1	-0.30	67.0	1.01
PP	74.9	-1.53	74.8	-1.67	74.8	-1.62	74.8	-1.62
KEL-F	81.0	0.25	80.8	0.04	80.1	-0.78	79.2	-1.98
TEFLON	57.9	-2.08	57.5	-2.87	58.3	-1.46	58.3	-1.46
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.3	-0.88	67.7	-0.29	67.2	-0.98	67.0	-1.28
XLPE	66.5	0.10	66.9	0.75	66.7	0.40	66.7	0.45
PP	75.2	-0.75	75.1	-0.97	75.3	-0.61	74.6	-1.54
KEL-F	80.8	-0.12	80.7	-0.33	80.8	-0.12	79.7	-1.48
TEFLON	57.2	-3.81	57.1	-3.98	57.2	-3.81	57.3	-3.70
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.0	-1.47	65.5	-3.71	67.3	-1.08	66.3	-2.60
XLPE	66.0	-0.50	65.0	-2.02	66.3	-0.10	65.5	-1.36
PP	75.4	-1.18	73.0	-4.37	73.7	-3.45	73.7	-3.45
KEL-F	80.4	0.04	80.0	-0.44	80.2	-0.12	78.8	-1.90
TEFLON	55.8	-5.95	55.3	-6.78	56.0	-5.67	53.8	-9.38
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE	HARDNESS	%CHANGE
HDPE	67.9	-0.44	67.9	-0.54	67.9	-0.54	66.1	-3.13
XLPE	66.9	-0.05	67.0	0.10	67.1	0.35	66.0	-1.39
PP	75.6	-1.30	75.4	-1.61	75.4	-1.61	73.2	-4.52
KEL-F	80.2	-0.71	80.0	-0.99	79.7	-1.28	78.9	-2.35
TEFLON	54.2	-8.44	53.4	-9.80	53.7	-9.29	51.2	-13.57

APPENDIX E
Stress-Cracking Data

FAILURES AND % FAILURE VALUES:								
18 C BASELINE	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
50 C BASELINE	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	9	90
XLPE	0	0	0	0	0	0	0	0
60 C BASELINE	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	10	100
XLPE	0	0	0	0	0	0	0	0
18 C RAD BASELINE, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C RAD BASELINE, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C RAD BASELINE, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C RAD BASELINE, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
50 C RAD BASELINE, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	4	40
50 C RAD BASELINE, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	0	0
50 C RAD BASELINE, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	3	30
XLPE	0	0	0	0	0	0	2	20
50 C RAD BASELINE, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	10	100
XLPE	0	0	0	0	0	0	0	0

Stress-Cracking Data (cont.)

60 C RAD BASELINE, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	4	40
60 C RAD BASELINE, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	4	40
60 C RAD BASELINE, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	4	40
60 C RAD BASELINE, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	4	40
XLPE	0	0	0	0	0	0	4	40
18 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	0	0
XLPE	0	0	0	0	0	0	0	0
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	9	90
XLPE	0	0	0	0	0	0	0	0
50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	10	100
XLPE	0	0	0	0	0	0	0	0
50 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	10	100
XLPE	0	0	0	0	0	0	0	0
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	0	0	6	60
XLPE	0	0	0	0	0	0	0	0

Stress-Cracking Data (cont.)

60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	2	20	10	100
XLPE	0	0	0	0	0	0	0	0
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	7	70	10	100
XLPE	0	0	0	0	0	0	0	0
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	0	0	0	0	10	100	10	100
XLPE	0	0	0	0	0	0	0	0
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Failure	% Failure	Failure	% Failure	Failure	% Failure	Failure	% Failure
HDPE	3	30	9	90	10	100	10	100
XLPE	0	0	0	0	0	0	0	0

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APPENDIX F
Tensile Strength Data

AVERAGE TENSILE STRENGTH AT YIELD (psi) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3730	3.04	3860	6.63	3740	3.31	3170	-12.4
XLPE	2820	6.82	2870	8.71	2700	2.27	2080	-21.2
PP	5030	2.24	5200	5.69	4950	0.61	4350	-11.6
KEL-F	5620	4.07	5900	9.26	5540	2.59	5180	-4.07
TEFLON	1370	-10.5	1560	1.96	1370	-10.50	752	-50.9
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3820	5.52	3690	1.93	3780	4.42	2140	-40.9
XLPE	2800	6.06	2730	3.41	2740	3.79	1430	-45.8
PP	4970	1.02	4870	-1.02	5030	2.24	3010	-38.8
KEL-F	5800	7.41	5490	1.67	5710	5.74	3830	-29.1
TEFLON	1420	-7.19	1290	-15.7	1460	-4.58	707	-53.8
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3750	3.59	3860	6.63	3850	6.35	3240	-10.5
XLPE	2790	5.68	2770	4.92	2830	7.20	2070	-21.6
PP	4970	1.02	5020	2.03	5100	3.66	4400	-10.6
KEL-F	5600	3.70	5760	6.67	6090	12.8	5460	1.11
TEFLON	1440	-5.88	1440	-5.88	1590	3.92	1040	-32.0
18 C,143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	4040	11.6	3900	7.73	3910	8.01	3020	-16.6
XLPE	2940	11.4	2900	9.85	2910	10.2	2110	-20.1
PP	5310	7.93	5180	5.28	5220	6.10	4350	-11.6
KEL-F	6150	13.9	6010	11.3	5950	10.2	5270	-2.41
TEFLON	1530	0.00	1470	-3.92	1490	-2.61	643	-58.0
18 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3790	4.70	3850	6.35	3950	9.12	3060	-15.5
XLPE	2810	6.44	2830	7.20	2920	10.6	1920	-27.3
PP	4860	-1.22	5150	4.67	5080	3.25	4320	-12.2
KEL-F	5480	1.48	5690	5.37	5820	7.78	5120	-5.19
TEFLON	1260	-17.7	1440	-5.88	1430	-6.54	579	-62.2
18 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	4070	12.4	3750	3.59	3890	7.46	1870	-48.3
XLPE	2970	12.5	2830	7.20	2880	9.09	1070	-59.5
PP	5310	7.93	5090	3.46	5180	5.28	3240	-34.2
KEL-F	6210	15.0	5950	10.2	5820	7.78	4440	-17.8
TEFLON	1360	-11.1	1340	-12.4	1350	-11.8	376	-75.4
18 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3670	1.38	3780	4.42	3700	2.21	3020	-16.6
XLPE	2840	7.58	2940	11.4	2860	8.33	2030	-23.1
PP	4790	-2.64	5060	2.85	4960	0.81	4280	-13.0
KEL-F	5170	-4.26	5460	1.11	5370	-0.56	5150	-4.63
TEFLON	1150	-24.8	1160	-24.2	1200	-21.6	453	-70.4
50 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3760	3.87	3850	6.35	3860	6.63	2200	-39.2
XLPE	2810	6.44	2900	9.85	2870	8.71	1570	-40.5
PP	5040	2.44	5150	4.67	5230	6.30	3070	-37.6
KEL-F	6010	11.3	5980	10.7	6490	20.2	4130	-23.5
TEFLON	1320	-13.7	1500	-1.96	1460	-4.58	725	-52.6
50 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3920	8.29	3950	9.12	3660	1.10	2120	-41.4
XLPE	2880	9.09	2830	7.20	2790	5.68	1520	-42.4
PP	5220	6.10	5070	3.05	5000	1.63	3010	-38.8
KEL-F	6280	16.3	6130	13.5	6000	11.1	3960	-26.7
TEFLON	1530	0.00	1470	-3.92	1350	-11.8	638	-58.3

Tensile Strength Data (cont.)

50 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3790	4.70	3980	9.94	4230	16.9	3130	-13.5
XLPE	2820	6.82	2990	13.3	3080	16.7	2350	-11.0
PP	5030	2.24	5230	6.30	5430	10.4	4460	-9.35
KEL-F	5750	6.48	6330	17.2	6610	22.4	5360	-0.74
TEFLON	1210	-20.9	1530	0.00	1690	10.5	592	-61.3
50 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3720	2.76	3800	4.97	3930	8.56	2810	-22.4
XLPE	2900	9.85	2930	11.0	3100	17.4	2140	-18.9
PP	4900	-0.41	5100	3.66	5240	6.50	4170	-15.2
KEL-F	5350	-0.93	5730	6.11	6090	12.8	5310	-1.67
TEFLON	917	-40.1	860	-43.8	405	-73.5	354	-76.9
60 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3680	1.66	3820	5.52	3810	5.25	2980	-17.7
XLPE	2730	3.41	2780	5.30	2910	10.2	530	-79.9
PP	4770	-3.05	5000	1.63	5000	1.63	4230	-14.0
KEL-F	5460	1.11	5890	9.07	6000	11.1	5460	1.11
TEFLON	1230	-19.6	1320	-13.7	1440	-5.88	624	-59.2
60 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3690	1.93	3740	3.31	4020	11.1	3120	-13.8
XLPE	2830	7.20	2820	6.82	2970	12.5	977	-63.0
PP	4990	1.42	4900	-0.41	5010	1.83	4500	-8.54
KEL-F	5910	9.44	5910	9.44	5960	10.4	5650	4.63
TEFLON	1280	-16.3	1460	-4.58	1240	-19.0	743	-51.4
60 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3730	3.04	3800	4.97	3790	4.70	3180	-12.2
XLPE	2830	7.20	2910	10.2	3020	14.4	675	-74.4
PP	4990	1.42	4980	1.22	5050	2.64	4370	-11.2
KEL-F	5820	7.78	5760	6.67	5950	10.2	5460	1.11
TEFLON	1290	-15.7	1350	-11.8	1430	-6.54	714	-53.3
60 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3870	6.91	3360	-7.18	3920	8.29	2690	-25.7
XLPE	2930	11.0	2820	6.82	2900	9.85	449	-83.0
PP	5000	1.63	4850	-1.42	5210	5.89	3950	-19.7
KEL-F	5640	4.44	5460	1.11	5970	10.6	5210	-3.52
TEFLON	752	-50.9	238	-84.4	1050	-31.4	356	-76.7
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3770	4.14	3750	3.59	3850	6.35	3130	-13.5
XLPE	2800	6.06	2780	5.30	2810	6.44	2130	-19.3
PP	5050	2.64	5010	1.83	5070	3.05	4350	-11.6
KEL-F	5560	2.96	5480	1.48	5640	4.44	5030	-6.85
TEFLON	1320	-13.7	1320	-13.7	1330	-13.1	666	-56.5
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	4050	11.9	3570	-1.38	3730	3.04	3110	-14.1
XLPE	2920	10.6	2660	0.76	2780	5.30	3030	14.8
PP	5270	7.11	4810	-2.24	4990	1.42	4360	-11.4
KEL-F	5940	10.0	5340	-1.11	5560	2.96	5120	-5.19
TEFLON	1590	3.92	1260	-17.7	1420	-7.19	721	-52.9
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	4000	10.5	3800	4.97	4040	11.6	2100	-42.0
XLPE	2920	10.6	2810	6.44	2930	11.0	1170	-55.7
PP	5240	6.50	5080	3.25	5230	6.30	3420	-30.5
KEL-F	6060	12.2	5740	6.30	5900	9.26	4450	-17.6
TEFLON	1350	-11.8	1340	-12.4	1390	-9.15	352	-77.0

Tensile Strength Data (cont.)

18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3710	2.49	3820	5.52	3910	8.01	2150	-40.6
XLPE	2790	5.68	2900	9.85	2980	12.9	1550	-41.3
PP	4930	0.20	5180	5.28	5100	3.66	3040	-38.2
KEL-F	5420	0.37	5820	7.78	5680	5.19	3690	-31.7
TEFLON	858	-43.9	900	-41.2	914	-40.3	202	-86.8
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3780	4.42	3900	7.73	3770	4.14	1350	-62.7
XLPE	2830	7.20	2880	9.09	2780	5.30	942	-64.3
PP	5080	3.25	5040	2.44	4950	0.61	2160	-56.1
KEL-F	5970	10.6	6080	12.6	5810	7.59	3240	-40.0
TEFLON	1310	-14.4	1340	-12.4	1310	-14.4	418	-72.7
50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	4020	11.1	3950	9.12	3770	4.14	2190	-39.5
XLPE	2880	9.09	2890	9.47	2760	4.55	1520	-42.4
PP	5170	5.08	5140	4.47	4910	-0.20	3080	-37.4
KEL-F	5970	10.6	6070	12.4	5820	7.78	3920	-27.4
TEFLON	1390	-9.15	1440	-5.88	1300	-15.0	659	-56.9
50 C, 571 K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3960	9.39	3720	2.76	3850	6.35	3150	-13.0
XLPE	2950	11.7	2790	5.68	2910	10.2	2210	-16.3
PP	5140	4.47	4920	0.00	5160	4.88	4440	-9.76
KEL-F	6220	15.2	5810	7.59	6180	14.4	5520	2.22
TEFLON	1360	-11.1	1240	-19.0	1400	-8.50	696	-54.5
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3730	3.04	3680	1.66	3920	8.29	3210	-11.3
XLPE	2830	7.20	2870	8.71	3040	15.2	2410	-8.71
PP	4860	-1.22	4980	1.22	5150	4.67	4450	-9.55
KEL-F	5470	1.30	5580	3.33	5900	9.26	5360	-0.74
TEFLON	1090	-28.8	1190	-22.2	11.6	-24.2	444	-71.0
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3910	8.01	3830	5.80	4040	11.6	3200	-11.6
XLPE	2880	9.09	2900	9.85	2940	11.4	2330	-11.7
PP	5100	3.66	5030	2.24	5240	6.50	4410	-10.4
KEL-F	5900	9.26	5850	8.33	6190	14.6	5400	0
TEFLON	1350	-11.8	1390	-9.15	1510	-1.31	731	-52.2
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3810	5.25	3800	4.97	3950	9.12	3000	-17.1
XLPE	2810	6.44	2820	6.82	3030	14.8	2080	-21.2
PP	4990	1.42	5000	1.63	5360	8.94	4370	-11.2
KEL-F	6020	11.5	5970	10.6	6590	22.0	5650	4.63
TEFLON	1340	-12.4	1320	-13.7	1560	1.96	669	-56.3
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3840	6.08	3690	1.93	3870	6.91	3240	-10.5
XLPE	2840	7.58	2750	4.17	2870	8.71	2320	-12.1
PP	5060	2.85	4930	0.20	5030	2.24	4420	-10.2
KEL-F	6030	11.7	5640	4.44	5830	7.96	5500	1.85
TEFLON	1510	-1.31	1280	-16.3	1430	-6.54	688	-55.0
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE	TENSILE STRENGTH	% CHANGE
HDPE	3760	3.87	3750	3.59	3830	5.80	3120	-13.8
XLPE	2940	11.4	2970	12.5	2930	11.0	2220	-15.9
PP	4990	1.42	5080	3.25	5080	3.25	4420	-10.2
KEL-F	5650	4.63	5770	6.85	5830	7.96	5480	1.48
TEFLON	815	-46.7	1050	-31.4	1200	-21.6	334	-78.2

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APPENDIX G
Yield Elongation Data

AVERAGE % YIELD ELONGATION AND CHANGE:

18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	9.50	1.86	7.38	-0.26	6.22	-1.42	7.66	0.02
XLPE	26.8	5.00	22.6	0.8	21.9	0.1	25.7	3.90
PP	8.27	.92	5.98	-1.37	5.82	-1.53	7.25	-0.10
KEL-F	5.39	1.87	6.04	2.52	4.92	1.4	6.06	2.54
TEFLON	22.2	-1.60	21.6	-2.2	21.9	-1.9	39.3	15.50
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	10.7	3.06	8.59	0.95	7.22	-0.42	8.51	0.87
XLPE	23.8	2.00	31.6	9.8	22.2	0.4	25.1	3.30
PP	6.94	-0.41	7.39	0.04	7.52	0.17	7.1	-0.25
KEL-F	3.76	0.24	4.01	0.49	4.06	0.54	5.51	1.99
TEFLON	20.8	-3.00	23.7	-0.1	20.2	-3.6	24.9	1.10
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.33	0.69	8.16	0.52	7.48	-0.16	7.95	0.31
XLPE	38.7	16.9	18.8	-3	29.9	8.1	8.27	-13.53
PP	7.56	0.21	7.46	0.11	8.16	0.81	8.26	0.91
KEL-F	5.41	1.89	5.06	1.54	5.16	1.64	6.12	2.60
TEFLON	21.5	-2.30	22.4	-1.4	37.2	13.4	28.7	4.90
18 C,143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.5	-0.14	7.22	-0.42	7.3	-0.34	7.45	-0.19
XLPE	20.9	-0.9	19.1	-2.7	24.8	3	27.6	5.80
PP	6.88	-0.47	6.6	-0.75	7.02	-0.33	7.1	-0.25
KEL-F	5.1	1.58	4.12	0.6	5.6	2.08	4.07	0.55
TEFLON	17.6	-6.2	17	-6.8	17.3	-6.5	32.2	8.40
18 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.42	-0.22	7.34	-0.3	7.31	-0.33	7.58	-0.06
XLPE	22.2	0.4	22.5	0.7	25.3	3.5	16.9	-4.90
PP	7.1	-0.25	5.9	-1.45	6.94	-0.41	7.5	0.15
KEL-F	11.3	7.78	4	0.48	5.67	2.15	6.06	2.54
TEFLON	16.1	-7.7	16	-7.8	17.7	-6.1	15.1	-8.70
18 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	6.98	-0.66	6.14	-1.5	7.42	-0.22	7.4	-0.24
XLPE	21.9	0.1	20.4	-1.4	23.4	1.6	26.1	4.30
PP	6.38	-0.97	6	-1.35	6.56	-0.79	7.4	0.05
KEL-F	4.7	1.18	3.52	0	4.52	1	3.61	0.09
TEFLON	1.11	-22.69	10.5	-13.3	12.2	-11.6	8.67	-15.13
18 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.45	-0.19	6.76	-0.88	7.89	0.25	7.58	-0.06
XLPE	14.6	-7.2	11.6	-10.2	17.5	-4.3	9.59	-12.21
PP	6.55	-0.8	7.4	0.05	6.64	-0.71	6.08	-1.27
KEL-F	3.52	0	4.92	1.4	4.01	0.49	5.14	1.62
TEFLON	2.3	-21.5	4.22	-19.6	2.3	-21.5	2.08	-21.70
50 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.14	0.5	7.72	0.08	7.32	-0.32	7.62	-0.02
XLPE	24.3	2.5	24	2.2	22.1	0.3	13.5	-8.30
PP	7.7	0.35	7.04	-0.31	6.34	-1.01	7.53	0.18
KEL-F	3.5	-0.02	4.38	0.86	4.7	1.18	4.61	1.09
TEFLON	17.4	-6.4	6.14	-17.7	3.32	-20.5	3.27	-20.53
50 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.16	0.52	8.36	0.74	7.34	-0.3	8.82	1.18
XLPE	24.5	2.7	21.8	0	17.1	-4.7	8.04	-13.76
PP	7.4	0.05	7.76	0.41	7.1	-0.25	7.74	0.39
KEL-F	5.04	1.52	4.08	0.056	3.5	-0.02	4.16	0.64
TEFLON	13.7	-10.1	14.5	-9.3	11.9	-11.9	5.28	-18.52

Yield Elongation Data (cont.)

50 C, 571 K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.86	0.22	6.72	-0.92	6.1	-1.54	8.85	1.21
XLPE	24	2.2	19.7	-2.1	21.3	-0.5	6.13	-15.67
PP	7.42	0.07	6.1	-1.25	6.14	-1.21	6.88	-0.47
KEL-F	3.56	0.04	3.8	0.28	3.8	0.28	3.64	0.12
TEFLON	10.1	-13.7	4.24	-19.6	1.2	-22.6	3.74	-20.06
50 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.5	0.86	7.82	0.18	7.36	-0.28	7.6	-0.04
XLPE	10.9	-10.9	11.3	-10.5	10.2	-11.6	4.62	-17.18
PP	7.37	0.02	7.64	0.29	7.37	0.02	6.68	-0.67
KEL-F	3.52	0	4.21	0.69	4.3	0.78	5.16	1.64
TEFLON	2.74	-21.1	2.31	-21.5	2.35	-21.5	2.3	-21.50
60 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.86	1.22	8.78	1.14	8.86	1.04	7.64	0.00
XLPE	24.9	3.1	23.5	1.7	14..2	-7.6	2.3	-19.50
PP	8.47	1.12	9.06	1.71	7.26	-0.09	7.92	0.57
KEL-F	3.47	-0.05	5	1.48	4.66	1.14	5.66	2.14
TEFLON	17.7	-6.1	11.8	-12	11	-12.8	13.8	-10.00
60 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	9.06	1.42	8.38	0.74	7.38	-0.26	8.36	0.72
XLPE	25.7	3.9	18.3	-3.5	12.7	-9.1	2.3	-19.50
PP	8.08	0.73	7.68	0.33	7.67	0.32	7.32	-0.03
KEL-F	3.5	-0.02	3.92	0.4	3.58	0.4	3.57	0.05
TEFLON	14.9	-8.9	14	-9.8	13.3	-10.5	10.9	-12.90
60 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.42	-0.22	7.84	0.2	7.44	-0.2	8.57	0.93
XLPE	28.6	6.8	14	-7.8	4.5	-17.3	2.33	-19.47
PP	7.44	0.09	7.46	0.11	7.4	0.05	8.89	1.54
KEL-F	4.04	0.52	5.02	1.5	4.1	0.58	5.63	2.11
TEFLON	3.3	-20.5	4	-19.8	3.32	-20.5	1.56	-22.24
60 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.54	-0.1	8.64	1	7.36	-0.28	8	0.36
XLPE	9.53	-12.3	8.74	-13.1	5.35	-16.5	2.3	-19.50
PP	7.48	0.13	6.19	-1.16	9.64	2.29	6.7	-0.65
KEL-F	4.22	0.7	3.44	-0.08	6.21	2.69	5.18	1.66
TEFLON	2.23	-21.6	2.28	-21.5	2.29	-21.5	2.3	-21.50
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	6.85	-0.79	6.82	-0.82	7.5	-0.14	7.45	-0.19
XLPE	35.2	13.4	27.8	6	25.7	3.9	23.4	1.60
PP	7.06	-0.29	6.3	-1.05	7.42	0.07	7.42	0.07
KEL-F	5.43	1.91	5.54	2.02	6.02	2.5	5.98	2.46
TEFLON	16.9	-6.9	17	-6.8	17.8	-6	18.2	-5.60
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.27	-0.37	8.77	1.13	6.3	-1.34	7.24	-0.40
XLPE	35.9	14.1	32.3	10.5	18.9	-2.9	21.2	-0.60
PP	7.21	-0.14	7.35	0	6.28	-1.07	7.17	-0.18
KEL-F	5.2	1.68	4.93	1.41	4.16	0.64	6.03	2.51
TEFLON	8.64	-15.2	10.3	-13.5	8.82	-15	8.51	-15.29
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.18	0.54	6.73	-0.91	7.32	-0.32	7.37	-0.27
XLPE	22.1	0.3	20.7	-1.1	20.7	-1.1	21.4	-0.40
PP	6.86	-0.49	6.22	-1.13	7.48	0.13	7.37	0.02
KEL-F	4.06	0.54	4.54	1.02	5.58	2.06	4.53	1.01
TEFLON	4.06	-19.7	11.5	-12.3	11.3	-12.5	10.7	-13.10

Yield Elongation Data (cont.)

18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	9.62	1.98	7.67	0.03	6.84	-0.8	7.37	-0.27
XLPE	14.1	-7.7	13.8	-8	12	-9.8	13.5	-8.30
PP	6.6	-0.75	6.14	-1.21	6.02	-1.33	6.09	-1.26
KEL-F	4.65	1.13	4.19	0.67	4.2	0.68	5.13	1.61
TEFLON	2.63	-21.2	2.3	-21.5	2.32	-21.5	2.31	-21.49

50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	9.02	1.38	9.48	1.84	7.76	0.12	8.07	0.43
XLPE	28.2	6.4	33.7	11.9	25.1	3.3	25.4	3.60
PP	7.4	0.05	8.14	0.79	7.72	0.37	8.45	1.10
KEL-F	3.5	-0.02	4.03	0.51	3.96	0.44	4.06	0.54
TEFLON	17.4	-6.4	16.5	-7.3	15.5	-8.3	16.1	-7.70

50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.27	0.63	7.6	-0.04	8.2	0.56	8.31	0.67
XLPE	26.2	4.4	22.6	0.8	21.6	-0.2	19.2	-2.60
PP	7.44	0.09	8.16	0.81	7.36	0.03	7.8	0.45
KEL-F	3.72	0.2	4.62	1.1	3.98	0.46	5.13	1.61
TEFLON	13	-10.8	14.6	-9.2	13.9	-9.9	7.58	-16.22

50 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.26	-0.38	7.48	-0.16	7.2	-0.44	7.82	0.18
XLPE	28.9	7.1	18.9	-2.9	24	2.2	24.7	2.90
PP	7.48	0.13	7.42	0.07	7.48	0.13	7.45	0.10
KEL-F	4.06	0.54	3.52	0	3.66	0.14	3.69	0.17
TEFLON	1.92	-21.9	9.94	-13.9	3.3	-20.5	2.9	-20.90

50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.26	-0.38	7.45	-0.19	7.5	-0.14	8.12	0.48
XLPE	15.6	-6.2	11.7	-10.1	11.4	-10.4	9.24	-12.56
PP	7.29	-0.06	6.91	-0.44	6.04	-1.31	6.64	-0.71
KEL-F	5.61	2.09	3.61	0.09	4.24	0.72	3.65	0.13
TEFLON	3.44	-20.36	4.22	-19.6	3.44	-20.4	3.06	-20.74

60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.82	1.18	7.78	0.14	7.5	-0.14	8.78	1.14
XLPE	24.9	3.1	36.2	14.4	27.4	5.6	6.24	-15.56
PP	8.33	0.98	7.44	0.09	7.22	-0.13	9.22	1.87
KEL-F	5.12	1.6	5.54	2.02	3.72	0.2	5.16	1.64
TEFLON	16.5	-7.3	16.4	-7.4	16.2	-7.6	14.2	-9.60

60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	8.48	0.84	8.95	1.31	9.1	1.46	8.89	1.25
XLPE	22.4	0.6	24.5	2.7	30.1	8.3	3.52	-18.28
PP	7.62	0.27	8.28	0.93	24.1	16.8	8.49	1.14
KEL-F	4	0.48	4	0.48	4.04	0.52	3.77	0.25
TEFLON	15.4	-8.4	15.4	-8.4	2.89	-20.9	4.55	-19.25

60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	7.96	0.32	7.4	-0.24	7.62	-0.02	10.1	2.46
XLPE	25.5	3.7	22.4	0.6	20.2	-1.6	3.38	-18.42
PP	13.1	5.75	7.38	0.03	7.52	0.17	7.89	0.54
KEL-F	4.25	0.73	4.08	0.56	6.02	2.5	6.13	2.61
TEFLON	5.18	-18.6	3.5	-20.3	3.58	-20.2	3.37	-20.40

60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change	% Yield Elong.	Change
HDPE	10.6	2.96	9	1.36	7.4	-0.24	9	1.36
XLPE	10.1	-11.7	9.1	-12.7	8..28	-13.52	9.1	-12.70
PP	9.61	2.26	7.32	-0.03	6.6	-0.75	7.32	-0.03
KEL-F	4.86	1.34	3.42	-0.1	3.98	0.46	3.42	-0.10
TEFLON	2.31	-21.5	4.2	-19.6	3.82	-20	4.2	-19.60

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APPENDIX H
Break Elongation Data

AVERAGE % BREAK ELONGATION AND CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1240	411	829	0	1300	471	867	38
XLPE	231	67	357	19	384	220	305	141
PP	169	19	109.00	-41	269	119	197	47
KEL-F	142	25	165	48	154	37	142	25
TEFLON	330	-53	458	75	559	176	39.3	-344
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	982	153	1200	371	503	-326	867	-333
XLPE	210	46	175	11	283	119	305	-12
PP	108	-42	426	276	140	-10	197	-46
KEL-F	145	28	140	23	182	65	142	0
TEFLON	541	158	568	185	417	34	39.3	-46
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	813	-16	813	-16	461	-368	867	-509
XLPE	159	-5	140	-24	128	-36	305	-150
PP	286	136	428	278	41.9	-108	197	-72
KEL-F	112	-5	142	25	106	-11	142	7
TEFLON	382	-1	556	173	248	-135	39.3	26
18 C,143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	549	-280	790	-39	813	-16	1170	341
XLPE	205	41	257	93	193	29	404	240
PP	342	192	436	286	581	431	968	818
KEL-F	103	-14	121	4	175	58	76.4	-41
TEFLON	62.1	-321	42.9	-340	66.9	-316	32.2	-351
18 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1180	351	740	-89	1230	401	574	-255
XLPE	183	19	179	15	146	-18	266	102
PP	110	-40	55.5	-95	223	73	34	-116
KEL-F	173	56	121	4	131	14	153	36
TEFLON	28.9	-354	38.4	-345	38.7	-344	24.9	-358
18 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	703	-126	1330	499	838	9	837	8
XLPE	211	47	318	154	215	51	232	68
PP	229	79	380	230	529	379	439	289
KEL-F	107	-10	129	12	129	12	82.2	-35
TEFLON	9.83	-373	12.6	-370	16.3	-367	376	-7
18 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1520	691	1260	431	1350	521	636	-193
XLPE	167	3	127	-37	203	39	190	26
PP	19	-131	20.6	-129	34	-116	15.2	-135
KEL-F	206	89	101	-16	209	92	124	7
TEFLON	4.2	-379	4.22	-379	6.04	-377	2.68	-380
50 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1160	331	862	33	870	41	573	-256
XLPE	198	34	346	182	261	97	41.9	-122
PP	417	267	488	338	157	7	164	14
KEL-F	84.9	-32	99	-18	92.6	-24	90.2	-27
TEFLON	33.1	-350	42.6	-340	58.6	-324	43.7	-339
50 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	530	-299	950	121	1060	231	807	-22
XLPE	215	51	202	38	244	80	17.7	-146
PP	308	158	367	217	539	389	368	218
KEL-F	111	-6	87.7	-29	123	6	143	26
TEFLON	19	-364	23.6	-359	15.4	-368	17.7	-365

Break Elongation Data (cont.)

50 C, 571 K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1100	271	469	-360	586	-243	1090	261
XLPE	212	48	221	57	165	1	9.48	-155
PP	468	318	146	-4	50.2	-100	276	126
KEL-F	98.8	-18	77	-40	100	-17	102	-15
TEFLON	11.5	-372	8.4	-375	4.1	-379	8.98	-374
50 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1180	351	900	71	908	79	915	86
XLPE	95.9	-68	84.9	-79	85	-79	9.1	-155
PP	33.8	-116	21.2	-129	22.7	-127	20.9	-129
KEL-F	142	25	118	1	98	-19	109	-8
TEFLON	2.74	-380	2.31	-381	2.35	-381	2.3	-381
60 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1090	261	885	56	1100	271	261	-568
XLPE	272	108	136	-28	35.2	-129	2.3	-161
PP	141	-9	116	-34	24.5	-126	34.4	-116
KEL-F	164	47	97.9	-19	99.5	-18	87.4	-30
TEFLON	33.6	-349	22.7	-360	23.4	-360	34.6	-348
60 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1090	261	688	-141	528	-301	636	-193
XLPE	235	71	162	-2	56.6	-107	4.17	-160
PP	521	371	406	256	332	182	214	64
KEL-F	101	-16	98.6	-18	139	22	64.3	-53
TEFLON	20.2	-363	16.7	-366	17.3	-366	13.5	-370
60 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1250	421	1054	225	656	-173	596	-233
XLPE	196	32	182	18	8.42	-156	2.33	-162
PP	63.1	-87	67.4	-83	49	-101	37.4	-113
KEL-F	126	9	143	26	104	-13	84.6	-32
TEFLON	4.46	-379	8.3	-375	5.98	-377	6.1	-377
60 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	770	-59	1090	261	502	-327	369	-460
XLPE	70.9	-93	34.4	-130	12.3	-152	2.3	-162
PP	15.8	-134	24.7	-125	25.9	-124	24.7	-125
KEL-F	83.4	-34	113	-4	180	63	107	-10
TEFLON	3.02	-380	2.29	-381	2.29	-381	2.3	-381
18 C,143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1190	361	1040	211	821	-8	1160	331
XLPE	216	52	356	192	205	41	379	215
PP	252	102	201	51	269	119	181	31
KEL-F	161	44	180	63	93.7	-23	135	18
TEFLON	50.6	-332	64.8	-318	45.7	-337	31.7	-351
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	424	-405	1450	621	1320	491	744	-85
XLPE	166	2	201	337	300	136	244	80
PP	154	4	113	-37	171	21	640	490
KEL-F	108	-9	150	33	155	38	110	-7
TEFLON	34.2	-349	24.5	-359	25.2	-358	16.6	-366
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	751	-78	1110	281	552	-277	1460	631
XLPE	201	37	295	131	227	63	131	-33
PP	405	255	466	316	247	97	24.6	-125
KEL-F	104	-13	173	56	143	26	130	13
TEFLON	11.5	-372	13	-370	17.5	-366	2.63	-380

Break Elongation Data

18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1460	631	1210	381	884	55	918	89
XLPE	131	-33	158	-6	138	-26	139	-25
PP	24.6	-125	28.9	-121	24.7	-125	21.8	-128
KEL-F	130	13	122	5	145	28	145	28
TEFLON	2.63	-380	2.3	-381	2.32	-381	2.31	-381
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1220	391	946	117	1010	181	807	-22
XLPE	192	28	221	57	264	100	170	6
PP	689	539	399	249	630	480	301	151
KEL-F	63.9	-53	94.1	-23	148	31	112	-5
TEFLON	55.1	-328	43	-340	34.2	-349	44.5	-339
50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	592	-237	1240	411	911	82	1110	281
XLPE	203	39	212	48	196	32	111	-53
PP	417	267	381	231	534	384	234	84
KEL-F	75.5	-42	108	-9	102	-15	150	33
TEFLON	18.5	-365	25	-358	18.9	-364	13.7	-369
50 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1050	221	1270	441	858	29	781	-48
XLPE	200	36	294	130	200	36	325	161
PP	333	183	831	681	345	195	112	-38
KEL-F	105	-12	156	39	88.4	-29	60.3	-57
TEFLON	7.84	-375	11.9	-371	46.2	-337	7.44	-376
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	639	-190	1350	521	640	-189	714	-115
XLPE	146	-18	91.4	-73	95.7	-68	22.3	-142
PP	33.6	-116	33.6	-116	25	-125	20.5	-130
KEL-F	90.1	-27	151	34	95.4	-22	120	3
TEFLON	3.44	-380	4.22	-379	3.44	-380	3.06	-380
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	517	-312	696	-133	634	-195	689	-140
XLPE	175	11	134	-30	195	31	8.76	-155
PP	79.5	-71	64.7	-85	75.2	-75	58.9	-91
KEL-F	97.5	-20	111	-6	87.8	-29	180	63
TEFLON	39.3	-344	43.3	-340	46.3	-337	24.2	-359
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	716	-113	598	-231	827	-2	401	-428
XLPE	163	-1	219	55	192	28	5.17	-159
PP	505	355	385	235	199	49	174	24
KEL-F	95.8	-21	82.4	-35	110	-7	53.3	-64
TEFLON	21.5	-362	21	-362	17.7	-365	14.3	-369
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	925	96	1020	191	985	156	832	3
XLPE	220	56	231	67	172	8	7.24	-157
PP	51	-99	82.7	-67	155	5	42.5	-108
KEL-F	172	55	119	2	144	27	117	0
TEFLON	8.37	-375	4..52	-378	5.1	-378	8.23	-375
60 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change	% Break Elong.	Change
HDPE	1150	321	900	71	917	88	315	-514
XLPE	65.7	-98	87	-77	71.7	-92	9.75	-154
PP	49.7	-100	41.6	-108	17.8	-132	26.4	-124
KEL-F	102	-15	155	38	110	-7	59.6	-57
TEFLON	2.31	-381	4.2	-379	3.82	-379	332	-51

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APPENDIX I
Modulus of Elasticity Data

AVERAGE MODULUS OF ELASTICITY (psi) AND % CHANGE:								
18 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	39300	-7	52100	23	52100*	23	41300	-3
XLPE	11300*	-7	13000	7	13000	7	11100*	-9
PP	61700	-8	86900.00	29	85100	26	57800	-14
KEL-F	151000*	5	97600	-32	160000*	11	85500	-41
TEFLON	6180	-4	7050	9	6120	-5	3410	-43
50 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	38600	-9	44400	5	50400	19	28500*	-33
XLPE	12500	2	10600*	-13	12800	5	6610*	-46
PP	69300	3	65800	-2	66700	-1	42200*	-37
KEL-F	142000	-1	143000	-1	146000	1	101000*	-30
TEFLON	6890	7	5170	-20	7240	12	2950*	-54
60 C BASELINE-CHEM	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45400	7	47700	13	51400	21	42200*	0
XLPE	11500*	-6	11800*	-3	10200*	-16	22600*	85
PP	61200	-9	67200	0	63100	-6	58000*	-14
KEL-F	160000*	11	167000*	16	160000*	11	89300	-38
TEFLON	6740	4	6300	-2	2920	-55	3610	-44
18 C,143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	53900	27	54400	28	53900	27	40500	-4
XLPE	11600*	-5	11200*	-8	11300*	-7	11100*	-9
PP	77900	16	79400	18	75200	12	64400*	-4
KEL-F	128000	-11	153000	6	157000*	9	150000*	4
TEFLON	8510	32	8730	35	8720	35	3590	-44
18 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	50900	20	52400	24	54600	29	40400	-5
XLPE	13500	11	13500	11	11900	-2	11500	-6
PP	69000	2	84500*	25	73800	9	57600	-15
KEL-F	135000	-6	148000	3	107000	-26	84400	-41
TEFLON	7880	22	8180*	27	8180	27	4200*	-35
18 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	59100	39	53300	26	52500	24	25300	-40
XLPE	14100	16	14200	16	12700	4	4980*	-59
PP	83700	24	84900	26	79800	18	43800	-35
KEL-F	140000	-3	169000	17	125000	-13	130000*	-10
TEFLON	12000*	86	12800	98	11100	72	11400*	76
18 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	49200	16	56800	34	47200	11	39900	-6
XLPE	19500	60	22100*	81	18600	52	16900	39
PP	73200	9	68400	1	75500	12	70500	5
KEL-F	147000	2	158000*	10	140000	-3	135000*	-6
TEFLON	27300	323	27600	327	19900	208	24400	278
50 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	47700	13	50100	18	51600	22	28900*	-32
XLPE	11900	-2	12200	0	13300	9	12200	0
PP	65700	-3	70000	4	73400	9	40800	-39
KEL-F	171000	19	145000	1	145000	1	117000*	-20
TEFLON	7600	18	8340	29	2510*	-61	3830	-41
50 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45100	6	46200	9	41500*	-2	28500*	-33
XLPE	12200	0	13600	11	14600*	20	13100*	7
PP	70500	5	65900	-2	67800	1	41000*	-39
KEL-F	133000	-8	158000	10	171000	19	116000*	-19
TEFLON	11300	75	11400*	76	11400	76	4820*	-25

Modulus of Elasticity Data (cont.)

50 C, 571 K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	48500	14	57900	37	69300	63	35700	-16
XLPE	13200	8	16600	36	15100	24	31600*	159
PP	67800	1	78700	17	88400	31	63000	-7
KEL-F	160000	11	166000	15	174000	21	148000	3
TEFLON	12100	87	18300*	183	27700*	329	23500	264
50 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	42800	1	44900	6	53700	27	37000	-13
XLPE	24900*	104	25200*	107	29900*	145	29200*	1339
PP	63800	-5	68300	1	74100	10	60400	-10
KEL-F	152000	6	151000	5	147000	2	108000	-25
TEFLON	29200*	352	35300*	446	41600*	544	12900	100
60 C, 143K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	41900	-1	43800	3	45200	7	39000	-8
XLPE	11500	-6	12500	2	20500	68	20900*	71
PP	57000	-15	55200	-18	64400	-4	55900*	-17
KEL-F	158000	10	127000	-12	136000	-6	144000*	0
TEFLON	7960*	23	9670*	50	11900*	84	4260	-34
60 C, 286K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	339300	-7	45100	6	54400	28	37700	-11
XLPE	11300	-7	17000	39	22300	83	23400*	92
PP	61900	-8	64300	-5	65600	-3	61400	-9
KEL-F	169000	17	157000	9	168000	17	159000	10
TEFLON	8650	34	10500	63	9480	47	8140*	26
60 C, 571K-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	50200	18	48700	15	50900	20	37500	-12
XLPE	9950	-18	20700	70	19900*	63	26000*	113
PP	67100	0	66800	-1	68200	1	49600	-26
KEL-F	122000	-15	123000	-15	151000	5	101000	-30
TEFLON	21300*	230	14700*	128	19200*	197	11700*	81
60 C, 3.6M-RAD	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45800	8	41400	-2	40600*	-4	33600	-21
XLPE	30300	148	32500	166	44000*	261	2300*	89
PP	67200	0	79000	17	53800	-20	59500	-12
KEL-F	139000	-3	159000	10	102000	-29	106000	-26
TEFLON	26700*	313	30200*	367	45900	611	15400	138
18 C.143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	55600	31	50900	20	51300	21	42000	-1
XLPE	8150	-33	10200	-16	11100	-9	9300	-24
PP	72000	7	76600	14	68200	1	58600	-13
KEL-F	107000	-26	104000	-28	93800	-35	84300	-41
TEFLON	7810	21	7610	18	7310	13	3660	-43
18 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	53700*	27	48800*	15	59500	40	43100	2
XLPE	8800	-28	86100	-29	15400	26	10500	-14
PP	70100	4	65500	-3	64700	-4	61200	-9
KEL-F	109000	-24	115000	-20	139000	-3	84900	-41
TEFLON	16900*	162	14000*	117	15200*	135	9760*	51
18 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	50500	19	57300	35	55500	31	28800	-32
XLPE	14300	17	14000	15	15100	24	59980	-51
PP	77500	15	83200	22	69900	4	45900	-32
KEL-F	157000	9	134000	-7	110000	-24	105000	-27
TEFLON	13800*	114	11800	83	10200	58	10800*	67

Modulus of Elasticity Data (cont.)

18 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	38600	-9	51900	22	57600	36	30300	-29
XLPE	20300	66	21200	74	24900*	104	11700	-4
PP	72200	7	84500	25	78300	16	49900	-26
KEL-F	125000	-13	144000	0	140000	-3	75400	-48
TEFLON	26300*	307	38800	501	39400	510	17100*	165
50 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	42000	-1	42700	1	47000	11	16000*	-62
XLPE	10100	-17	11000*	-10	11400	-7	6000*	-51
PP	66200	-2	62700	-7	64400	-4	30500*	-55
KEL-F	171000	19	157000	9	153000	6	91900*	-36
TEFLON	7570	17	8140	26	8380	30	2700*	-58
50 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	49000	16	52000	23	45000	6	25600	-40
XLPE	11600	-5	12900	6	14100	16	9330	-24
PP	69500	3	63700	-5	67600	0	39800	-41
KEL-F	160000	11	141000	-2	152000	6	79900	-45
TEFLON	10700	66	9870*	53	9360	45	5470	-15
50 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	50800	20	49800	17	49500	17	38800	-8
XLPE	11300	-7	14800	21	13300	9	9490	-22
PP	69800	4	66200	-2	68900	2	59600	-12
KEL-F	161000	12	165000	15	169000	17	150000	4
TEFLON	14700*	128	12500	93	42700	561	30400	371
50 C, 3.6M	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	51600	22	47500	12	52300	23	40100	-5
XLPE	18700	53	23700*	94	25000*	105	24800*	103
PP	68600	2	72700	8	85600	27	67600	0
KEL-F	102000	-29	155000	8	145000	1	134000	-7
TEFLON	29700*	360	28100	335	31400*	386	15100*	134
60 C, 143K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45500	7	49400	17	53900	27	36700	-13
XLPE	12900	6	8660	-29	11300	-7	25600*	110
PP	61700	-8	67700	0	73100	8	47900	-29
KEL-F	123000	-15	80500	-44	166000	15	111000	-23
TEFLON	7850	22	8310	29	9040	40	6000	-7
60 C, 286K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45400	7	43900	4	45600	8	32600	-23
XLPE	13400	10	12300	1	10600	-13	15900*	30
PP	65800	-2	61000	-9	59000	-12	52000	-23
KEL-F	158000	10	142000	-1	17100	-88	150000	4
TEFLON	8710	35	8590	33	10600	64	5380	-17
60 C, 571K	7 DAYS		14 DAYS		28 DAYS		180 DAYS	
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	45700	8	49800	17	50700	20	34800*	-18
XLPE	12100	-1	12800	5	14700	20	13300*	9
PP	41100*	-39	66600	-1	66900	-1	54500	-19
KEL-F	146000	1	130000	-10	96900	-33	89700	-38
TEFLON	24400*	278	21400*	231	23400*	262	20500	217
7 DAYS		14 DAYS		28 DAYS		180 DAYS		
MATERIAL	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE	Modulus	%CHANGE
HDPE	32200	-24	41400	-2	51600	22	41000	-3
XLPE	24900*	104	32600	167	31600*	159	23600*	93
PP	51200	-24	69400	3	68200	1	58900	-13
KEL-F	129000	-10	169000	17	155000	8	134000	-7
TEFLON	35100	443	30800	377	31000*	380	15300*	137
* Adjusted Data								

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