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Long Term Aging and Surveillance of 9975 Package Components

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The mission of the 9975 package, originally designed only for transportation of radioactive materials, has been broadened to include storage at the Savannah River Site. Two components of this package, namely the containment vessel O-rings and fiberboard overpack, require continued integrity assessment under the storage conditions. The performance of the components over time is being evaluated using accelerated-aging studies. Compression stress relaxation (CSR) and leak testing are being used to measure the performance of O-rings. The performance of the fiberboard is being evaluated using compression strength, thermal conductivity, specific heat capacity and other physical properties. Models developed from the data collected provide an initial prediction of service life for the two components, and support the conclusion that normal service conditions will not degrade the performance of the package beyond specified functional requirements for the first assessment interval. Increased confidence in this conclusion is derived from field surveillance data and destructive evaluation of packages removed from storage.

Introduction

The Savannah River Site (SRS) is storing plutonium (Pu) materials in the K-Area Materials Storage (KAMS) facility. The Pu materials are packaged according to the standard DOE-STD-3013 which requires nested, welded, stainless steel containers. Within KAMS, the welded 3013 containers are stored in Department of Transportation (DOT) Type B 9975 packages. The 9975 package consists of two nested stainless steel containment vessels (CV) closed with threaded Cone-Seal Plugs, surrounded by a Lead Shielding Body and fiberboard overpack, all contained within a 35 gallon stainless steel drum, Figure 1. The 9975 package is part of the approved storage configuration for Pu materials in KAMS. As such, it will be continuously exposed to the service environment for a period of time greater than the approved transportation service period. The studies documented in this report were undertaken to verify the integrity of the containment vessels' O-ring seals and the fiberboard overpack over time in the environment they will be exposed to in KAMS for an initial storage assessment period of 10 years. It is anticipated that the packages will be used up to 50 years and that replacement of aged components may be necessary. The work described in this paper presents data to an intial assessment period of 10 years.

Each containment vessel is sealed with O-rings (compounds V0835-75 or VM835-75, Parker Hannifin Corporation, Lexington, KY) based on Viton® GLT/GLT-S fluoroelastomer (Dupont Performance Elastomers, Wilmington, DE). Viton® fluoroelastomer O-rings are placed on the Cone-Seal Plugs in each package: two O-rings, inner and outer, sealing the primary containment vessel (PCV) and two O-rings, inner and outer, sealing the secondary containment vessel (SCV). In transportation service, the O-rings are replaced on an annual basis and leak tested to a 1 x 10^{-7} ref cc air/sec (leaktight) criterion per ANSI N14.5. However, while in storage the O-rings are not replaced and cannot be leak tested. The outer O-ring in each vessel is credited for containment. The inner O-ring provides a volume for leak testing and a secondary barrier to product release. To function as a seal, the O-rings must maintain mechanical elasticity and exert a compressive force against the sealing surfaces.

The overpack used in the 9975 package is Celotex® cane or softwood fiberboard (Knight Industries, Northfield, IL) and is located between the outer Type 304L stainless steel drum and the lead shield. The fiberboard performs three main functions: i) thermal insulation to limit internal temperature during a fire; ii) criticality control (by neutron moderation and spacing); and iii) resistance to mechanical crushing of the package. Properties of importance to demonstrate acceptable performance of the material over time include dimensional stability, density, compressive strength, thermal conductivity and specific heat capacity. Baseline and initial aging data on these properties have been previously reported. [1-4]

Experimental

Laboratory Testing

Viton® GLT O-rings

<u>Compression Stress-Relaxation</u>

Compression stress-relaxation (CSR) is an industry standard measure of seal performance [5, 6]. When an elastomer is compressed, the internal cross-linked polymer structure imposes a spring-like counterforce on mating surfaces to provide a seal. Over time, the sealing force is reduced due to physical and chemical relaxation processes. If the elastomer is exposed to aging conditions long enough, all of the sealing force can be lost, compromising the seal in a dynamic situation. Once the elastomer ceases to apply a counterforce, it is considered to have lost 100% of sealing capability.

Long-term CSR behavior of the O-rings is being measured per ASTM D6147. Parker Seals O-rings (compound V0835-75) size 2-213, with a nominal thickness of 0.353 cm (0.139"), the same thickness as O-rings used in 9975 packages, are used in the CSR jigs (Figure 2) along with metallic inserts to create a nominal inner diameter (ID) stretch of 20% and a nominal 18% compression to duplicate the sealed O-ring configuration in the 9975 package. A 0.0025-0.0050 mm (0.0001-0.0002") gap is maintained between mating surfaces in the CSR jig to maintain electrical insulation between the two platens. Electrical insulation is needed for the CSR measurement device (relaxometer) to function. The sealing force is measured periodically during aging.

Samples were thermally aged at 79, 113, 121, 149, and 177 ºC (175, 235, 250, 300, and 350 ºF). The lowest temperature, 79 ºC, corresponds to the maximum service temperature in KAMS; 149 ºC is the containment vessel design temperature limit, 121 ºC and 177 ºC were chosen to flank the CV design temperature limit with 177 ºC being halfway between the CV design temperature limit and the O-ring manufacturer's "continuous" service temperature limit. In addition to thermal effects, the possible effects of gamma radiation on CSR behavior were investigated. O-rings were irradiated to a 50-year dose of 8.8 x 10^{-3} Gy (0.88 Mrad) at a dose rate of 4.4 x 10^{-3} Gy/hr (0.44 Mrad/hr) prior to thermal aging. This dose was selected because it corresponds to the maximum dose the O-rings would receive during 50 years of exposure in the 9975 packages at a bounding dose rate of 2 rad/hr. For comparison purposes, a non-stretched O-ring was also aged at 121 ºC (250 ºF). K-type thermocouples were mounted onto each jig to monitor temperature during aging and CSR measurement.

Compression Set

Compression set is a measure of permanent change in seal dimensions as a result of compression over time. Upon 100% loss of sealing force, O-ring samples aged at 149 ºC (300 ºF) and 177 ºC (350 ºF) were removed from the stretch inserts and measured dimensionally. The equation used for compression set (CS) comes from ASTM D395 Method B:

$$\left(\frac{0.139-t}{0.0395}\right)\times 100 = \%CS \qquad (1)$$

where t is the average thickness of the O-ring at four locations along the circumference after the compression set tests, 0.139" is the original O-ring thickness and 0.0395" is the depth the non-compressed O-ring protrudes beyond the O-ring gland. This equation takes into account that the samples were compressed within an O-ring gland of known depth and could not compress more than 0.0395" (0.1 cm). Compression set is also being determined on O-rings removed from surveillance packages.

Leak Testing

Full-sized PCV O-rings are tested on modified Cone-Seal Plugs with an additional weep hole to allow for leak testing of both inner and outer O-rings to a criterion of 1×10^{-7} std cc air/sec. The dimensions of the O-ring gland are identical to the Cone-Seal gland in service. O-rings are being aged at two temperatures, 93 ºC and 149 ºC (200 ºF and 300 ºF), and periodically leak tested at room temperature.

Cane Fiberboard Overpack

Thermal Properties

Cane fiberboard samples were tested for thermal conductivity. The thermal conductivity instrument interrogates an area of 10 x 10 cm (4 x 4 inch) within a sample up to 30 x 30 cm (12 x 12 in) in size, following ASTM C518. Two sample orientations are tested; the axial orientation measures the conductivity of heat perpendicular to the fiberboard layers, and the radial orientation measures the conductivity of heat parallel to the fiberboard layers. Mean testing temperatures were 25, 50, and 85 ºC (77, 122 and 185 ºF). Specific heat capacity was measured following ASTM C351 on 2.5 cm (1.0") diameter by 3.8 cm (1.5") long cylinders.

Mechanical Properties

Compression testing is performed in two orientations, with the load applied either parallel or perpendicular to the plane of the fiberboard layers. A load cell that is controlled to an 11,300 kg (25,000 lb) limit, was used. Samples were 5 cm (2 inch) cubes with no side constraint. The displacement rate applied was 4.8 cm/min (1.9 inch/min) and samples were compressed at this rate until the test was terminated.

The weight and density of samples in each environment have been tracked. Each property is normalized to its initial value.

Cane fiberboard samples were taken from several different packages, with a range of package histories. Table 1 summarizes the total duration of exposures for each aging environment. Environments which include humidity control have the shortest duration, as all samples rely on a single environmental chamber and have been aged sequentially.

Field Surveillance Testing

Viton® GLT O-rings

The 9975 packages selected for surveillance were disassembled in KAMS and O-rings were removed from the cone-seal plug. Within 30 minutes of loosening the containment vessel lid, thickness is measured on four areas of the O-ring in the radial and axial directions. O-rings are then individually packaged and sent to SRNL where they are re-measured an average of 100 days after field testing. Compression set values are then calculated assuming nominal initial dimensions and following Equation 1.

Cane Fiberboard Overpack

The fiberboard assemblies from four packages removed from service have been destructively examined. These packages had been stored in KAMS from 4 months to 5 years. Testing included thermal and mechanical properties, following the same protocols described for aged material.

Results

Experimental Results

Viton® GLT Fluoroelastomer O-ring

<u>Compression Stress-Relaxation</u>

The compression stress-relaxation behavior of Viton® GLT O-rings is shown in Figure 3. The effects vary with aging temperature. The aging temperature of 176 ºC (350 ºF) resulted in a 100% loss of relative retained sealing force over a period of 162 days, see Figure 3. It is noted that this temperature is lower than the O-ring manufacturer's "continuous" service temperature limit of 204 ºC (400 ºF) based on 1000 hours of aging and demonstrates the difficulty in using short term tests to predict long term behaviors. The O-ring exposed to an aging temperature of 148 ºC (300 ºF) resulted in a 100% loss of relative compression stress-relaxation force over a period of 310 days, see Figure 3. The O-rings exposed to the lower aging temperatures have experienced less severe changes and have not yet reached complete loss of sealing force. As expected, the O-rings exposed to the lowest aging temperature appear to have the greatest potential for the longest lifetime before failure.

No significant effect of ID stretch or irradiation has been observed. The measurable absence of irradiation effects may be due to the fact that the irradiation occurred prior to the thermal aging. This might allow some annealing or self-healing of radiation damage to occur. However, the 50-year dose of 8.8 x 10^{-3} Gy (0.88 Mrad) is relatively low for most polymeric materials and the dose was imposed at a relatively high rate. In addition, characterization of O-rings immediately after irradiation indicates no significant damage. Dose rate effects are possible but are not expected at the low dose rates involved. However, if the lack of simultaneous irradiation and thermal exposure mitigated the irradiation damage, then the CSR-based lifetime could be shortened.

Compression Set

The calculated CS values for the O-ring thermally aged at 148 ºC (300 ºF) for 18 months and 177 ºC (350 ºF) for 11.5 months were ~62% and ~70%, respectively. A slight difference in CS exists between the two samples with the more extreme temperature resulting in a higher CS. It is difficult to directly compare the CS values because the CS calculation assumes nominal initial dimensions. Furthermore, the time period between removing the O-ring from compression and the actual dimensional measurement varies. The 148 ºC O-ring was measured 10 months after compression removal whereas the 177 ºC O-ring was measured 12 months after compression removal.

Leak Testing

No fixtures with 3+ years of aging have failed the leak criterion.

Cane Fiberboard Overpack

Physical Properties

Normalized weight and density versus time at temperature are summarized in Figures 4 and 5. Samples from multiple material source packages that have been environmentally aged show similar behavior. A continuous weight loss beyond an initial change due to moisture loss/gain is observed in samples aged at temperatures equal to or greater than 71 ºC (160 ºF). The rate of weight or density loss is greater with higher temperatures and increased humidity. No noticeable change was observed in material aged at 52 ºC (125 ºF) and below. The fluctuation in the physical properties of an overpack aged at 52 ºC (Figures 4 and 5) results primarily from seasonal humidity variation.

Mechanical Properties

Typical compression stress-strain curves for samples aged in ovens at 121 ºC (250 ºF), see Figure 6, show a noticeable drop in compression strength over time. However, no significant decrease is seen at 85 ºC (185 ºF) or lower, except in the presence of elevated humidity.

A range of behaviors has been observed during compression testing, making sample-to-sample comparisons difficult. The integrated area under the stress-strain curve up to a strain of 40% provides a relative measure of the energy absorption capability of the sample, and is a consistent metric for comparison. While the 40% strain level ignores part of the stress-strain curve, it provides a degree of consistency between unconstrained test samples and the partially constrained fiberboard within the package. Compressive strength varies from one package to another. However, the rate of degradation in strength is similar for all packages.

Thermal Conductivity

Thermal conductivity data for two aging environments are summarized in Figure 7. In Figure 7(a), samples aged at 121 ºC (250 ºF) show continued decrease in thermal conductivity over time. Figure 7(b) shows data for samples aged at 85 ºC (185 ºF), but with two humidity levels. The box symbols indicate periods when the samples were held at 70% RH, and the remainder of the time the samples were in an oven without humidity control. The relative humidity in this oven is typically 2% or less, depending on ambient conditions. No significant change occurs with low humidity, but a steep decrease in thermal conductivity is seen at 70% RH at this temperature. This decrease is not recovered by returning to a lower humidity.

The specific heat capacity data exhibit scatter from one trial to the next. Accordingly, the results are averaged over all samples and trials for a given aging interval and test temperature. The measured specific heat capacity decreased by about 10% following long-term aging at 121 ºC (250 ºF). This may be an artifact resulting from sample shrinkage, which has occurred during 2½ years at this temperature. No change in specific heat capacity has been observed in materials tested in other environmental conditions.

Field Surveillance Results

Viton® GLT Fluoroelastomer O-rings

Approximately 480 O-rings have been evaluated from 120 field packages having up to 5 years of service. Dimensional measurements are taken in the field within 30 minutes of package disassembly. The average nominal compression set (CS) value of O-rings from measurements performed on field packages is 26% after an average of 1200 days or approximately 3.3 years in service. O-rings were subsequently re-measured on average 100 days later. The later measurements showed that the average CS was found to relax to 7%, reverting back toward the original shape and thickness. Actual compression set values are unknown as starting O-ring dimensions and part dimensions are not documented. However, the results demonstrate that after a service exposure of ~5 years at true storage conditions, the O-rings maintain elasticity and are able to relax toward original thickness.

Cane Fiberboard Overpack

Fiberboard material from four surveillance packages has been tested following up to 5 years storage. Testing included thermal and mechanical properties, following the same protocols described for aged material. The fiberboard from these packages has shown a range of thermal and mechanical behavior, and that range is consistent with the range of behavior observed in laboratory samples without any exposure. While the baseline condition for these field packages is unknown, their aggregate behavior suggests that the fiberboard properties were not significantly degraded by the service history. This, in turn, supports the model predictions that indicate minimal changes in properties for nominal storage conditions.

Discussion

Viton® GLT Fluoroelastomer O-ring

Using the time-temperature superposition theory based on the William-Landel Ferry (WLF) method [7], estimated times to failure can be determined for the O-rings based on the thermal aging CSR data. A master curve using 79 ºC (175 ºF), the lowest temperature data set, as a reference temperature, T_{ref}, was constructed from the CSR data, Figure 8. Empirically determined shift factors, a_T, were utilized to develop the master curve. The shift factors were then used to determine the activation energy, E_a through the relationship:

$$\log a_T = E_a/(T-T_{ref}) \tag{2}$$

The calculated E_a for the degradation reaction from the fit of the shift factor at various temperatures was 56 kJ/mol, see Figure 9. From the master curve, the estimated lifetime of the O-ring is 20-27 years at a constant seal temperature of 79 ºC (175 ºF), based on 100% loss of sealing force. This is a bounding case, assuming a constant ambient temperature of 40 ºC or 104 ºF and maximum payload of 19 W. Lower ambient temperatures and/or payloads reduce seal temperatures and increase seal lifetime. Seal temperatures also lag behind the ambient temperature by many hours or days due to the overpack thermal insulation, so the assumption of constant exposure at peak temperature is conservative. This model assumes no significant influence of radiation or ID stretch, as these effects have not yet been observed. The model also assumes that the activation energy will remain constant across the service temperature range. This is expected, though it is possible that the activation energy or degradation mechanism could change at lower temperatures. This can only be determined by continuing tests at lower temperatures or by measuring ultrasensitive parameters such as oxygen consumption rates. The activation energy of 56 kJ/mol suggests that the oxidation degradation mechanism for CSR behavior in the O-rings is impeded due to the lack of oxygen exposure with the O-ring resting in the O-ring gland. When oxygen permeation is unimpeded, activation energies associated with the oxidation reaction range from 80-120 kJ/mol. [8]

Cane Fiberboard Overpack

The 9975 package does not provide an air-tight or water-tight seal for the fiberboard enclosure. However, a properly closed drum does provide a significant degree of isolation of the fiberboard from the ambient environment [4]. Accordingly, it is recognized that any moisture originally in the fiberboard assembly will likely remain in the package for a long time. Due to the heat generated in the 3013 containers, the fiberboard within a package will develop temperature and moisture gradients. Moisture will tend to migrate to the cooler regions of the fiberboard, and the total moisture content of the package will change very slowly.

During a postulated loss of ventilation accident in the KAMS facility, the maximum ambient temperature is 58 ºC (137 °F), and the corresponding Lead Shielding Body temperature is 91 ºC (196 °F). The maximum fiberboard temperature is assumed to be similar to the Shielding Body temperature. However, the normal ambient temperature in KAMS is less than 32 ºC (90 °F), even in the summer. The fiberboard temperature should remain below ~65 ºC (~150 °F). Therefore, testing for storage induced changes in the fiberboard must include exposure to several temperatures.

Exposures of the fiberboard to moisture and temperature cause time-dependent property changes. Such changes may occur as the sample comes to equilibrium in the 9975 package. The change in moisture content simply induced by the thermal gradients developed in the package may produce changes in the sample's properties and long-term changes may occur as a result of degradation. The literature identifies that slow pyrolysis occurs at modest temperatures [9]. In addition to water vapor, compounds from pyrolysis are evolved at temperatures as low as 95 ºC (203 ºF). This is strongly evidenced in samples aged at 121 ºC (250 ºF). Such samples show an immediate weight loss of 8-10% (moisture loss), followed by an additional 15-20 % per year weight loss. At the higher temperature and humidity levels, test samples change visually. The samples darken, and the coarse fibrous appearance changes to a finer particulate texture.

The aging models that are discussed below do not include the effect of initial moisture and given the tendency for the 9975 drum to provide a high degree of isolation, significant moisture-related changes might not occur in service unless the package was closed in a very humid atmosphere.

Fiberboard Service Life Estimates

Data for each property have been analyzed statistically for best fit models. The model for fiberboard density and the corresponding service life predictions are described below. A similar approach is used for the other properties and provides additional service life estimates. The limiting property may vary depending on the specific service conditions.

Density data were fit to a model, which predicts the rate of change as a function of temperature and humidity. The rate is the percentage change in density per year, T is the exposure temperature in ºC, and RH is the percent relative humidity. A constant rate of change is consistent with the data shown in Figure 5.

$$\text{Rate (density)} = 0.0004496 - 4.876E\text{-}6 * T - 2.389E\text{-}6 * RH - 5.446e\text{-}8 * (T - 76.11)^2 - 7.18E\text{-}8 * (T - 76.11)*(RH - 21.65) - 1.263E\text{-}7\,(RH - 21.65)^2 * 365 * 100 \qquad (3)$$

Predictions from this model are shown in Figure 10 for several temperature/humidity combinations. Density is predicted to increase slightly at the lower temperature environments, while the data have shown no net change in these mild environments. This tendency of the model to predict a density change is likely a result of the minor seasonal fluctuations driven by variation in ambient humidity. While this produces no long-term change in density, some samples which were aged for shorter durations may show a net increase or decrease in density depending on when they began aging. This aspect of the model should improve with the accumulation and incorporation of additional data.

Predictions from the density model can provide a service life estimate based on density. The minimum allowable density to provide the required criticality control is 0.21 g/cc, and the minimum measured density for a fiberboard assembly is 0.242 g/cc. Therefore, the service life within a specific environment will be the time required for a 13% decrease in the overall density of the fiberboard assembly. Since the fiberboard will develop temperature and moisture gradients in service, potential exists for local variations in degradation rate throughout the assembly.

For an ambient temperature of 28 ºC, typical fiberboard temperatures in service might range from ~35 ºC along the outer diameter surface to ~58 ºC along the ID surface, with a maximum heat load present. The total moisture content will vary from package to package, but it can be assumed that the typical package will have no more moisture than would be absorbed from the air at 23 ºC and 100% RH. Without any redistribution of moisture, the elevated service temperatures would reduce the relative humidity in the package to ~55% along the outer diameter surface and ~17% along the inner diameter surface. For these conditions, the model predicts no decrease in density along either the inner diameter or outer diameter surface.

In reality, however, there will be moisture redistribution within the package. As the local humidity increases above 55% for a range of temperatures, the model predicts a decrease in density over time, with a corresponding finite service life. However, this rate would apply only to a local region along the fiberboard exterior surface. The overall average rate of density change for the full assembly will still be low, and is judged to provide a service life in excess of the initial storage period in KAMS. This judgment is supported by observation of packages removed from service after up to 5 years storage in KAMS. Examination of these packages has shown a range of fiberboard densities consistent with that of un-aged fiberboard, with no discernable change in the fiberboard exterior surface compared to the rest of the assembly.

Conclusions

Two components of the 9975 package, Viton® GLT fluoroelastomer O-rings and Celotex® cane fiberboard overpack have been studied for lifetime evaluation in KAMS storage conditions. The GLT fluoroelastomer O-rings were subjected to accelerated thermal and radiation aging and evaluated for changes in compression stress-relaxation, compression set, and leakage behavior. Fiberboard was evaluated for changes in dimensions, thermal conductivity, specific heat capacity, and mechanical strength. Service life is strongly dependent on actual storage conditions. Combined surveillance and laboratory results conclude that both the Viton® GLT based fluoroelastomer O-rings and Celotex® cane fiberboard are expected to exceed the initial storage period in KAMS. Based on current data, O-rings are expected to last at least 20 years in service, but will require replacement before the end of the 50 year service period. Increased confidence in this conclusion is expected with the accumulation of additional data from both the laboratory testing and surveillance.

Acknowledgements

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Figures

Table 1. Summary of fiberboard sample exposures prior to testing, for data used for statistical analysis

Temperature	**Exposure in "dry" oven (weeks)**	**Exposure in chamber with humidity controlled to the specified value (weeks/% RH)**		
121 ºC (250 ºF)	≤ 142	- - -	- - -	- - -
101 ºC (215 ºF)	≤ 100	- - -	- - -	- - -
90 ºC (195 ºF)	2	2/40	2/100	- - -
85 ºC (185 ºF)	≤ 139	≤ 32/30	≤ 28/70	- - -

71 ºC (160 ºF)	- - -	≤ 32/50	- - -	- - -
51 ºC (125 ºF)	≤ 122	2/40	≤ 17/70	2/100
25 ºC (77 ºF)	- - -	2/40	8/70	2/40

Table 2. Decrease in area under the stress-strain curve for material parallel and perpendicular orientation with increasing aging time period.

LD2 material, parallel orientation	
Aging Period (wks)	Area under Curve to 40% Strain (ksi)
8	0.020
16	0.018
32	0.016
64	0.011
MSC material, perpendicular orientation	
Aging Period (wks)	Area under Curve to 40% Strain (ksi)
2	0.052
7	0.052
32	0.021
47	0.012
64	0.016

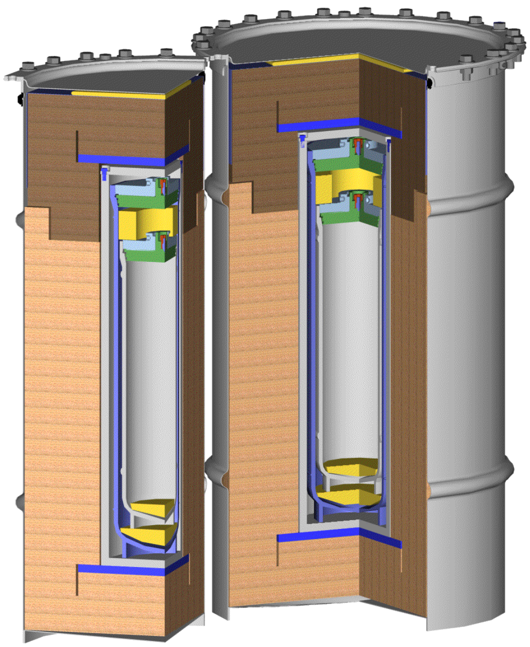


Figure 1. Illustration of 9975 package including fiberboard, lead shielding, and double containment vessels.

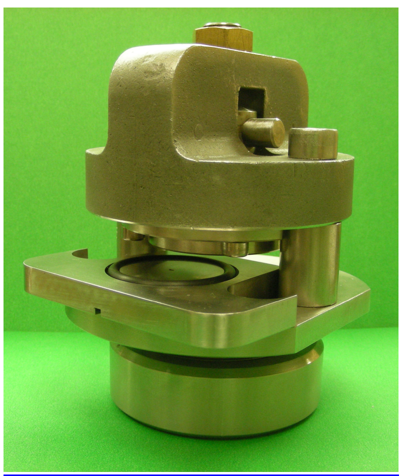


Figure 2. CSR jig with custom stretch insert.

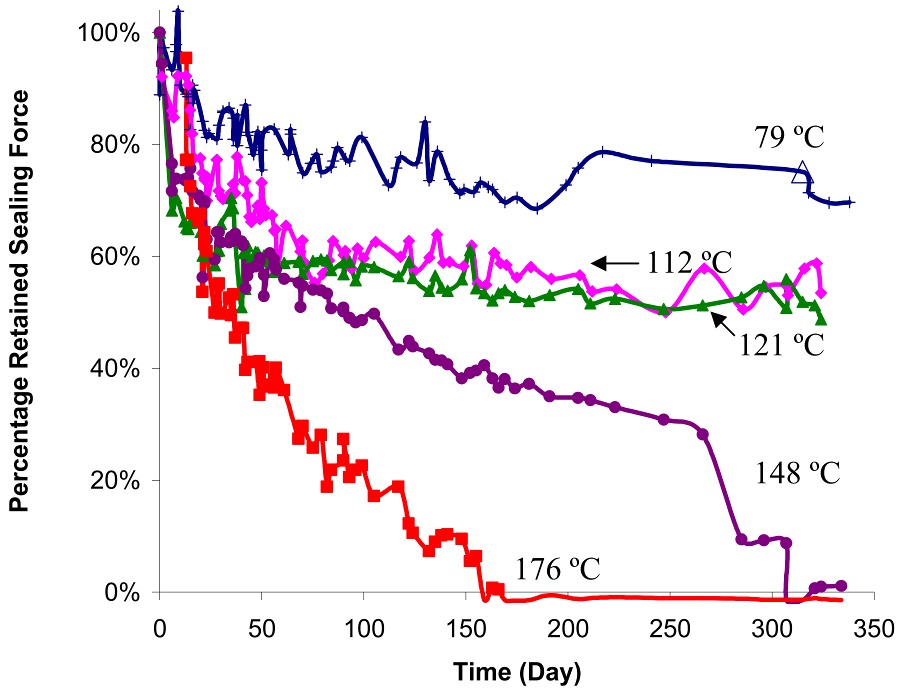


Figure 3. Percentage retained sealing force versus aging time. Aging temperature noted in plot for each sample.

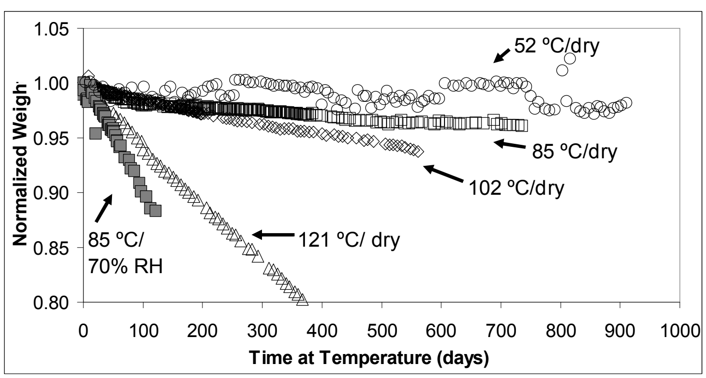


Figure 4. Normalized weight versus time at temperature for fiberboard in several temperature and relative humidity environments.

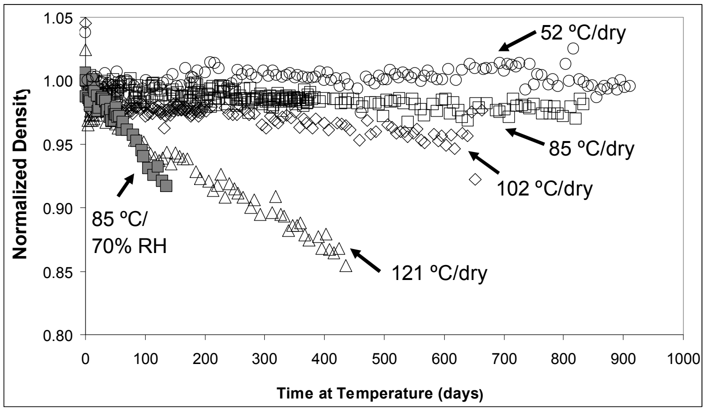
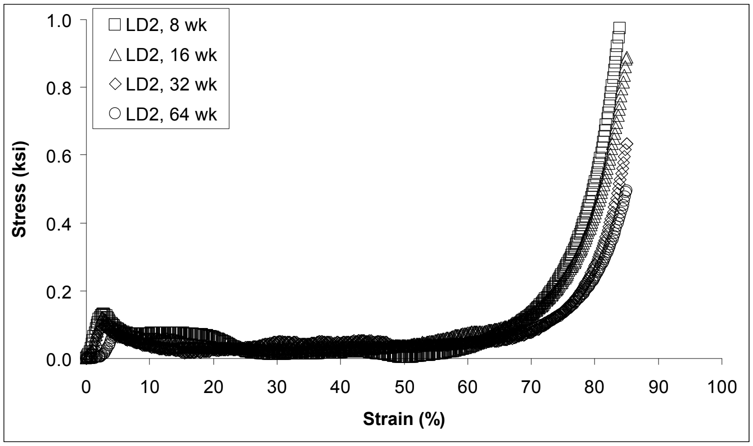


Figure 5. Normalized density versus time at temperature for fiberboard in several temperature and relative humidity environments.

(a)



(b)

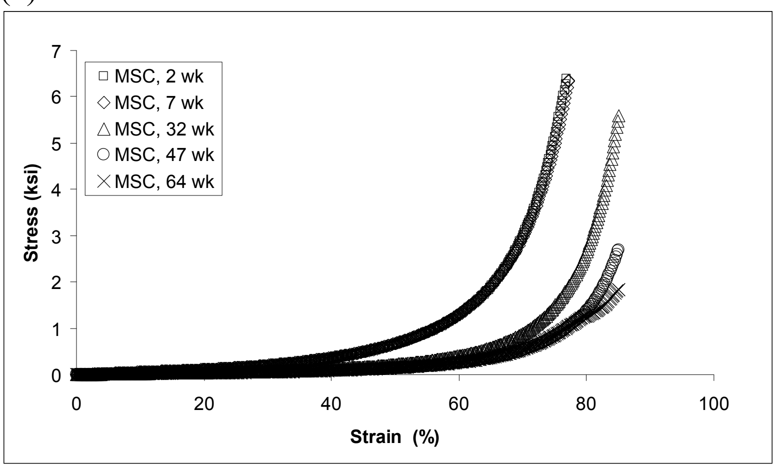
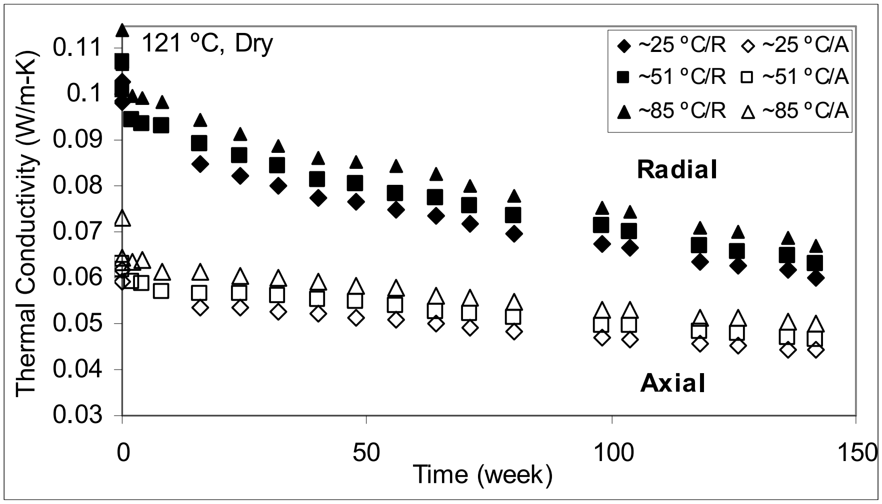


Figure 6. Engineering stress-strain compression curves for select fiberboard samples aged and tested at 121 ºC (250 ºF), (a) parallel orientation, LD2 material (b) perpendicular orientation, MSC material.

(a)



(b)

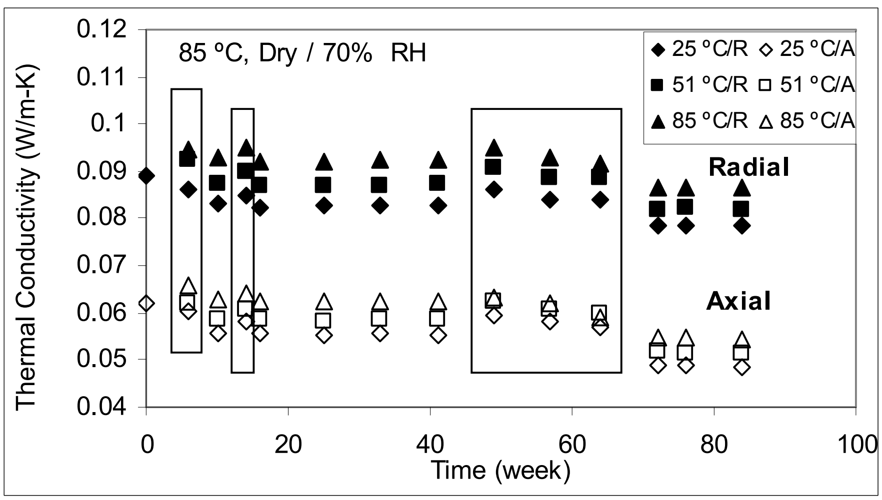


Figure 7. Thermal conductivity versus time data for two aging environments. In each plot, the test temperature is indicated by the symbol: diamonds – 25 ºC, squares – 51 ºC, triangles - 85 ºC. Open symbols denote axial orientation samples, closed symbols denote radial orientation samples. In plot (b) with the cycling humidity, the periods within the boxes are at 70% relative humidity.

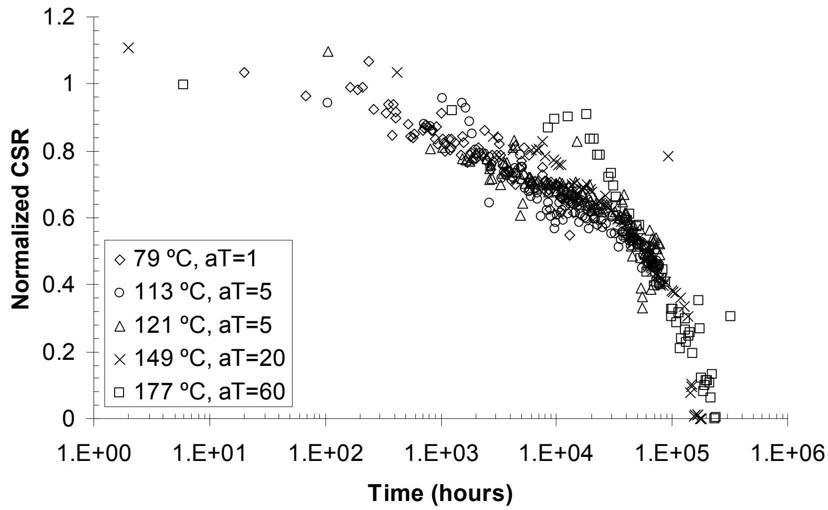


Figure 8. Time-temperature superposition curve for V0835-75 CSR data (T_{ref}=76 ºC, 175 ºF).

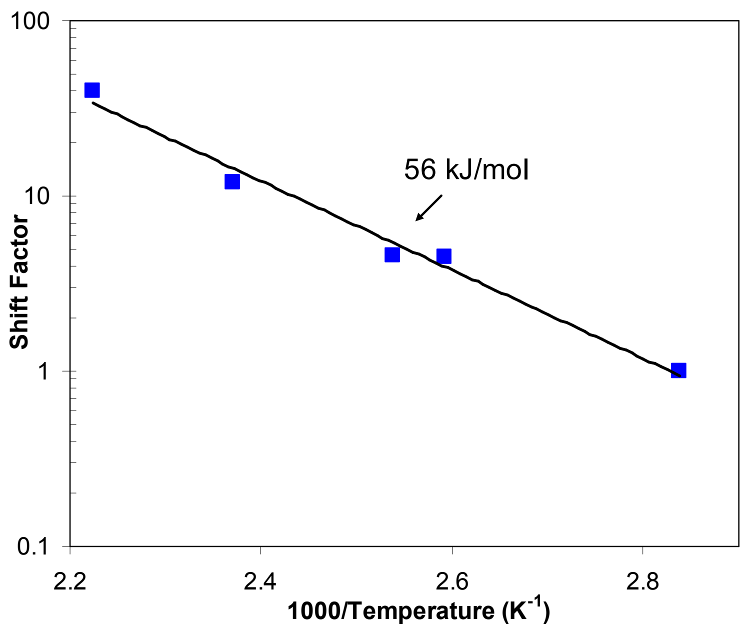


Figure 9. Plot of log a_T shift factors versus temperature. The activation energy derived from the linear fit is 56 kJ/mol.

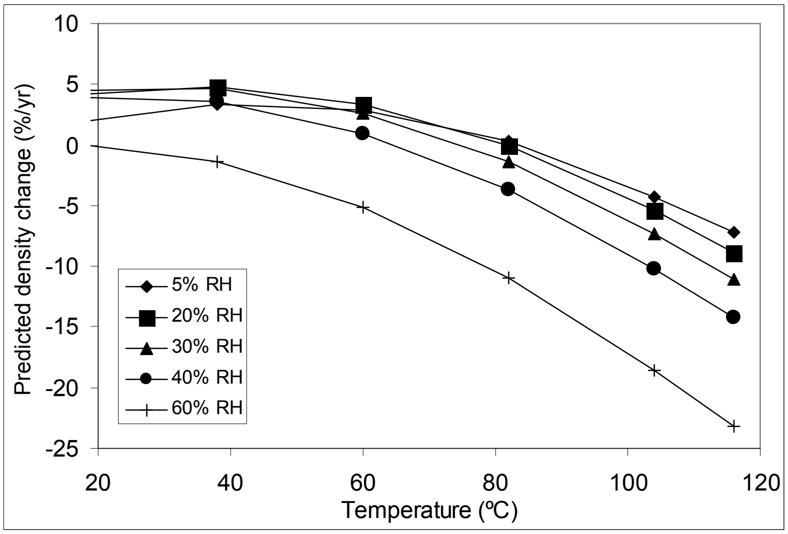


Figure 10. Predicted density change of fiberboard versus aging temperature.