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STATUS REPORT –CANE FIBERBOARD PROPERTIES AND DEGRADATION RATES FOR STORAGE OF THE 9975 SHIPPING PACKAGE IN KAC

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Summary

Thermal, mechanical and physical properties have been measured on cane fiberboard samples following accelerated aging for up to approximately 10 years. The aging environments have included elevated temperature $\leq$ 250 ºF (the maximum allowed service temperature for fiberboard in 9975 packages) and elevated humidity. The results from this testing have been analyzed, and aging models fit to the data. Correlations relating several properties (thermal conductivity, energy absorption, weight, dimensions and density) to their rate of change in potential storage environments have been developed. Combined with an estimate of the actual conditions the fiberboard experiences in KAC, these models allow development of service life predictions.

Further work should be performed to better define KAC storage conditions and the environment within the 9975 shipping packages, and to identify appropriate limits for each property. This should be a joint effort by SRNL and NMM personnel.

Some of the predicted degradation rates presented in this report are extreme. However, these relate to environments that do not exist within KAC, or would be postulated only as upset conditions that would not likely persist for an extended period. For a typical package stored in KAC with ~10 watts internal heat load or less, and ambient temperatures below 90 ºF, the fiberboard experiences storage conditions less severe than any of the aging environments. Fiberboard in conforming packages with lower internal heat loads should experience little or no degradation, and is expected to provide a service life beyond the currently approved 15 year storage period. Packages with higher internal heat loads may not continue to perform their required safety functions beyond 15 years. Ultimately, the service life will be determined by the cumulative effect of degradation from all the conditions these packages might encounter. The assumptions and inputs behind the models in this report should be well understood before attempting to identify an actual service life in KAC. Additional data continue to be collected to permit future refinements to the models and assumptions.

For developing service life predictions, the ambient conditions within KAC can be reasonably identified, and the temperature profiles within the various packages (with a range of heat loads and at varying locations within an array of packages) can be calculated. However, the humidity within the package is not as well characterized. Preliminary efforts have identified a relationship between the moisture content of fiberboard samples and the relative humidity of the surrounding air, but further work is needed in this area. Improvement in understanding this relationship might be realized with a change in the way humidity data are collected during field surveillances. It is recommended that the humidity be measured through a caplug hole before the package is removed from its storage location. The package would remain in thermal equilibrium during this measurement, providing humidity data that is more relevant to the storage condition.

The results and model predictions presented in this report are applicable to 9975 packages with cane fiberboard overpack assemblies. A separate effort is underway to identify whether softwood fiberboard would behave similarly. In addition, the degradation models do not address the effects of non-conforming conditions such as the presence of excess moisture and mold, or beetle infestations.

Background

Celotex® fiberboard material is used in the 9975 shipping package between the outer 304L stainless steel drum and the lead shielding, and provides three safety functions: thermal insulation to limit internal temperature during a fire, criticality control and resistance to package crushing [1].

A recent review of KAC facility temperatures [2] identified an average ambient temperature in the storage areas of 74 ºF. Seasonal temperatures in the facility recorded since 2009 have ranged from 54 to 91 ºF. This review further concluded that the overall effect of the seasonal temperature variation was equivalent to that which would be produced by exposure to a constant temperature of 76 ºF. In order to account for local temperature increases within the storage array and other variables, this reference proposed that 9975 package aging analyses assume a constant facility ambient temperature of 94 ºF.

The fiberboard material must retain its dimensions and density within certain ranges to provide the required impact resistance, criticality control and fire resistance. Several properties of interest to demonstrate acceptable long-term performance of the material include dimensional stability, moisture absorption/retention, density, compressive strength, thermal conductivity and specific heat capacity. In some cases, limits on property ranges have not been identified. In other cases, sensitivity analyses may not have been performed to evaluate the impact of out-of-range values.

Samples are conditioned in support of several specific tests [3] that address thermal, mechanical or physical properties. Samples have been taken from several different packages, with a range of package histories. Duplicate samples from multiple package sources have been conditioned to identify the range of variability. The package sources are as follows:

- LD1, LD2 – undamaged portions of 2 lower fiberboard assemblies from drop tested packages, which were in storage for ~10 years prior to this effort.
- MSC – undamaged portions of several fiberboard assemblies from drop tested packages, which were in storage for ~10 years prior to this effort. Traceability to specific assemblies was not maintained for these samples.
- KT2 – lower assembly from an unused package following several (<5) years in storage.
- 2234, 826 – lower assemblies removed from packages following 2 and 3 years service in KAC, respectively, and subsequent surveillance activities.
- 826U, 600U – upper assemblies removed from packages following 3 and 5 years service in KAC, respectively, and subsequent surveillance activities.
- New – remnant portions of a new assembly (upper and lower) purchased in 2005 for a separate effort.

Table 1 summarizes the maximum conditioning times for each environment through August 2015. Due to different start times, the duration may vary for different samples in a given environment. Environments which include humidity control typically have shorter durations since only a single environmental chamber was available through 2010, and samples were conditioned sequentially. Since 2010, three or more environmental chambers have been available for conditioning samples.

Baseline and long-term testing of mechanical and thermal properties have been reported previously. Reference 4 summarized available data on cane fiberboard through September 2012 and presented degradation models for several of the measured properties. Additional data have since been collected, and the cumulative data set through August 2015 has been analyzed for the refinement of aging models. All the data considered herein have been collected on cane fiberboard samples. The conclusions of this report are applicable only to cane fiberboard. The use of softwood fiberboard in 9975 packages has also been approved. The properties and modelling efforts for softwood fiberboard will be reported separately.

Test Data

Compression Tests

Unlike the thermal and physical tests, compression testing is destructive – each sample can be tested only once. Therefore, these samples become increasingly important after extended conditioning periods as fewer conditioned samples remain for future testing. Compression testing has been performed following aging for as long as 4 years in some environments.

Compression test samples are nominally 2 x 2 x 2 inches in size, and are tested at a crosshead speed of 1.9 inch/minute. The load is applied either parallel or perpendicular to the fiberboard layers. The test continues until a limit is reached, either a maximum strain (85%), or a maximum load (20,000 or 25,000 pounds, depending on the load cell used).

Typical compression stress-strain curves are shown in Figures 1-2 for samples conditioned in two of the aging environments – 185 ºF dry and 250 ºF dry. These show a noticeable drop in compression strength over time at 250 ºF, but not at 185 ºF. Compression testing of conditioned material has been performed on samples from five of the source packages, although only four of the source packages have contributed sufficient data to be included in modelling efforts (LD1, LD2, MSC and New).

A range of behaviors has been observed during compression testing (varying shape of the stress-strain curve). Because of this variation, two metrics have been used for quantifying and comparing the performance of different samples. For samples loaded parallel to the fiberboard layers, the stress at which the layers buckle is an indication of the load sustained before the accumulation of significant damage. For all samples (tested either parallel or perpendicular to the fiberboard layers), 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. The 40% strain level is arbitrary, but provides a consistent point of comparison. These two metrics are summarized in Tables 2-4 for all compression tests to date from the four primary source packages, and representative groupings of these data are presented in Figures 3-5.

Thermal Tests

Thermal conductivity samples are typically ~7 x 7 inches by 1 – 2 inches thick. Some of the initial samples were larger in area (~12 x 12 inches). The samples are removed from the fiberboard assemblies in an orientation so as to characterize heat flow through the assembly in either the axial (perpendicular to the fiberboard layers) or radial (parallel to the fiberboard layers) direction. Thermal conductivity samples have been removed from each of the source packages, although varying numbers of source packages are included among the samples aged in each environment.

Thermal conductivity is measured in either a Fox 300 or Fox 314 heat flow meter instrument from LaserComp. Tests are conducted at mean temperatures of 25 and 50 ºC on all samples. Samples aging in the higher temperature environments have also been tested at a mean temperature of 85 ºC. The LaserComp instruments conduct the test in accordance with ASTM C518-91 (Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus).

Thermal conductivity data for each environment are summarized in Figure 6. For ease of comparison, the thermal conductivity data for each sample are normalized to the first measurement taken after conditioning began. These first conditioned values are listed in Table 5 to show the range of sample-to-sample variation that might be expected, and the degree to which thermal conductivity varies with each environment.

Specific heat capacity is measured in accordance with ASTM C351-92b (Reapproved 1999) (Standard Test Method for Mean Specific Heat of Thermal Insulation) at mean test temperatures of 25 and 51 ºC. Samples are cylindrical in shape, with 1 inch diameter and ~1.5 inch height. Between 3 and 5 specific heat capacity samples (removed from the same source package) are aged in selected environments, and each may experience multiple trials at each test interval. The specific heat capacity data can show a significant degree of scatter from one trial to the next. Accordingly, the results are averaged over all samples and trials for a given conditioning interval and test temperature. A summary of these averaged data is shown in Figure 7. The nominal rate of decrease in specific heat capacity is shown under Figure 7 by the coefficient in each equation that was fit to the data for each environment.

Physical Tests

The weight, dimensions and density of samples in each environment have been tracked with small samples (~2 inch cubes). In addition to the elevated temperature environments mentioned above, these physical property samples have also been conditioned at temperatures of 50 and 15 ºF, at ambient humidity and in a desiccated environment. For these low temperature environments, the ambient humidity is approximately 10% at 50 ºF and 60% at 15 ºF. No significant change in physical properties was noted in these two low-temperature environments.

In order to better compare samples and highlight changes among samples with different initial property values, the properties (weight, density, height and length / width) of each sample are normalized to their initial conditioned value. The normalized data from these samples are summarized in Figures 8-11. Samples from multiple material sources are conditioned in each of the elevated temperature environments. Initially, data were collected on a single sample source (MSC) only. Samples from additional package sources (LD1, LD2, New and 2234) were added subsequently.

Ovens are used to provide nominally dry environments for aging fiberboard samples. These environments typically have a very low relative humidity consistent with the ambient laboratory environment (<10 %RH at 125 ºF, <2 %RH at 185 ºF, etc). Since the laboratory experiences seasonal variations in relative humidity, samples in these dry environments can exhibit comparable seasonal variation in physical properties. This is most pronounced at the lowest temperature (125 ºF), and less obvious at the higher temperatures.

Termination of Samples

Compression testing is destructive in nature, and the compression samples are tested once and retired from further testing. The remaining tests are non-destructive, and provide for repeated testing after periods of aging. Some of these samples have been retired from testing for various reasons. Typically, samples will be retired after their properties degrade to a point beyond the established acceptance criteria, or if they become sufficiently fragile to compromise the ability to handle them and make additional meaningful measurement. This has been the case for all samples aging in 250 ºF dry, and 185 ºF 70 %RH environments.

In the milder environments, some of the physical property samples have been removed from test as well. This was done after significant exposures were achieved (typically 3 – 8 years), and the samples from the various source packages were observed to have very similar degradation rates. Several of these retired samples were then re-purposed as compression test samples to provide a few data points at much longer exposures than were otherwise available.

Analysis

No significant degradation has been observed in fiberboard assemblies from conforming packages (i.e. packages without excessive moisture and/or mold) examined following up to 7 years storage in KAC. The typical package stored in KAC contains a modest amount of moisture within the fiberboard assembly, and has an internal heat load significantly less than the 19 watt rating of the package.

To date, seven of the packages removed from storage for destructive examination have contained cane fiberboard overpacks. They had been held in storage for periods ranging from ~5 months to 7 years. The consistent trend indicates the storage environment is sufficiently mild to preclude significant degradation over this time period, although baseline data from these specific cane fiberboard assemblies are not available for comparison. In contrast, the environments used for accelerated aging of the test samples described in this report are more severe than typical KAC storage conditions. This difference is necessary in order to observe degradation and develop models for predicting service life in advance of unacceptable degradation occurring in KAC.

The ambient temperature within KAC can vary seasonally, or due to changes in HVAC status. Temperature data from the facility were analyzed in Reference 2 relative to the storage environment for 9975 shipping packages. This reference identified that an assumed average facility ambient temperature of 94 ºF would conservatively capture the effects of the actual facility temperature, including seasonal variations, on the aging behavior of the package components. For a package with a bounding 19W internal heat load, the maximum fiberboard temperature is assumed to match the maximum shield temperature of 153 ºF, based on the temperature profiles reported in Reference 5. The outer surfaces of the fiberboard would be up to ~40 ºF cooler or 113 ºF, based on data from instrumented test packages [6]. The temperature gradients and peak temperatures would be reduced proportionally for lower internal heat loads. For example, the maximum fiberboard temperature would be ~125 ºF for a 10W internal heat load and 94 ºF ambient temperature.

The fiberboard within a heated package will develop temperature and moisture gradients. Moisture will tend to migrate to the cooler regions of the fiberboard, while the total moisture content will change very slowly (if at all). Packages that have been destructively examined have had a fiberboard moisture content ranging from 6 to 20 %WME. Lower values (< ~13 %WME) occurred along the ID surface, while values along the OD surface tended to be higher (> ~10 %WME). These measurements were typically taken ~2 – 4 months after the package was unloaded during field surveillance, indicating the degree of persistence of a moisture gradient after the heat load is removed, and suggesting the moisture gradient was greater while in storage. Current testing to characterize the moisture / humidity distribution within a fiberboard assembly suggests that moisture re-distributes in a manner that maintains a relatively constant level of absolute humidity [7].

A further indication of the moisture gradient that can exist in service is seen in an instrumented test package that has been conditioning at elevated temperature (LE1). It contained an internal heat source of 12 watts (creating a temperature gradient in the fiberboard), and was held in a chamber at 142 ºF. Before conditioning, the fiberboard moisture content in this package ranged from 13 – 15 %WME along the ID, and 16 – 18 %WME along the OD. After conditioning for 57 weeks, the fiberboard moisture content was a maximum of 6.4 %WME along the ID, and ranged from 12 – 22 %WME along the OD. Some regions of the bottom of the lower fiberboard assembly had significantly higher moisture content. Thus, a significant amount of the moisture within this package had migrated from the inner (hotter) regions near the shield to the (cooler) outside and bottom.

The 9975 SARP notes that the package does not provide an air- or water-tight seal. However, upper fiberboard subassembly testing [4] has demonstrated that a properly closed drum does provide a significant degree of isolation of the fiberboard from the ambient environment. Accordingly, any moisture originally in the fiberboard assembly will likely remain in the package for a long time. The range of moisture content measured in the upper fiberboard subassemblies exposed to the ambient environment is ~6 – 14 %WME (wood moisture equivalent) or ~7 – 12 wt%. This moisture content will define the relative humidity within a package, which needs to be identified to correlate the laboratory test data to degradation under storage conditions. Humidity measurements have been taken in the upper air space of a number of packages in KAC [7]. However, significant variation is observed between packages. Some of this variation is driven by the package internal heat load and the storage position, but these variables do not explain all the scatter. The primary unknown is the initial moisture content of the fiberboard assembly.

Some efforts have been performed or are in progress to develop an improved understanding of the environment within the 9975 drum in storage. KAC personnel have begun collecting fiberboard moisture data during field surveillance activities. These data should help understand the actual range of moisture conditions among the many packages in storage. Humidity readings are also taken within the package during field surveillance. However, these data are less useful since the package is moved from its storage location prior to measuring relative humidity, and any change in the ambient temperature around the drum will alter the humidity reading. It is expected that this shortcoming could be avoided if the humidity measurement could be taken before the package is moved from its storage location (by inserting the humidity probe through a caplug hole). The humidity within a limited number of packages has been recently measured in the storage environment. Finally ongoing tests to characterize the humidity profile within packages with internal heat loads is helping to understand the range of environments that might exist within a package for a given moisture level and heat load. Note, however, that there is a wide range of possible moisture conditions that are possible, and a corresponding range of fiberboard degradation behaviors. The actual moisture content of most packages is unknown.

In the laboratory testing, there are two contributions to property changes – immediate, reversible effects due to change in moisture content, and long-term irreversible changes due to degradation. When fiberboard is placed in an environment, there may be a change in moisture content as the sample comes to equilibrium with the environment (typically within ~1 day for smaller samples, or after many weeks for a full assembly). The following summarizes the type of reversible changes likely to occur due to moisture change.

- Thermal conductivity will decrease as moisture content decreases. This effect is reported in the literature [8] for wood products (and by extension is applicable to fiberboard) and is observed in the laboratory data.
- The layer buckling strength will increase as moisture content decreases.
- There is significant variation in the energy absorption behavior. However, the general trend for loading perpendicular to the fiberboard layers is increasing energy absorption as moisture content decreases, and decreasing energy absorption as moisture content increases. The general trend for loading parallel to the fiberboard layers is decreasing energy absorption as moisture content decreases or increases. This dual behavior is an artifact of the samples being unconstrained and an increased tendency for drier samples to split apart when loaded in the parallel direction.
- Specific heat capacity will decrease as moisture content decreases. This effect is reported in the literature [8] for wood products (and by extension is applicable to fiberboard) and is observed in the laboratory data.
- Physical properties (weight, density, dimensions) all decrease as moisture content decreases.

Table 6 summarizes short-term (initial) physical property changes observed in the various environments. The weight changes are generally consistent with an initial moisture content of up to 10 wt%.

In addition to short-term moisture effects, longer 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 203 ºF. This is strongly evidenced by samples conditioned at 250 ºF, with an immediate weight loss of 8-10% (moisture loss), followed by an additional 15 – 20 %/year weight loss. At the higher temperature and humidity levels, the samples also change visually. The samples darken, and the coarse fibrous appearance changes to a finer particulate texture.

The aging models that are discussed below deal with long-term degradation rates. They do not include the short-term effect of initial moisture change. Given the tendency for the 9975 drum to provide a high degree of isolation, much of this initial moisture-related change might not occur in service, except as driven locally within the drum by a temperature gradient.

Several physical property samples have been maintained at ambient laboratory conditions, and measured periodically. These control samples serve to show if there is an overall bias in the data over time. The data for one of these control samples are shown in Figure 12. The control samples show a slight decrease in weight and dimensions over time (~0.1 – 0.2 %/year), and a small increase in density. Modest changes in fiberboard physical properties are occurring constantly, especially as a result of seasonal variation in moisture level. Overall, these data suggest there is no significant permanent change in properties occurring at ambient conditions. The slight decreases in weight and dimensions are attributed to wear from handling. As such, these control sample rates are used to adjust the measured degradation rates of the aging samples.

There may be sources of degradation to the fiberboard that are not captured in the above testing. For example, a limited number of 9975 packages have been removed from service and found to contain mold or were infested with drugstore beetles. The identified scope of beetle infestation to date is 3 packages. However, the possibility of additional / future infestations exists. On the other hand, mold spores are ubiquitous, and mold growth can be expected whenever the environmental conditions are favorable.

Laboratory testing has observed mold growth at high humidity (approximately 100% RH) with temperatures of approximately 50 and 77 ºF. Mold was not observed on samples at approximately 100% RH and 125 ºF, indicating a modest temperature increase beyond ambient may be sufficient to limit or prevent the growth of mold. However, given the tendency for moisture in the fiberboard to migrate toward the cooler regions of the package, packages with higher internal heat loads are much more likely to develop conditions conducive to mold growth on the outer, cooler surfaces of the fiberboard.

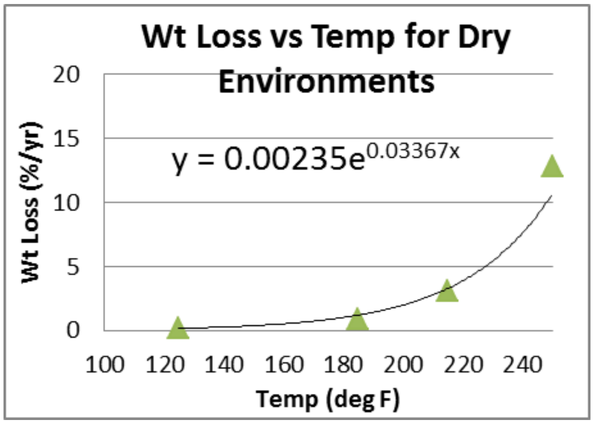
Mold has been observed in at least 11 9975 packages in service in K Area. In one case (9975-01903), small patches of mold were observed near the bottom of the lower fiberboard assembly. The fiberboard moisture content was 11 – 18 %WME, with readings around 17 %WME near the mold [10]. An extreme example of mold associated with water intrusion was observed in package 9975-01819. Moisture levels were elevated throughout the fiberboard (16 %WME on the ID, 20 – 26 %WME on the OD, the bottom ~2 inches were saturated) [11]. The specific impact of mold on fiberboard properties or package service life has not been examined, and is not addressed in this report.

Degradation Models

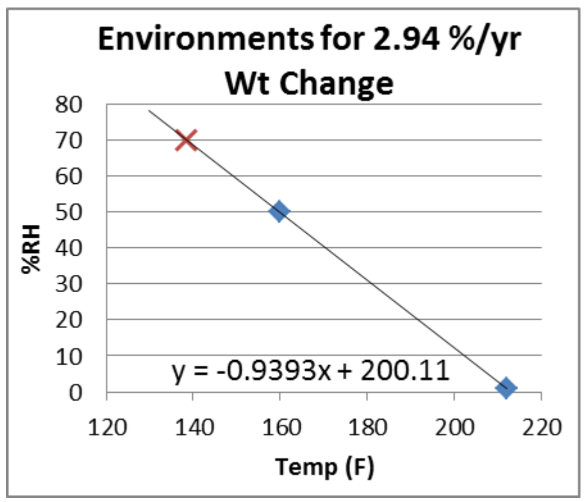
Aging models have been constructed based on the observed changes in several fiberboard properties. These include weight, density, dimensions, thermal conductivity (axial and radial) and energy absorption (area under the stress-strain curve to 40% strain). Most of the models are based on the average behavior of all samples, and do not reflect any variation among packages or samples. The following approach was used to model the change in fiberboard weight, dimensions, density, and thermal conductivity. Specific steps are illustrated for the change in weight.

1. The data are normalized, to show the relative decrease in each property over time (see Figure 8 for normalized weight change).

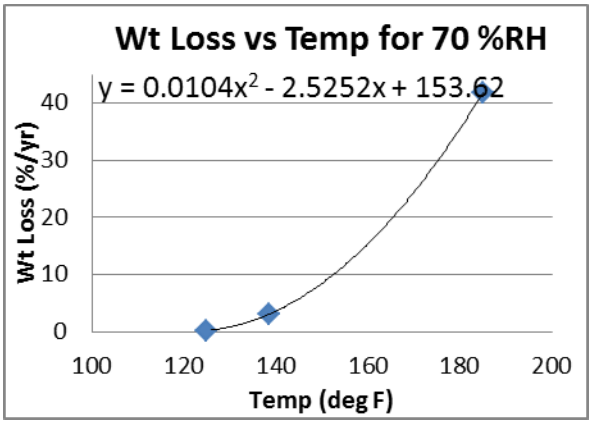
2. A curve is fit to rate of change vs temperature for 4 dry oven environments – 125, 185, 215 and 250 °F. An exponential relationship provides the best fit, and represents the variation with temperature at a low value of relative humidity (~1-10%).



3. It is observed that similar rates of change occur for 215 °F dry, 185 °F 30%RH and 160 °F 50%RH environments, and that these 3 environments fall close to a common straight line in humidity – temperature space. This suggests a linear relationship would apply. The degradation rate for 160 °F 50%RH is 2.94 %/yr. From the curve fit to the dry environments, this same rate would be expected at 212 °F 1%RH. Extrapolating from these two environments, the same degradation rate is predicted for 138.5 °F 70%RH.

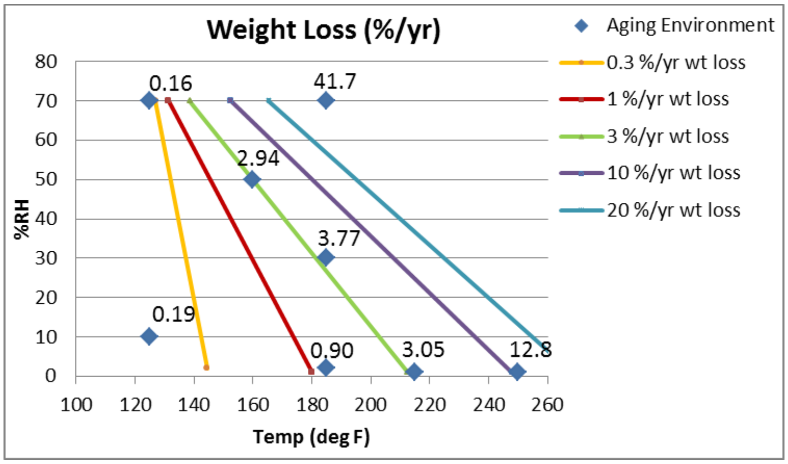


4. A curve is fit to rate of change vs temperature for 3 humid environments – 125 °F 70%RH, 138.5 °F 70%RH and 185 °F 70%RH. A binomial equation provides the best fit, and represents the variation with temperature at a constant relative humidity of 70%.

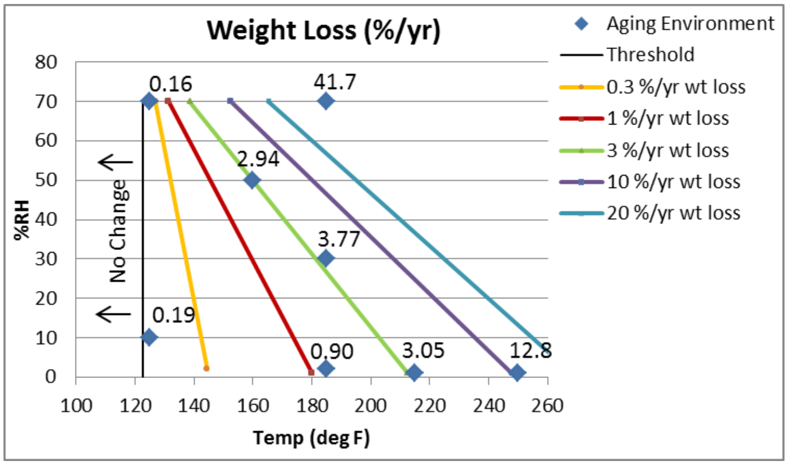


5. The two curve fits developed for the two relative humidity extremes are used to predict the temperatures at which specific rates of change will occur (e.g. a 1% rate of weight loss is predicted at 180.1 °F for low relative humidity, and at 131.4 °F for 70% RH).

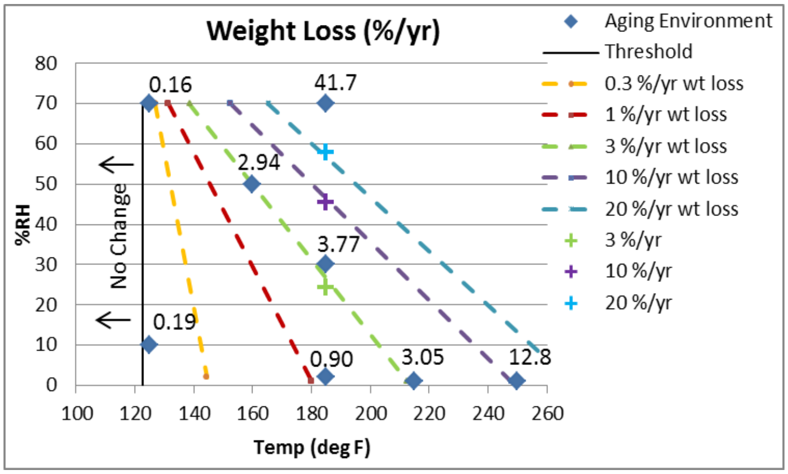
6. For the two temperatures identified in the above step, linear interpolation is used to identify combinations of intermediate temperature and relative humidity values that should provide the same rate of change. This provides lines of constant rate change that are plotted on a graph of relative humidity vs temperature.



7. The binomial curve fit for 70%RH environments can be extrapolated to a degradation rate of zero at 122.8 °F. It is assumed that there is also no degradation at this temperature with lower humidity values as well. Therefore, this temperature is taken as a threshold below which there is no degradation.



8. The validity of linear interpolation for intermediate relative humidity values is seen by considering the rates of change for 185 °F at the 3 relative humidity levels (~2%, 30% and 70%). An exponential curve is fit to the rates of change from these 3 environments, and that curve used to calculate the relative humidity for which specific rates of change are expected.



From this relationship, the relative humidity values that correspond to specific rates of change are calculated. These values are plotted on the graph of relative humidity vs temperature ("+" symbols), and show good agreement with the lines of constant rate change.

9. For a given temperature / relative humidity combination within the envelope provided by the data, the contour lines on the graph provide an estimate of the rate of change for fiberboard weight.

The aging models are shown graphically in Figures 13 – 18 for weight, height, length/width, density and thermal conductivity (axial and radial orientations). Each of these models was developed through the same process described above for weight.

A further check on the model predictions for weight comes from the thermal conductivity samples. The weight of these samples was measured periodically, but was not used in developing the physical property models. They therefore present a set of independent data for comparison. Trends for the change in weight of thermal conductivity samples are shown in Figure 19 and Table 7.

A different approach was taken in modeling the change in energy absorption, as measured by the area under the compression test stress-strain curve up to 40% strain. This different approach was necessary for several reasons, including:

- There is significant scatter in the data from sample to sample, and from one material package source to another (Tables 3 and 4).
- Since compression testing is destructive, each datum represents a different sample.
- For those samples that were tested after aging, their comparable baseline (unaged) condition is unknown, although tests on other unaged samples from the same source package provide an estimate of that condition. Due to sample-to-sample scatter, data cannot reliably be normalized to an initial value.

Finite element analysis has been performed to demonstrate that the 9975 package in KAC will survive a forklift impact scenario even if the nominal fiberboard compression strength is reduced by 80% [12]. The main contribution of the fiberboard to this scenario is energy absorption, which is proportional to the area under the compression test stress-strain curve. The Reference 12 calculation uses a fiberboard stress-strain curve for sample “16pkg”, reported in Reference 13. This sample was conditioned at ambient temperature and 40% RH prior to testing in the perpendicular orientation. As such, it represents a typical undegraded fiberboard condition. Using the data from this sample, the area under the engineering stress-strain curve up to a strain of 40% is 55 psi. Reducing this value by 80% produces 11 psi, which is used as the minimum acceptance value for fiberboard mechanical properties.

The forklift impact scenario primarily loads a local region of the fiberboard from the side (in a parallel orientation). Within a 9975 package, the drum and shield provide a degree of constraint to limit the motion of fiberboard under load. This constraint allows the load to re-distribute throughout a much larger fiberboard volume. During compression testing, no constraint is applied to the samples, and parallel orientation samples tend to spread out significantly with less energy absorbed. Therefore, these samples conservatively under-estimate the energy absorption capacity. A more realistic behavior is seen from perpendicular samples, which tend to be self-constrained due to the orientation of the glue layers. As a result, the perpendicular samples provide a more realistic estimate of energy absorption applicable to the accident scenario. Model development will consider two approaches, which provide different degrees of conservatism. The more conservative approach is based solely on degradation rates of parallel orientation samples. The second approach uses degradation rates that are an average of the two orientations. The degradation rates (times to reach the failure criterion) for all source packages and orientations are summarized in Table 8.

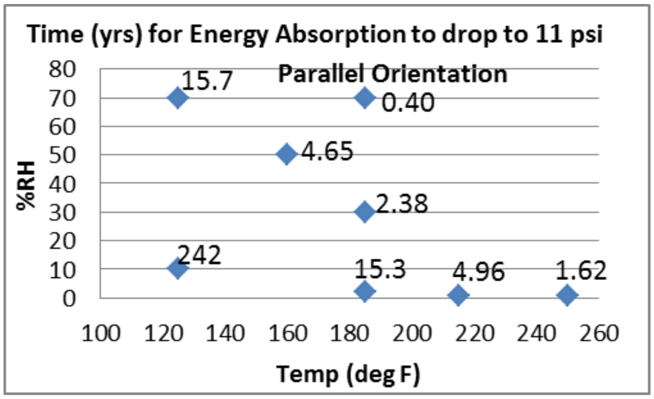
Decreases over time in the area under the stress-strain curve up to 40% strain are significantly non-linear for the more severe environments. It was observed that an exponential equation provides a good fit to the data for all environments, including the milder environments in which the limited degradation could also be approximated by a linear relationship. Therefore, an exponential fit was adopted to provide a parameter for modeling purposes. This fit takes the form

Area under Curve = a * exp(-b*time)

In this equation, the exponential factor “b” describes the rate of decrease of the area under the stress-strain curve. The exponential fit is applied separately to data from each source package in each environment and the time for the energy absorption of each source package in that environment to decrease to 11 psi is averaged as noted in Table 8.

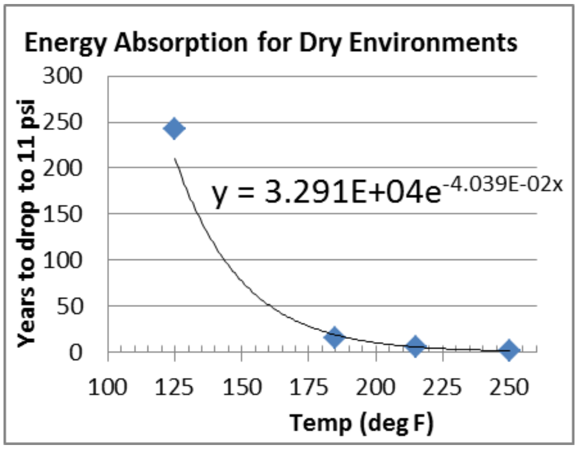
With these average “failure” times for each environment, the following approach was used to develop a model to describe the energy absorption behavior for any environment of interest. This model is developed first with the parallel orientation data (i.e. the more conservative approach).

1. The initial data are characterized in terms of the minimum time (years) for the area under the stress-strain curve to a strain of 40% to decrease to 11 psi.



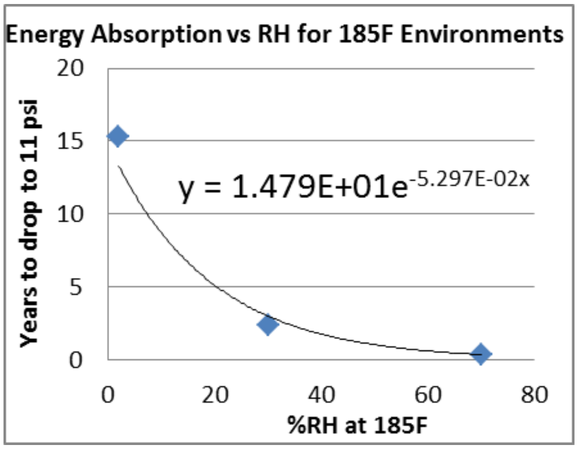
2. Fit an exponential curve to low humidity environments (125, 185, 215 and 250 °F), and extrapolate to additional temperatures of interest.

Prediction for 219.6 °F (dry) = 4.6 yrs
Prediction for 190.5 °F (dry) = 15 yrs
Prediction for 183.3 °F (dry) = 20 yrs



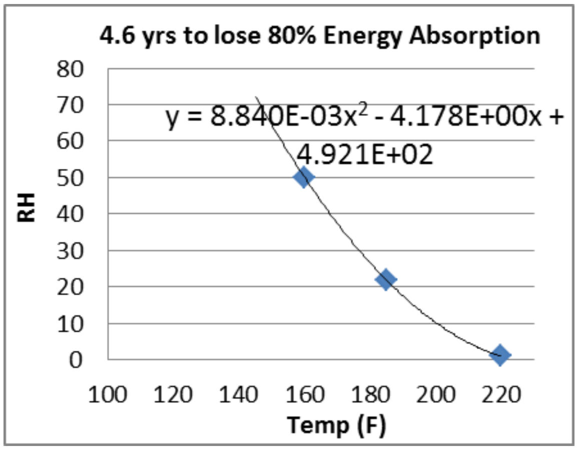
3. Fit an exponential curve to 185 °F environments (dry, 30 and 70 %RH), and interpolate to additional humidity values of interest.

Prediction for 41.9 %RH = 1.6 yrs
Prediction for 21.8 %RH = 4.6 yrs



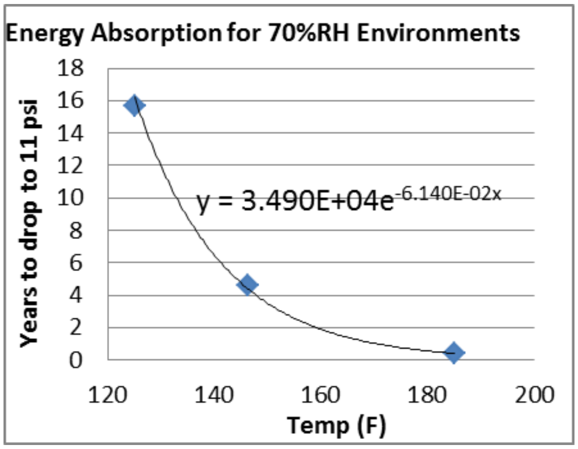
4. There are now 3 environments with an estimated decrease in energy absorption to 11 psi in 4.6 yrs – 219.6 °F dry, 160 °F 50 %RH, and 185 °F 21.8 %RH. Fit a binomial curve to these data to describe all environments which will produce a similar drop in energy absorption in 4.6 yrs.

Prediction for 4.6 yrs = 146.3 °F 70 %RH

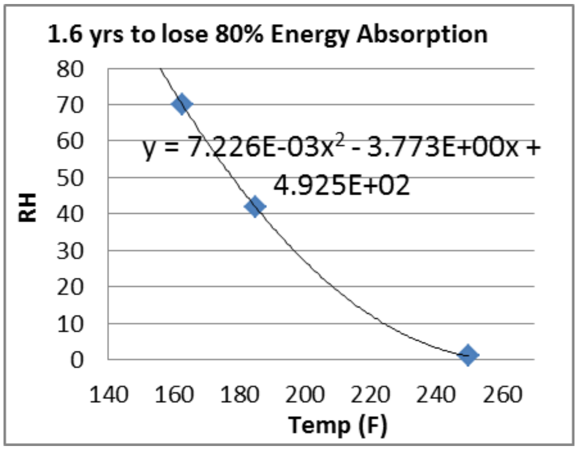


5. There are now 3 temperatures with estimated time for energy absorption to decrease to 11 psi at 70 %RH – 125 °F, 146.3 °F and 185 °F. Fit an exponential curve to these data, and interpolate to additional temperatures of interest.

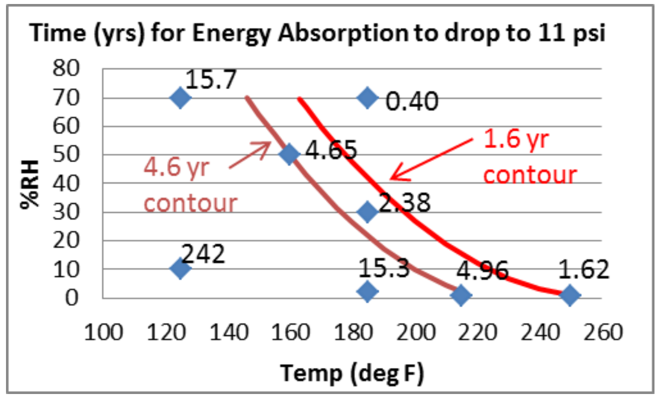
Prediction for 162.7 °F 70 %RH = 1.6 yrs



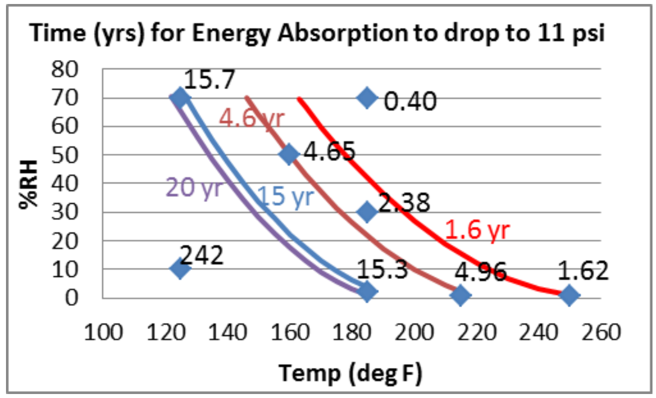
6. There are now 3 environments with energy absorption decrease to 11 psi in 1.6 yrs – 250 °F dry, 185 °F 41.9 %RH, and 162.7 °F 70 %RH. Fit a binomial curve to these environments to describe all environments which will produce a similar drop in energy absorption in 1.6 yrs.



7. The two binomial curve fits developed in steps 4 and 6 provide contour lines describing environments which lead to energy absorption decrease to 11 psi in periods of 1.6 yrs and 4.6 yrs.



8. The two contours in step 7 show essentially the same shape. It is assumed that contour lines for additional durations will also follow the same shape. This curve shape can be combined with specific predictions for dry environments (step 2) and 70%RH environments (step 5) to develop additional contours.



9. No degradation is indicated in the models for other properties below temperatures of ~120 – 125 °F, and it is expected that any degradation that impacts one property will also impact other properties. Therefore, a threshold is assumed to occur at ~120 °F for energy absorption degradation. The complete energy absorption model is shown in Figure 20.

In the second approach to modelling the energy absorption data, it is recognized that the parallel orientation data are overly conservative because the tests did not incorporate any lateral restraint. The self-restraint provided by the perpendicular orientation tests is much closer to representing the degree of constraint provided by the drum during an accident scenario. However, in order to retain some conservatism, an average of the parallel and perpendicular orientation energy absorption values will be used. The times for energy absorption to decrease to 11 psi in each environment under this second approach are shown in Figure 21, along with the contour curves from the first approach. In comparing the two approaches, the projected service life in the milder environments (areas for which a life of ~15 years or more are indicated) is approximately doubled in the second approach. In the more extreme environments, this benefit decreases. Since neither approach incorporates possible package-to-package variation, it is recommended that the more conservative first approach be used at the present time.

The limiting need for fiberboard compressive strength is the postulated forklift impact event in KAC. In this scenario, an impact of the forklift tine near the elevation of the containment vessel closure can compromise the containment vessel leak-tight seal without sufficient energy absorption by the fiberboard. As a significant moisture gradient develops in the fiberboard, some of the moisture migrates toward the bottom of the package, with the result that the fiberboard near the seal elevation is relatively drier and stronger, even along the OD surface.

The property limits are developed as bulk average properties. It is judged that even if local surface regions were to degrade at a significant rate, the overall average rate of change in the bulk fiberboard property may still be low. This judgement is supported by observation of packages removed from service after up to 7 years storage in KAC. Examination of these packages has shown a range of fiberboard properties (density, thermal conductivity, specific heat capacity and compression strength) consistent with that of un-aged fiberboard, with no discernable change in the fiberboard surfaces compared to the rest of the assembly. Measured values of density and thermal conductivity from these packages are summarized in Table 9, and might be used to approximate typical beginning-of-life values.

Additional data continue to be collected for each property, following successive conditioning intervals. In time, the models will be re-visited based on the additional data, and revised service life predictions can be developed. Note, however, that since the compression tests are destructive, most of the available samples being aged have been tested, and relatively little additional compression test data will become available in the future.

Conclusions and Recommendations

Thermal, mechanical and physical property data for cane fiberboard samples have been summarized following aging in several environments (elevated temperature and/or humidity) for periods up to ~10 years. Most of the aging environments are bounding to the conditions expected within the 9975 shipping package during storage in KAC. Models have been developed from these data to provide estimates of degradation rate under potential storage conditions for several fiberboard properties, including thermal conductivity, energy absorption, weight, dimensions and density. Development of the predictive models considers the effect of temperature, humidity, time and material source.

Additional data continue to be collected to permit future refinements to the models and assumptions.

The prediction of service life for packages stored in KAC would utilize the degradation rate models developed within this report, along with specific allowable ranges on each property under consideration. For potential storage environments, package service life is dependent on the most limiting service life estimate based on each of the relevant fiberboard properties, recognizing that some properties are inter-related, and all properties are degrading simultaneously. This process is continuing as a joint effort between SRNL and NMM.

Some of the degradation rates and model predictions presented in this report are extreme and may not represent the behavior of the typical package in KAC. The internal heat load and temperature profiles within many packages in storage are such as to produce milder conditions in storage than in any of the aging environments. Many conforming packages with lower internal heat loads are expected to experience no degradation, and should provide a service life beyond the currently approved 15 year storage period. Nevertheless, the possibility of accelerated degradation to a limited number of packages, whether from high heat load, elevated moisture levels, or other conditions, should be recognized. These packages could experience higher degradation rates and may not perform their required safety functions beyond 15 years.

The assumptions and inputs behind the predictions in this report should be well understood before attempting to identify an actual service life in KAC. Improvement in understanding the impact of these models might be realized with a change in the way humidity data are collected during field surveillances. If the humidity was measured through a caplug hole before the package is removed from its storage location, the package would remain at thermal equilibrium, and the data should better represent actual storage conditions.

A limited number of 9975 packages have been found with non-conforming conditions (e.g. moldy fiberboard). The analysis and predictions of this report should not be applied to these packages. Additional efforts would be needed to address the integrity of the fiberboard in such packages.

References

[1] WSRC-SA-2002-00005, “K Area Complex Documented Safety Analysis”, Rev. 10, June 2014

[2] SRNL-STI-2015-00441, “Temperature Environment for 9975 Packages Stored in KAC”, W. L. Daugherty, September 2015

[3] WSRC-TR-2003-00325, Rev. 4, “Task Technical and Quality Assurance Plan for Characterization and Surveillance of Model 9975 Package O-Rings and Celotex® Materials”, K. A. Dunn, January 2009

[4] SRNL-STI-2013-00020, “Status Report – Cane Fiberboard Properties and Degradation Rates for Storage of the 9975 Shipping Package in KAMS”, W. L. Daugherty, January 2013

[5] M-CLC-K-00727, Rev. 0, “Thermal Model Study for the 9975 Package in KAMS during Facility Fire”, N. K. Gupta and D. Tamburello, June 11, 2008

[6] SRNL-STI-2013-00689, “Model 9975 Life Extension Package 3 – Interim Report”, W. L. Daugherty, December 2013

[7] SRNL-STI-2015-00324, “Fiberboard Humidity Data for 9975 Shipping Packages”, W. L. Daugherty, July 2015

[8] DOE/USDA-21697/1, ORNL/Sub/87-21697/1, “Thermal Properties of Wood and Wood Panel Products for Use in Buildings”, A. TenWolde, J. D. McNatt and L. Krahn, September 1988

[9] FPL Report #2136, “Theories of the Combustion of Wood and Its Control a Survey of the Literature”, F. L. Browne, Forest Products Laboratory, USDA

[10] SRNL-STI-2009-00742, “Examination of Shipping Packages 9975-01818, 9975-01903 and 9975-02287”, W. L. Daugherty, November 2009

[11] SRNL-STI-2009-00240, “Examination of Fiberboard from Shipping Package 9975-01819”, W. L. Daugherty, April 2009

[12] M-CLC-K-00657, Rev. 1 Addendum, “Structural Analysis of 9975 Package Subjected to Two Forklift Truck Impact”, T. Wu, December 16, 2005

[13] WSRC-TR-2004-00523, “Baseline Mechanical Property Data for Model 9975 Package Celotex® Material”, W. L. Daugherty, December 2004

Table 1. Summary of maximum sample exposure times prior to testing, for data through August 2015.

	Maximum exposure time (weeks) through August 2015			
Environment	Thermal Conductivity	Specific Heat Capacity	Compression Strength	Physical Properties
250 ºF oven	255 [1]	258	193	275 [1]
215 ºF oven	456	—	383	486
185 ºF oven	512	486	442	495
185 ºF 30% RH	338	318	282	350
185 ºF 70% RH	22	22	61	67
160 ºF 50% RH	243	143	179	261
125 ºF oven	483	463	444 [2]	463
125 ºF 70% RH	217	17	114	225
77 ºF 70% RH	—	—	8	—
50 ºF refrigerator	—	—	—	288
15 ºF freezer	—	—	—	288
Other environments			[3]	

[1] Due to a thermal gradient in the 250 ºF oven, the temperature of the thermal conductivity samples ranged from ~242 – 279 ºF during the first 56 weeks, and the temperature of the physical property samples was ~236 ºF during the first 26 weeks.

[2] Some of these samples were tested after aging in a 125 ºF oven for the stated period, but also include additional aging time at 125 ºF 70 %RH. No significant degradation has been observed from the aging periods at 125 ºF 70 %RH.

[3] Additional aging environments, for compression testing only, include 2 weeks exposure in the following environments: 195 ºF oven, 195 ºF 40% RH, 195 ºF 100% RH, 125 ºF 40% RH, 125 ºF 100% RH, 77 ºF 40% RH, and 77 ºF 100% RH.

Table 2. Buckling strength for compression test samples tested in the parallel orientation

Environ-	ment (wks)	Buckling Strength (psi) for LD1	LD2	MSC	New
Ambient	**0**	228	185	164	393
		200	171	242	410
		192	189	180	357
			152		288
125F Dry	**2**	242	152	246	
			173	248	
	4	289	158	264	
	6	223**	151**		
	7		208	234	
	8	202	189	270	
	12	255**	196**		
	16	258	206	279	
			172		
	32		160	257	
				262**	
	64	228**	183	193	
			191**	259**	
				234**	
	111	204**	176**		
	133			217**	
	422	240	162		
	444			311	
125F 70%	**0.28**	160			
	2	173	136	184	
	4	178	136	186	
	6	165*	79*		
		183	136	170	197
	8	146*	146*		
	10	185*	120*		
	16	175	102		197
	32				217
	33	160	124		
	64	156	114		214
	114				208
160F 50%	**0.28**				256
	2	243	126	203	
		218		220	
	4	181			
		257			
	8	184	113	201	245
		216		231	
	16				275
	32				260
	33	181	137		
	64				189
	105				201
	146				189
185F dry	**0.28**				327
	2	196	170	187	308
	4	240	196	148	
	8	212	155	196	
	16	206	89		
	32	227	80	222	346
					348
185F dry (cont.)	**64**	269	184	217	
	96	168	148	231	
	139	206	123	203	
	179	209		206	
	211			204	
185F 30%	**2**	200		214	283
	8	269		226	314
	16	284		226	294
	32	229		201	290
	75	100		109	224
	98	98		114	212
185F 70%	**0.28**				213
	2	187	123	182	
		184*	146*		
	4	150	53	159	199
	6	113*	110*		
	8	124	112	130	206
	12	142	93		
	16				157
	20	64			
	23			32*	
	29	62	54	40	
	31				60
	52				14
	61			3	
215F dry	**2**	222	147	223	
		306		207	
	8	296	115	200	
	16	209	153	201	
		255		206	
	32	199	152	185	
	64	146	111	147	
		219			
	96	194	116	130	
	148	157		109	
	200	146		98	
250F dry	**2**	214	212	288	
		187			
	4	173			
	7			222	
	8	125	132		255
					257
	16	109	121		
	32		95	94	135
	47			58	
	51				165
	64		71	49	
	96	74			
	134		24	29	
	153	44			
	193		12	33	

* Samples tested after aging at 70 %RH for stated period, but also include additional time at the same temperature in a dry oven.
** Samples tested after aging in a dry oven, but aging time includes additional time at 125 ºF 70 %RH.

Table 3. Area under stress-strain curve to 40% strain for compression test samples, parallel orientation

Environ- ment (wks)		Area under Curve (psi) for			
		LD1	LD2	MSC	New
Ambient	**0**	35.9	42.4	45.8	69.8
		58.4	47.6	60.0	78.2
		46.0	49.0	41.9	77.9
			37.8		59.5
125F	**2**	46.2	37.8	41.0	
Dry			42.7	47.2	
	4	55.8	46.0	56.8	
	6	51.2**	30.5**		
	7		43.5	37.4	
	8	35.9	44.9	58.3	
	12	45.0**	45.1**		
	16	40.4	41.6	40.4	
			36.3		
	32		41.8	34.8	
				45.7**	
	64	39.5**	48.6	51.6	
			41.3**	59.0**	
				40.4**	
	111	38.0**	41.1**		
	133			44.4**	
	422	44.2	41.3		
	444			47.0	
125F	**0.28**	34.3			
70%	**2**	43.8	28.3	41.7	
	4	37.3	37.1	43.6	
	6	34.4*	25.6*		
	8	37.3	37.2	38.0	44.3
		50.3*	36.2*		
	10	33.4*	34.5*		
	16	45.3	25.5		46.7
	32				56.2
	33	36.0	30.4		
	64	36.5	25.2		48.0
	114				50.3
160F	**0.28**				65.1
		57.1	31.8	36.5	
50%	**2**	52.4		41.0	
	4	33.4			
		50.6			
	8	56.5	36.5	46.6	55.1
		51.9		62.6	
	16				52.4
	32				50.8
	33	35.2	32.5		
	64	24.9	26.7		38.1
	105				27.5
	146				28.0
185F	**0.28**				53.5
dry	**2**	35.3	34.9	33.2	47.0
	4	31.1	45.9	24.8	
	8	38.0	36.6	37.4	
	16	45.7	25.1		
	32	31.2	19.0	45.8	67.3
					65.3
	64	24.3	36.2	46.2	
185F	**96**	29.5	29.1	38.6	
dry	**139**	33.0	29.8	38.2	
(cont.)	**179**	22.8		32.5	
	211			32.5	
185F	**2**	50.4		48.5	68.8
30%	**8**	27.3		39.8	67.1
	16	24.8		32.1	51.4
	32	27.6		43.1	41.8
	75	16.7		14.8	28.3
	98	10.5		11.7	25.5
185F	**0.28**				49.7
		49.9	27.6	43.3	
70%	**2**	40.2*	29.8*		
	4	36.7	18.0	24.2	38.8
	6	21.4*	27.1*		
	8	18.1	24.8	25.3	28.8
	12	18.0	21.5		
	16				18.7
	20	6.6			
	23			6.0*	
	29	6.1	8.9	6.4	
	31				8.6
	52				1.6
	61			0.3	
215F	**2**	49.3	25.8	39.8	
dry		41.6		35.4	
	8	33.5	28.7	18.8	
	16	41.8	28.0	26.4	
		34.2		37.4	
	32	30.2	29.1	28.6	
	64	32.7	31.3	23.7	
		31.6			
	96	16.8	19.5	14.1	
	148	15.0		13.6	
	200	16.4		5.6	
250F	**2**	39.9		47.2	52.2
dry		50.7			
	4	27.3			
	7			41.0	
	8	11.2	19.9		40.0
					35.6
	16	11.3	17.8		
	32		15.9	15.8	20.6
	47			6.9	
	51				29.1
	64		11.0	9.2	
	96	9.0			
	134		3.4	6.3	
	153	6.6			
	193		1.8	5.0	

* Samples tested after aging at 70 %RH for stated period, but also include additional time at the same temperature in a dry oven.
** Samples tested after aging in a dry oven, but aging time includes additional time at 125 ºF 70 %RH.

Table 4. Area under stress-strain curve to 40% strain for compression test samples, perpendicular orientation

Environ-	ment (wks)	Area under Curve (psi) for LD1	LD2	MSC	New
Ambient	**0**	46.1	30.8	33.1	52.7
		36.8	29.7	29.4	51.7
			25.3	47.6	60.9
125F	**2**	57.5	25.2	53.9	
Dry	**6**	57.5**	34.8**		
	8	55.9			
		55.7			
	12	54.1**	34.5**		
	16	58.2			
		56.5			
				55.4	
	32			36.3**	
	48				
	53				
				40.0	
	64	49.2**	32.0**	56.6**	
	111	53.7**	39.5**		
	133			57.8**	
	385	71.3			
	422		36.7		
	444			53.8	
125F	**0.28**				38.4
70%	**2**	39.3	21.6	27.9	
	6	38.8*	23.1*		
	8	32.3			44.0
		36.3			
	10	33.4*	23.6*		
	16	34.9			36.4
	32				42.2
	64				41.5
160F	**2**	44.6	30.3	47.2	
50%		49.3		33.2	
	8	40.9			52.8
		35.9			
	16				59.3
	32				47.7
	64	39.2			55.6
	179	31.2		43.5	
185F	**2**	48.0	32.3	37.2	69.0
dry	**8**	55.5			
		53.6			
	16	47.1			
		42.9			
185F	**32**			40.1	
dry	**64**	57.3	32.6	45.8	
(cont.)	**96**	49.4	25.2	47.5	
	139	45.7	35.0	47.0	
	442			33.1	
185F	**2**	49.4		39.9	57.6
30%	**8**	48.0		49.7	53.0
	16	53.9		47.9	56.8
	32	42.9		28.2	56.3
	282	20.1			26.1
185F	**0.28**				42.7
		36.2	26.7	27.7	
70%	**2**	34.4*	26.5*		
	6	35.8*	23.5*		
	8	35.5			
		34.4			41.4
	16	18.5			33.0
	23			11.0*	
	24				16.9
	29	9.8	13.7	10.8	
	31				14.4
	33	2.4			
	43	1.0	1.2		
	52				3.2
	61			1.0	
215F	**2**	53.6	33.3	32.9	
dry	**16**	53.0	31.1	31.9	
	32	48.7	30.4	35.1	
	64	47.9	27.4	31.5	
		46.0			
	96	41.0	26.2	31.7	
	148	34.1		21.1	
	200	24.9		30.0	
	383	23.2			
250F	**0.28**				0.056.8
dry	**2**	0.048.8		0.052.2	0.065.0
		0.045.9			
	7			0.052.0	
	8	0.042.6			0.053.8
		0.044.5			
	16	0.026.5			
		0.021.7			
	32		0.023.5	0.020.5	0.039.8
	47			0.012.3	
	63				0.027.8
	64		0.0153.	0.016.0	
	96	0.015.8			
	178				0.010.1
	193	0.009.6	0.001.6	0.005.0	

* Samples tested after aging at 70 %RH for stated period, but also include additional time at the same temperature in a dry oven.
** Samples tested after aging in a dry oven, but aging time includes additional time at 125 ºF 70 %RH.

Table 5. Thermal conductivity data at 25 ºC mean temperature for each sample following initial period in the aging environment. Variation results primarily from moisture level and sample source package. The source package is identified within the sample ID, except for samples TCxx which are from MSC source packages.

Sample ID	Aging Time (wk)	Thermal Conductivity (W/m-K)	Sample ID	Aging Time (wk)	Thermal Conductivity (W/m-K)	Sample ID	Aging Time (wk)	Thermal Conductivity (W/m-K)
250 ºF oven, radial orientation			**215 ºF oven, radial orientation**			**185 ºF oven, radial orientation**		
TC2R	2	0.0900	00826R	8	0.0897	TC3R	2	0.0927
MSC-3R	2	0.0933	MSC-6R	8	0.0921	MSC-2R	2	0.0909
LD1-1R	6	0.0864	LD2-3R	8	0.0872	New-1R	8	0.1092
2234-R	6	0.0838	New-4R	8	0.1063	826U-1R	3	0.0868
New-3R	6	0.1015						
600U-2R	3	0.0863						
185 ºF 30 %RH, radial orientation			**185 ºF 70 %RH, radial orientation**			**160 ºF 50 %RH, radial orientation**		
2234-3R	8	0.0909	LD2-1R	2	0.0862	LD2-2R	4	0.0854
New-6R	8	0.1138	MSC-1R	2	0.0972	MSC-4R	4	0.0953
TC1R(B)	8	0.1044				2234-2R	11	0.0972
826U-2R	3	0.0888				New-5R	11	0.1144
125 ºF oven, radial orientation			**125 ºF 70 %RH, radial orientation**					
MSC-5R	2	0.0955	MSC-4R(B)	5	0.1002			
TC1R	6	0.0950						
LD1-1R	6	0.0909						
250 ºF oven, axial orientation			**215 ºF oven, axial orientation**			**185 ºF oven, axial orientation**		
TC2A	2	0.0560	00826A	8	0.0564	TC3A	2	0.0537
LD1-2A	2	0.0530	TC1A	8	0.0564	MSC-4A	2	0.0565
2234-2A	6	0.0540	LD2-3A	8	0.0557	New-1A	8	0.0595
New-3A	6	0.0575	New-4A	8	0.0585	826U-1A	3	0.0522
600U-2A	3	0.0503	600U-1A	3	0.0518			
185 ºF 30 %RH, axial orientation			**185 ºF 70 %RH, axial orientation**			**160 ºF 50 %RH, axial orientation**		
2234-3A	8	0.0572	MSC-2A	2	0.0602	LD1-1A	4	0.0608
New-6A	8	0.0624	MSC-3A	6	0.0582	2234-A	4	0.0589
MSC-1A(B)	8	0.0608				MSC-1A	11	0.0629
826U-2A	3	0.0545				New-5A	11	0.0633
125 ºF oven, axial orientation			**125 ºF 70 %RH, axial orientation**					
TC1A	6	0.0587	TC1A	2	0.0581			
MSC-1A	6	0.0591	MSC-1A	2	0.0590			
			2234-A(C)	5	0.0622			
			LD1-1A(C)	5	0.0629			

Table 6 Change in physical properties during initial transition to aging environment

	Approximate initial change in			
Environment	Weight	Density	Height	Length, Width
250 ºF, dry oven	8 – 10% decr	3 – 6% decr	2 - 3% decr	0 - 2% decr
215 ºF, dry oven	7 – 9% decr	3 – 6% decr	0.5 - 3% decr	0 - 2% decr
200 ºF, dry oven	7% decr	5% decr	2% decr	< 0.5% decr
185 ºF, dry oven	7 – 8% decr	4 – 5% decr	2 - 3% decr	< 1% (+ and -)
125 ºF, dry oven	5 – 6% decr	3 – 4% decr	1 - 2% decr	< 0.5% (+ and -)
50 ºF, dry (desiccated)	8% decr	3 – 4% decr	2 - 3% decr	< 1% decr
15 ºF, dry (desiccated)	6% decr	2- 3% decr	2% decr	< 0.5% decr
185 ºF, 70%RH	< 1% (+ and -)	2 – 6% decr	1 – 3% incr	< 1% (+ and -)
185 ºF, 30%RH	4 – 5% decr	2 – 3% decr	1 - 2% decr	< 0.5% decr
160 ºF, 50%RH	< 1% (+ and -)	3% decr – 2% incr	< 1% (+ and -)	< 0.5% decr – < 1% incr
125 ºF, 70%RH	2% incr	0.5% decr – 2% incr	0 – 3% incr	1% decr – 2% incr
50 ºF, ~10%RH	4% decr	2 – 3% decr	1 - 2% decr	< 0.5% (+ and -)
15 ºF, ~60%RH	< 1% incr	1% (+ and -)	1 - 2% decr	< 0.5% (+ and -)

Table 7. Comparison of weight changes for physical property and thermal conductivity samples (averaged over all samples in each environment) to model predictions

		Average Slope from Actual Data (%/yr)	
Environment	Model Prediction (%/yr)	Physical Prop. Samples data through 9-12	Thermal Conductivity Samples
125 °F dry (5%)	-0.15	-0.19	-0.14
185 °F dry (2%)	-1.2	-0.90	-0.90
215 °F dry (1%)	-3.3	-3.05	-2.82
250 °F dry (1%)	-10	-12.8	-12.3
125 °F 70%	-0.1	-1.06	-0.24
160 °F 50%	-3.0	-2.94	-2.75
185 °F 30%	-3.6	-3.77	-3.61
185 °F 70%	-42	-41.7	-21.6

Table 8. Estimated times to reach (fail) energy absorption acceptance criterion

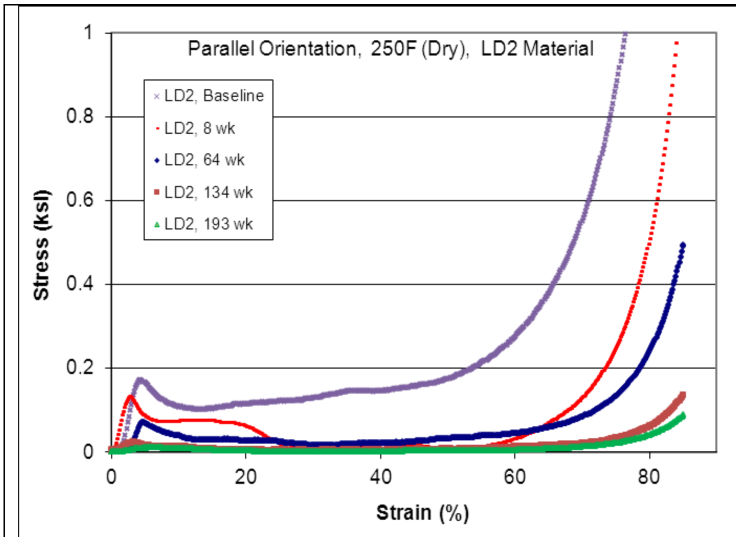
Environment	Source Package	Estimated Time to Fail (yrs)	Duration of Data used for Estimate	Source Package Time to Fail (yrs)	Basis for Source Pkg Time to Fail
Parallel Orientation					
125ºF dry	LD1	242 yrs	422 wks	242 yrs	Minimum value
	LD2	No failure	422 wks		
	MSC	No failure	444 wks		
	New				
125ºF 70 %RH	LD1	26.1 yrs	64 wks	15.7 yrs	Omit the no failure point, average 2 longer durations
	LD2	5.4 yrs	64 wks		
	MSC	1.5 yrs	8 wks		
	New	No failure	114 wks		
160ºF 50 %RH	LD1	2.6 yrs	64 wks	4.7 yrs	Average all 3 values
	LD2	5.9 yrs	64 wks		
	MSC	No failure	8 wks		
	New	5.4 yrs	146 wks		
185ºF dry	LD1	10.9 yrs	179 wks	15.3 yrs	Average 2 lower values (ignoring the MSC value gives a conservative result more in line with the other environments)
	LD2	19.7 yrs	139 wks		
	MSC	1102 yrs	211 wks		
	New	No failure	32		
185ºF 30 %RH	LD1	1.9 yrs	98 wks	2.4 yrs	Average all values
	LD2				
	MSC	2.0 yrs	98 wks		
	New	3.3 yrs	98 wks		
185ºF 70 %RH	LD1	0.35 yrs	29 wks	0.40 yrs	Average all values
	LD2	0.48 yrs	29 wks		
	MSC	0.35 yrs	61 wks		
	New	0.44 yrs	52 wks		
215ºF dry	LD1	4.5 yrs	200 wks	5.0 yrs	Average all values
	LD2	7.7 yrs	96 wks		
	MSC	2.7 yrs	200 wks		
	New				
250ºF dry	LD1	1.7 yrs	153 wks	1.6 yrs	Average all values
	LD2	1.1 yrs	193 wks		
	MSC	1.6 yrs	193 wks		
	New	2.2 yrs	51 wks		

Table 8. (continued) Estimated times to reach (fail) energy absorption acceptance criterion

Environment	Source Package	Estimated Time to Fail (yrs)	Duration of Data used for Estimate	Source Package Time to Fail (yrs)	Basis for Source Pkg Time to Fail
Perpendicular Orientation					
125ºF dry	LD1	No failure	385 wks	No failure	Average behavior
	LD2	No failure	422 wks		
	MSC	No failure	444 wks		
	New				
125ºF 70 %RH	LD1	2.5 yrs	16 wks	No failure	Behavior of longest duration data
	LD2	No failure	10 wks		
	MSC				
	New	No failure	64 wks		
160ºF 50 %RH	LD1	14.6 yrs	179 wks	19.4 yrs	Average all values
	LD2				
	MSC				
	New	24.2 yrs	179 wks		
185ºF dry	LD1	104.6 yrs	139 wks	54.5 yrs	Shortest time to fail and longest duration of data is conservative
	LD2	1459 yrs	139 wks		
	MSC	54.5 yrs	442 wks		
	New				
185ºF 30 %RH	LD1	8.9 yrs	282 wks	10.2 yrs	Average values for 2 longest durations
	LD2				
	MSC	2.0 yrs	32 wks		
	New	11.3 yrs	282 wks		
185ºF 70 %RH	LD1	0.37 yrs	43 wks	0.44 yrs	Average all values
	LD2	0.35 yrs	43 wks		
	MSC	0.42 yrs	61 wks		
	New	0.62 yrs	52 wks		
215ºF dry	LD1	12.1 yrs	383 wks	12.2 yrs	Average all values
	LD2	8.4 yrs	96 wks		
	MSC	16.2 yrs	200 wks		
	New				
250ºF dry	LD1	2.6 yrs	153 wks	2.3 yrs	Average all values
	LD2	1.5 yrs	193 wks		
	MSC	2.1 yrs	193 wks		
	New	23.1 yrs	178 wks		

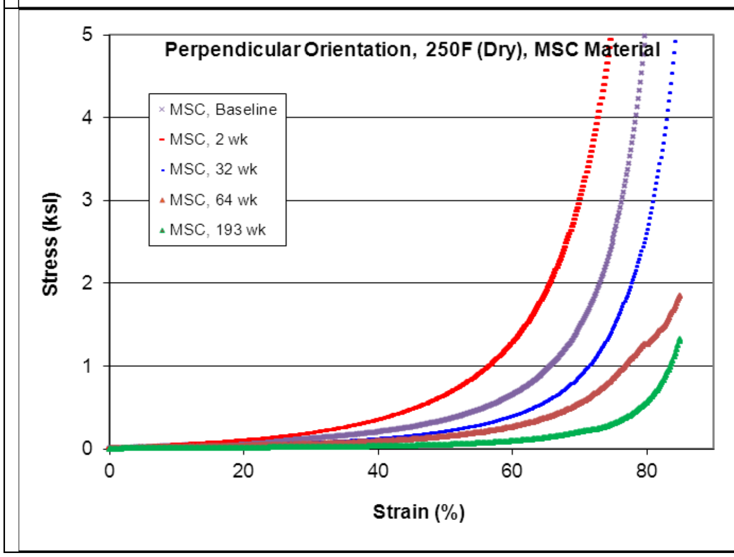
Table 9. Fiberboard property values from packages removed from storage in KAC for destructive examination. Variation in these values is driven by differences in package-to-package and sample-to-sample variation, as well as moisture levels.

Package ID (9975-)	Time in Storage	Density upper assembly (g/cc)	Density lower assembly (g/cc)	Axial thermal conductivity, (W/m-K)	Radial thermal conductivity, (W/m-K)
02234	1.7 yrs	0.269	0.281	0.0626	0.0948
00826	3.0 yrs	0.242	0.295	0.0614	0.0937
00600	5.0 yrs	0.248	0.293	0.0604, 0.0646	0.1060
05128	4.4 yrs	0.292	0.302	0.0642	0.1069
02028	4.9 yrs	0.272	0.286	0.0626	0.0979
02168	6.9 yrs	0.268	0.281	0.0628	0.1006
03431	3.9 yrs	0.290	0.296	0.0623	0.1040
Avg +/- 1 sigma		0.269 +/- 0.019	0.291 +/- 0.008	0.0626 +/- 0.0009	0.1006 +/- 0.0053



(a) LD2 material, parallel orientation

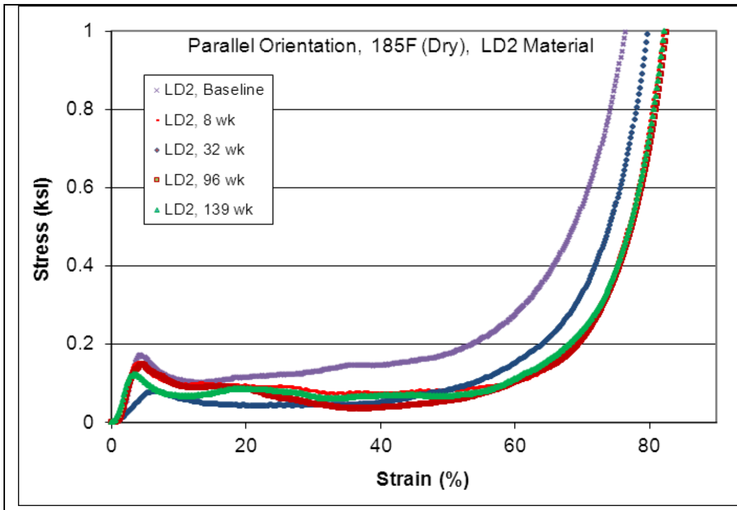
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.171	0.0476
8	0.132	0.0199
64	0.071	0.0110
134	0.024	0.0034
193	0.012	0.0018



(b) MSC material, perpendicular orientation

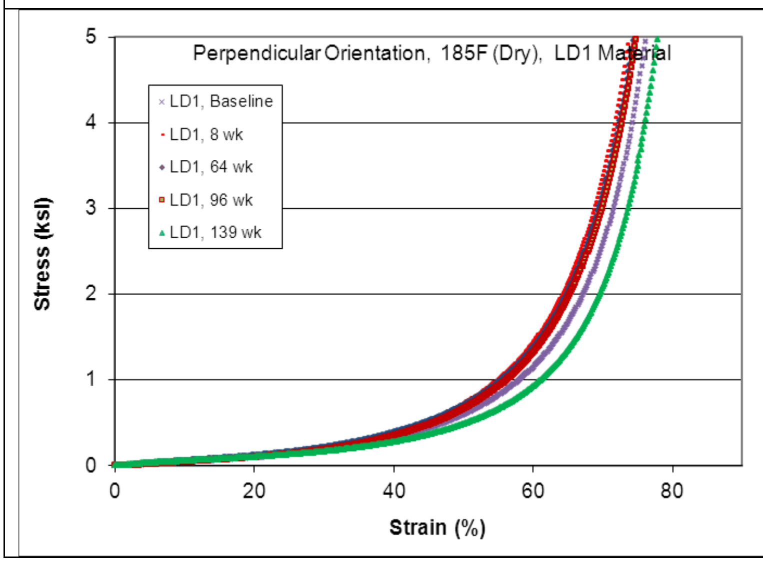
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0338
2	0.0522
32	0.0205
64	0.0160
193	0.0050

Figure 1. Engineering stress-strain compression curves for select fiberboard samples conditioned and tested at 250 ºF



(a) LD2 material, parallel orientation

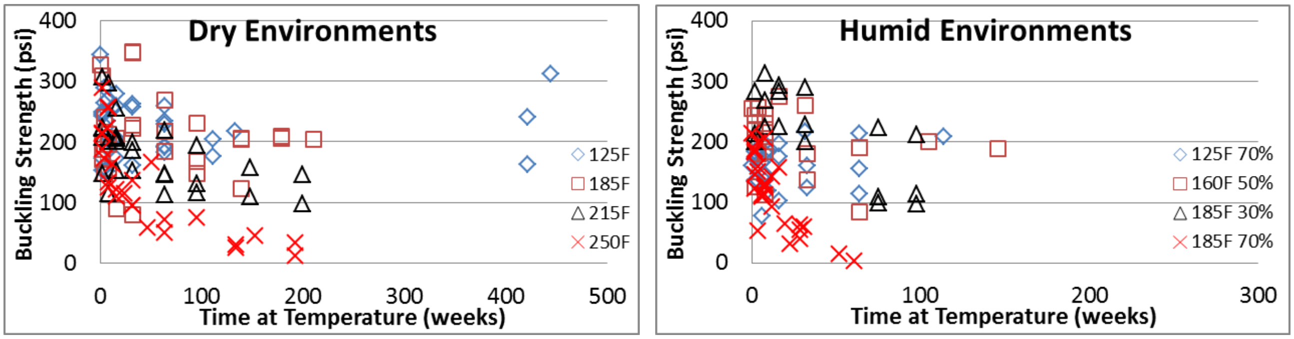
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.171	0.0476
8	0.155	0.0366
32	0.080	0.0190
96	0.148	0.0291
139	0.123	0.0298



(b) LD1 material, perpendicular orientation

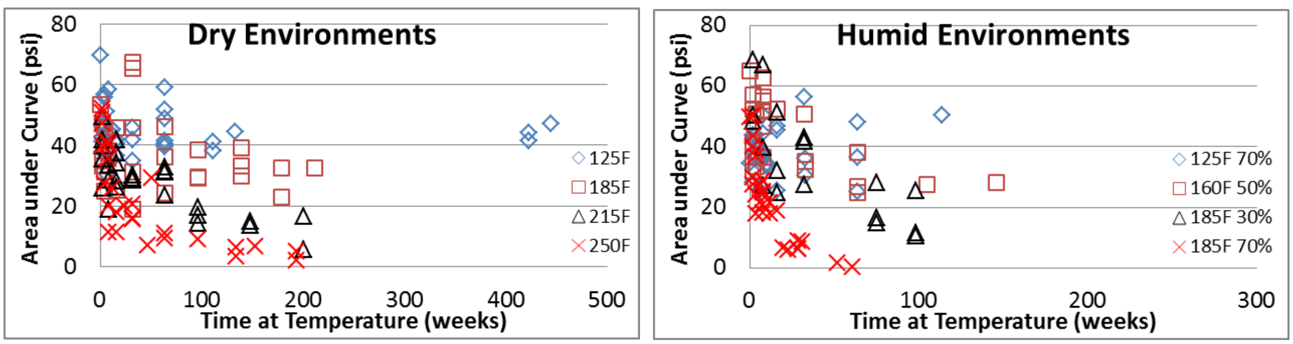
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0461
8	0.0555
64	0.0573
96	0.0494
139	0.0457

Figure 2. Engineering stress-strain compression curves for select fiberboard samples conditioned and tested at 185 ºF



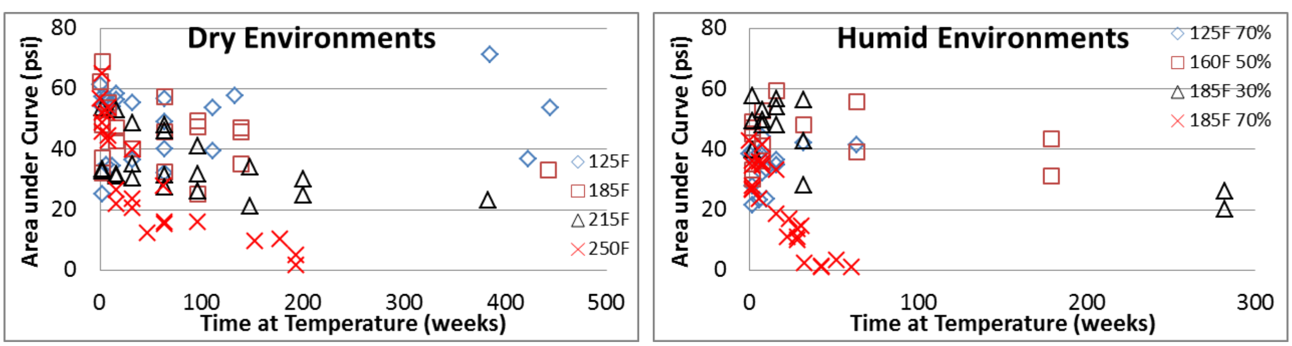
(a) (b)

Figure 3. Buckling strength (ksi) for all cane fiberboard compression samples, parallel orientation. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned in humid environments as noted.



(a) (b)

Figure 4. Area under the stress-strain curve up to 40% strain, for all parallel orientation cane fiberboard samples. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned in humid environments as noted.



(a) (b)

Figure 5. Area under the stress-strain curve up to 40% strain, for all perpendicular orientation cane fiberboard samples. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned in humid environments as noted.

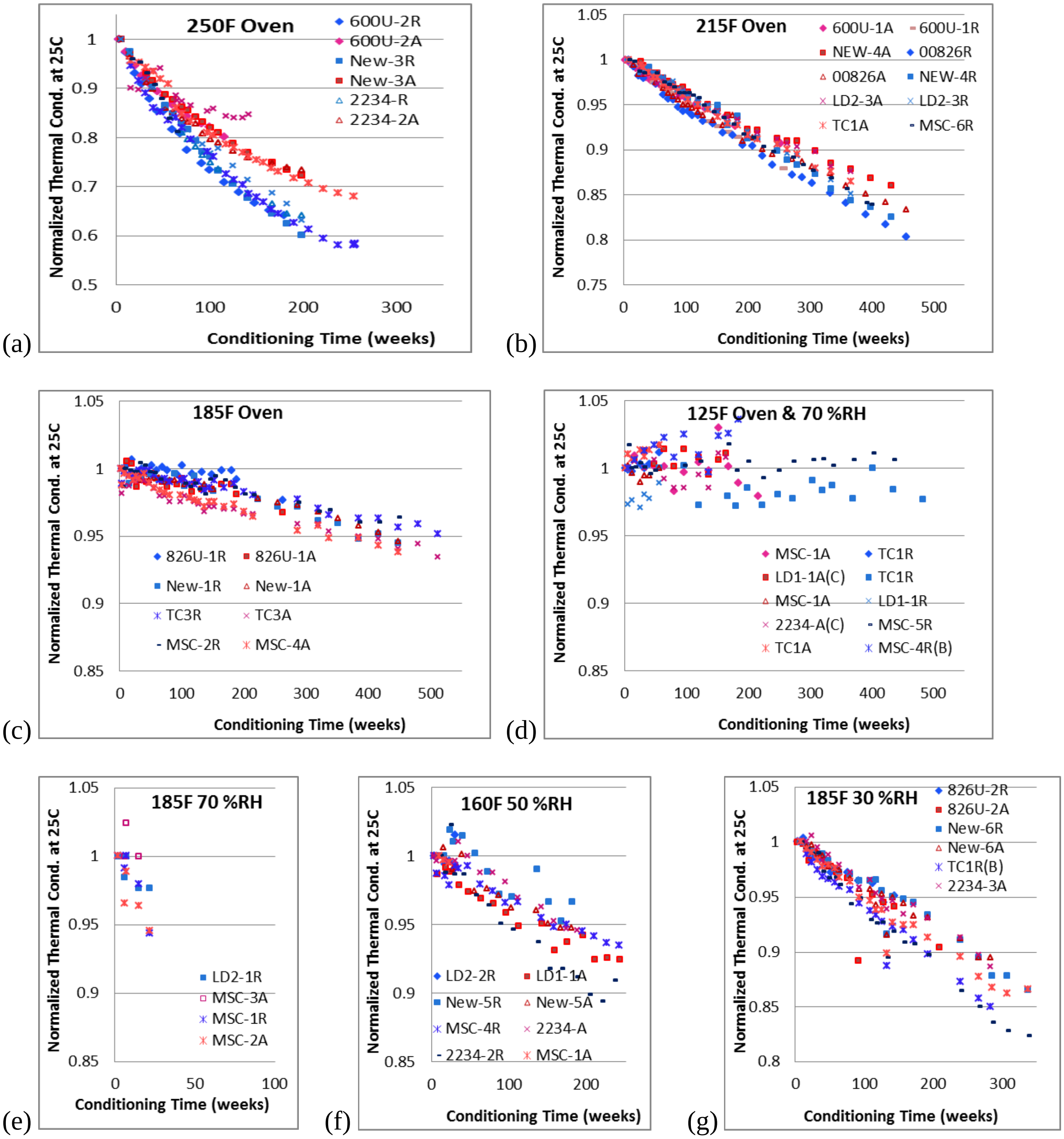


Figure 6. Thermal conductivity data measured at 25 ºC (77 ºF) mean temperature for each conditioning environment as noted. Data for each sample are normalized to the first conditioned value. The first conditioned value for each sample is identified in Table 5. Axial orientation samples are shown in red, and radial orientation samples are shown in blue.

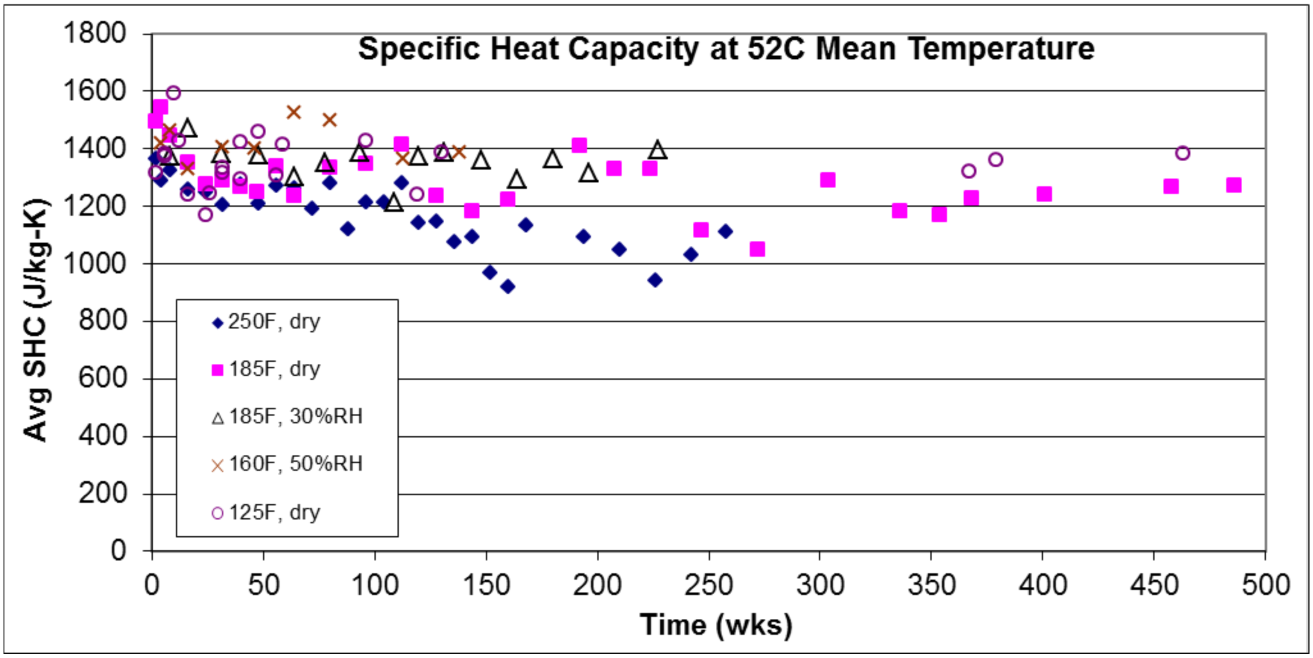
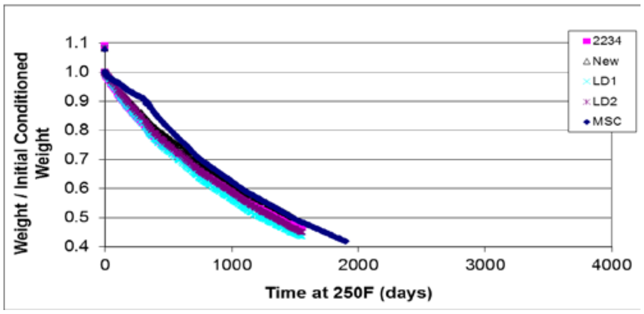
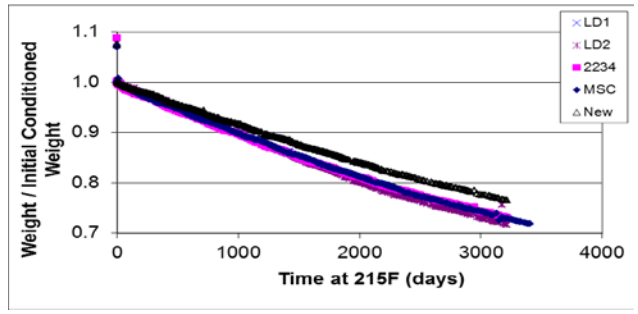


Figure 7. Specific heat capacity data at a mean temperature of 52 ºC (125 ºF) for each conditioning environment. A linear fit to the data for each environment produces the following trends:

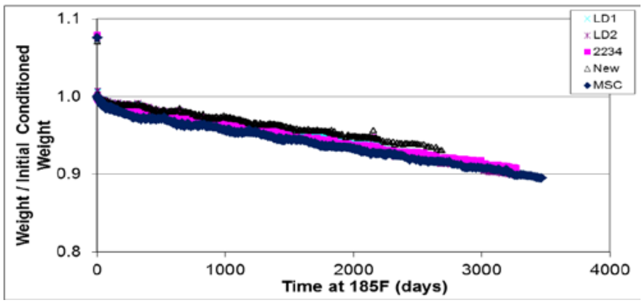
250 °F, dry	SHC (J/kg-K) = 1299.4 – 1.263 * time (weeks)
185 °F, dry	SHC (J/kg-K) = 1354.2 – 0.368 * time (weeks)
125 °F, dry	SHC (J/kg-K) = 1353.2 + 0.0053 * time (weeks)
185 °F, 30%RH	SHC (J/kg-K) = 1383.0 – 0.240 * time (weeks)
160 °F, 50%RH	SHC (J/kg-K) = 1419.9 – 0.035 * time (weeks)



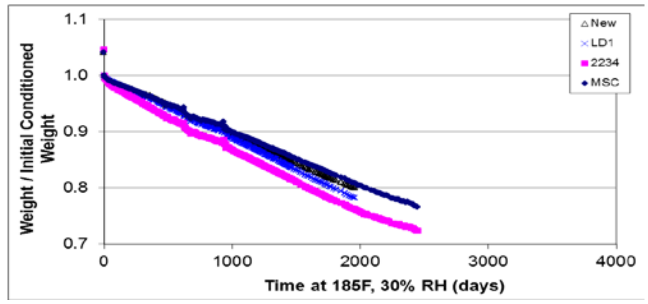
(a) 250 ºF, dry



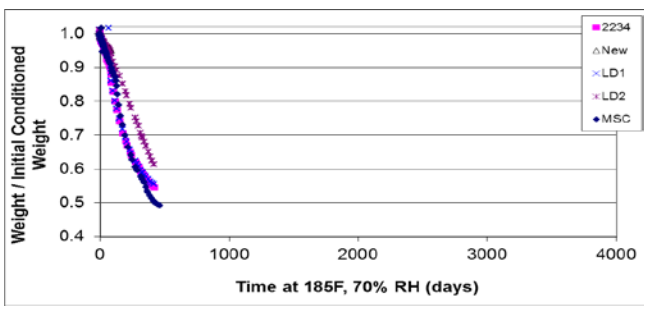
(b) 215 ºF, dry



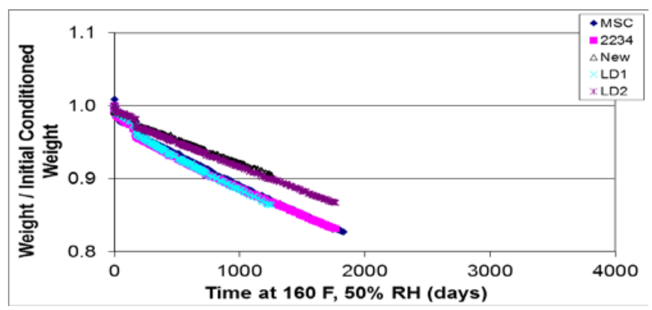
(c) 185 ºF, dry



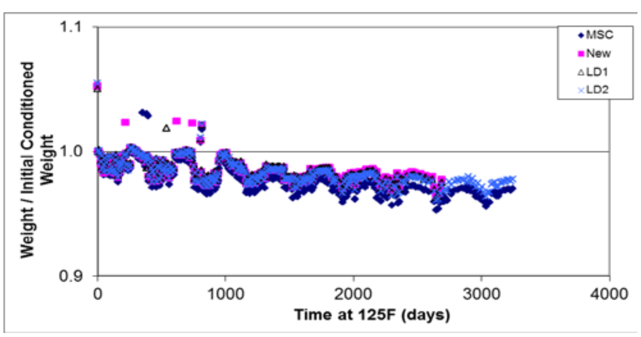
(e) 185 ºF, 30% RH



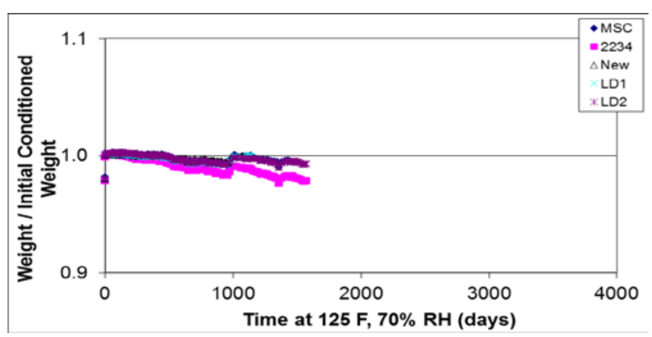
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

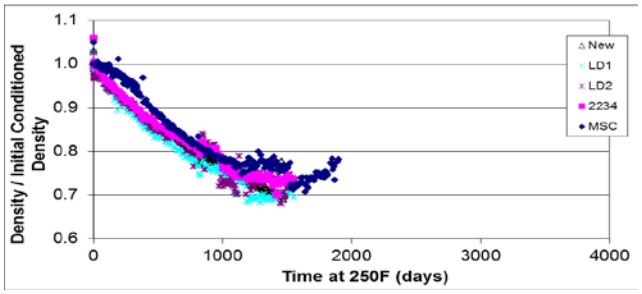


(g) 125 ºF, dry

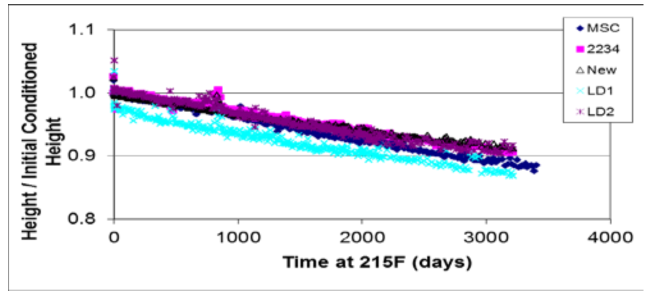


(h) 125 ºF, 70% RH

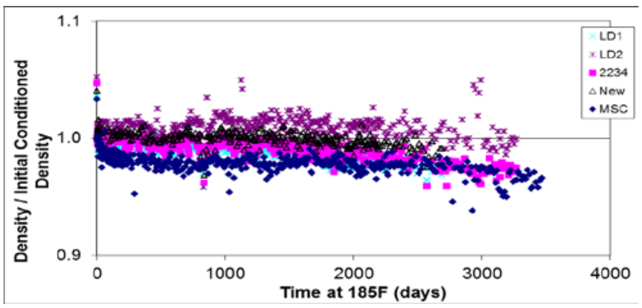
Figure 8. Weight data for physical property samples in the identified environments.



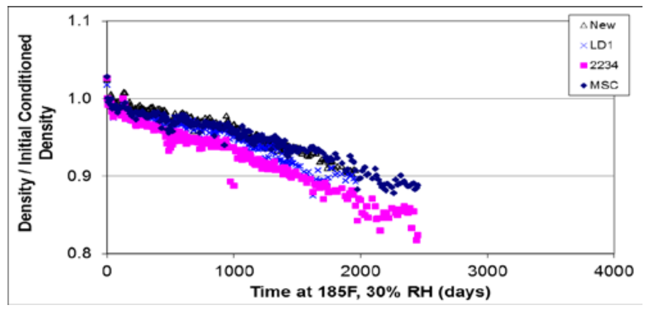
(a) 250 ºF, dry



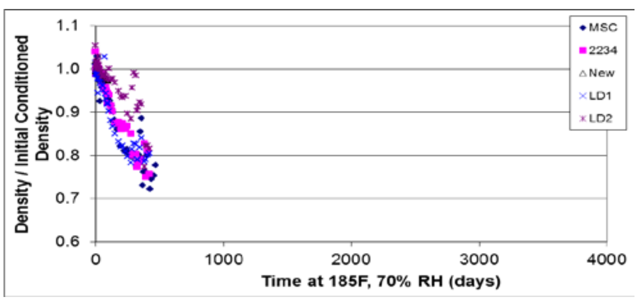
(b) 215 ºF, dry



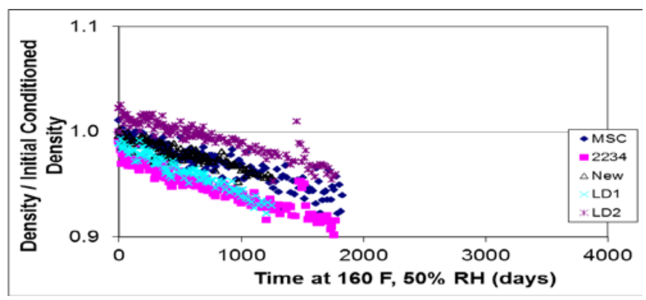
(c) 185 ºF, dry



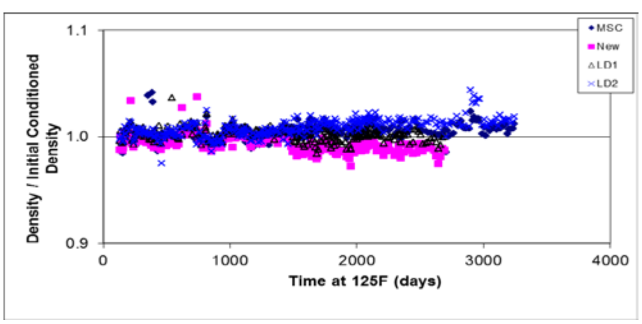
(e) 185 ºF, 30% RH



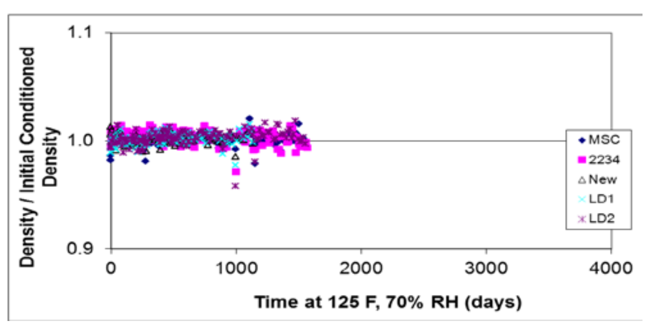
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

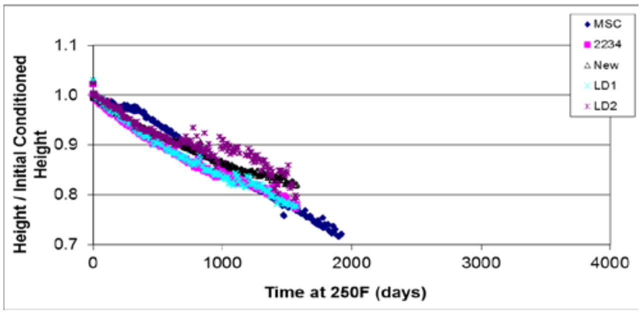


(g) 125 ºF, dry

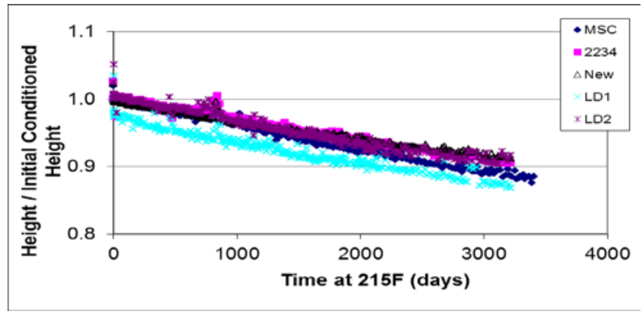


(h) 125 ºF, 70% RH

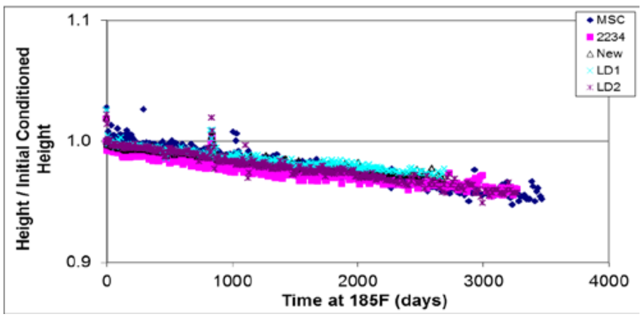
Figure 9. Density data for physical property samples in the identified environments



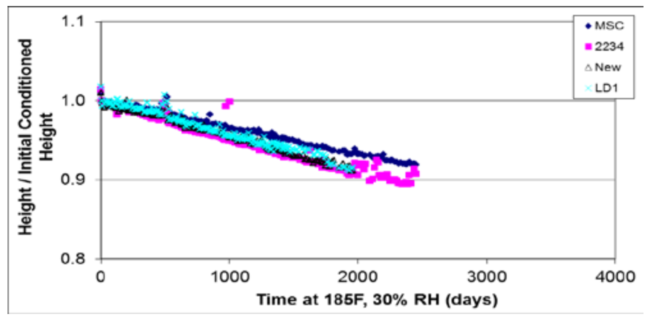
(a) 250 ºF, dry



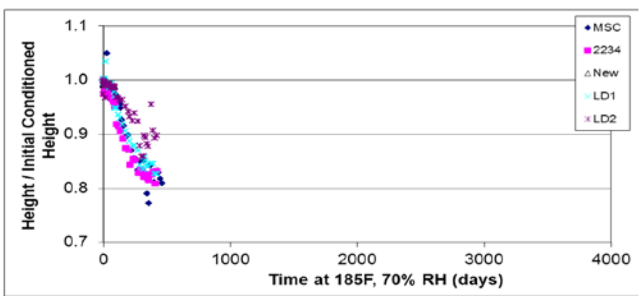
(b) 215 ºF, dry



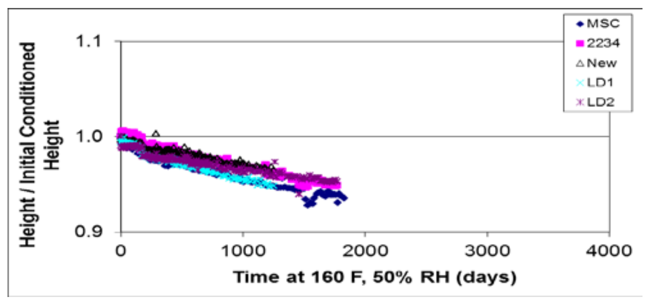
(c) 185 ºF, dry



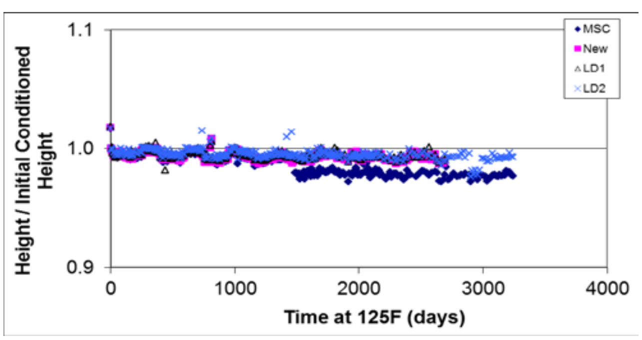
(e) 185 ºF, 30% RH



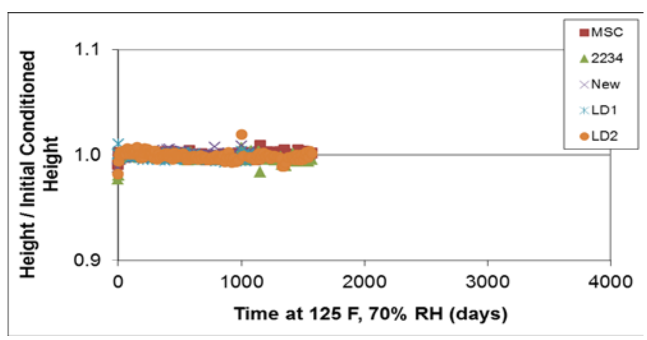
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

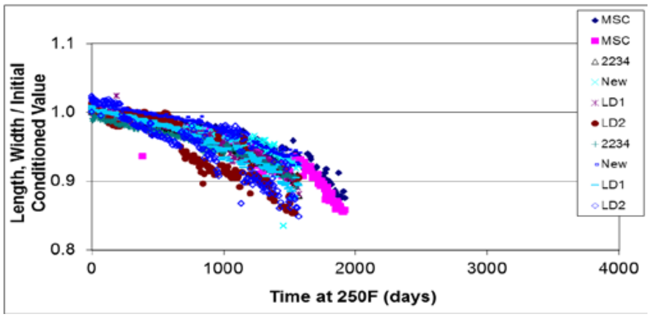


(g) 125 ºF, dry

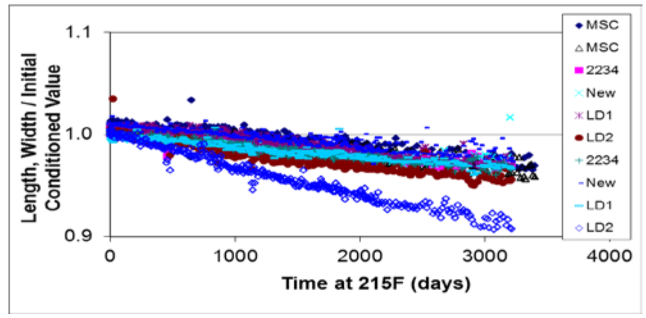


(h) 125 ºF, 70% RH

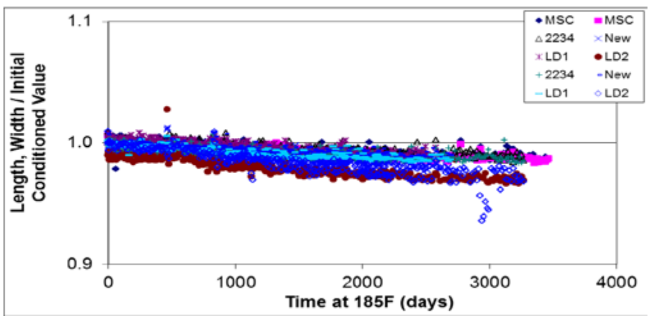
Figure 10. Height data for physical property samples in the identified environments



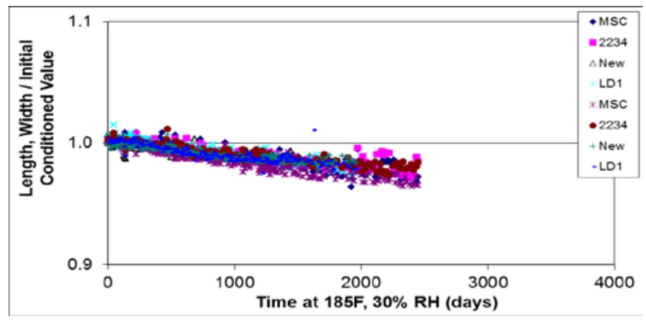
(a) 250 ºF, dry



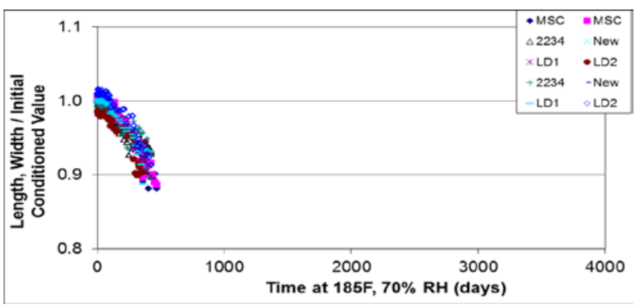
(b) 215 ºF, dry



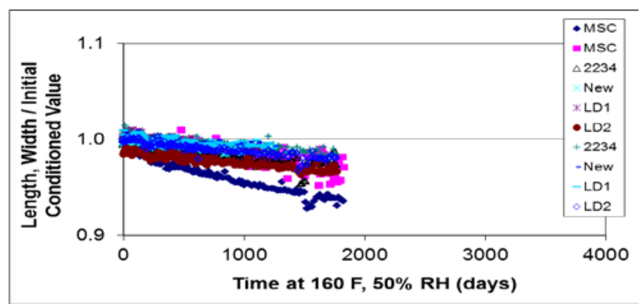
(c) 185 ºF, dry



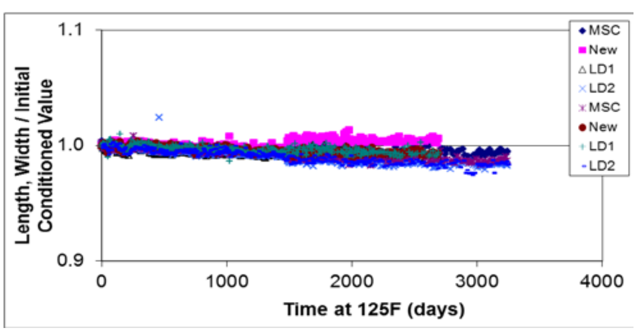
(e) 185 ºF, 30% RH



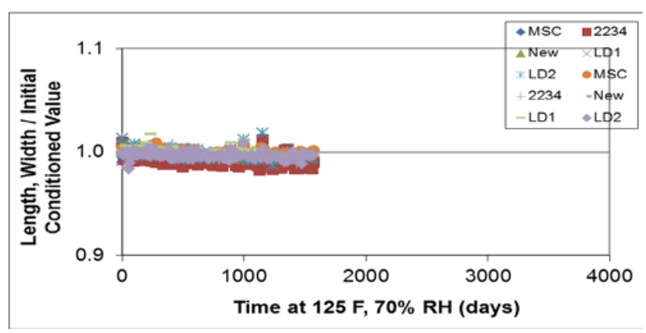
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH



(g) 125 ºF, dry



(h) 125 ºF, 70% RH

Figure 11. Length & width data for physical property samples in the identified environments

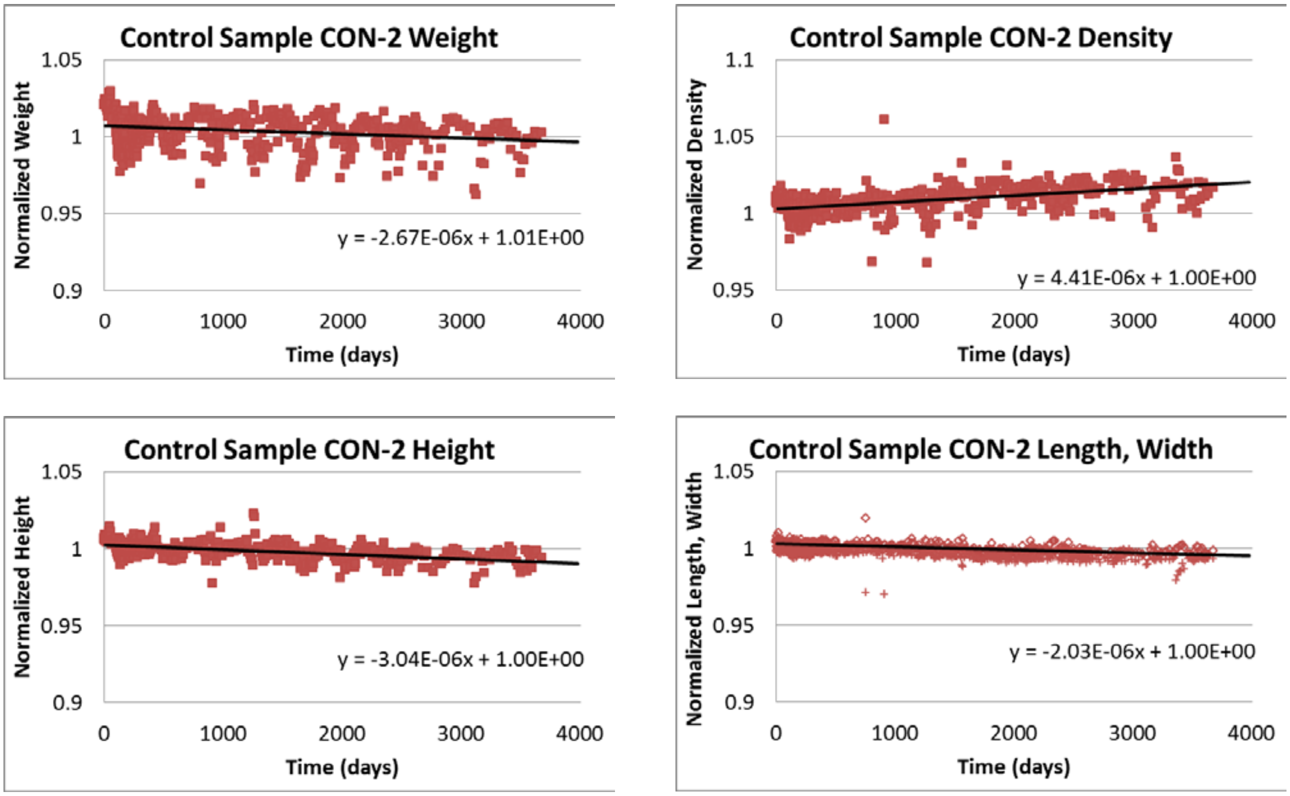


Figure 12. Physical property data for control sample CON-2.

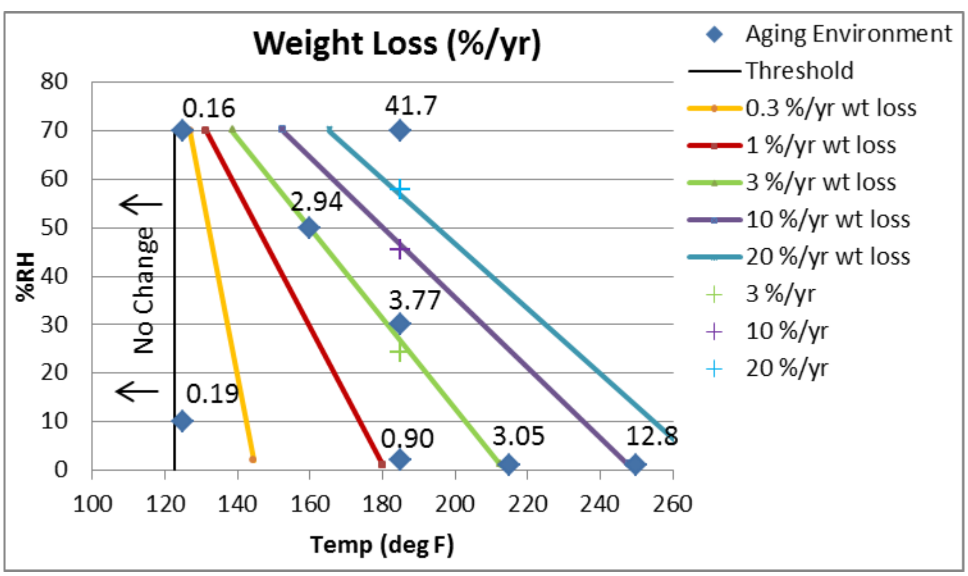


Figure 13. Fiberboard weight loss model. Lines represent contours of equal rate of weight loss. Numerical values are the average degradation rates of aged samples.

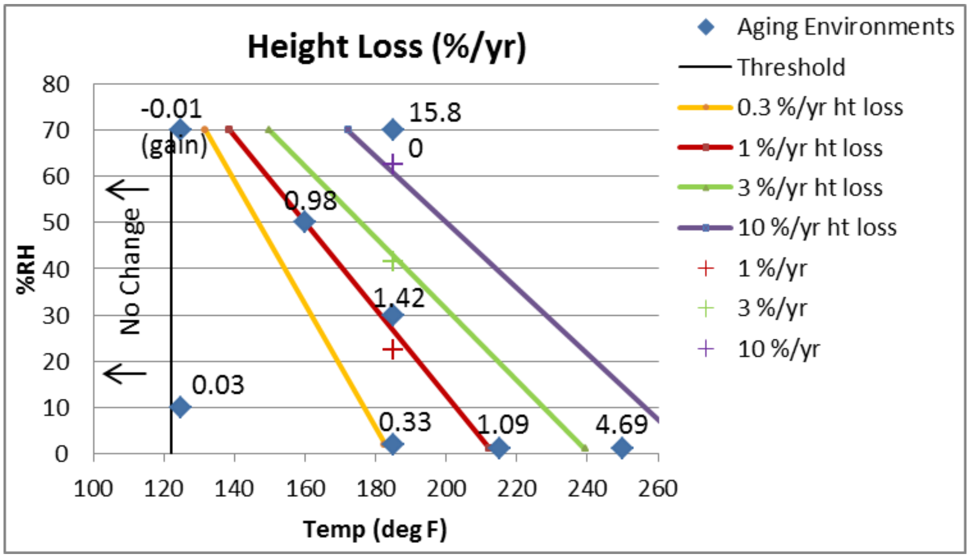


Figure 14. Fiberboard height loss model. Lines represent contours of equal rate of height loss. Numerical values are the average degradation rates of aged samples.

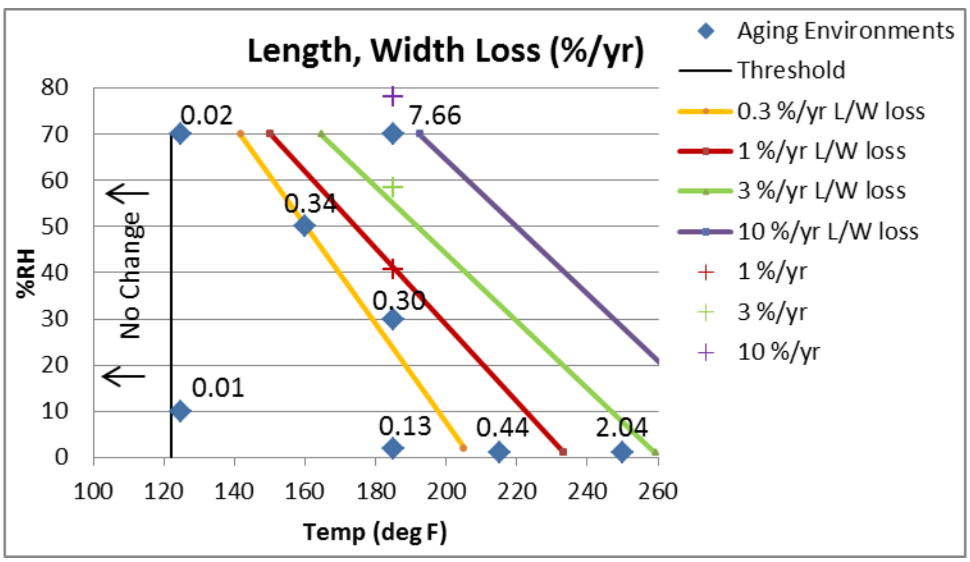


Figure 15. Fiberboard length / width loss model. Lines represent contours of equal rate of length / width loss. Numerical values are the average degradation rates of aged samples.

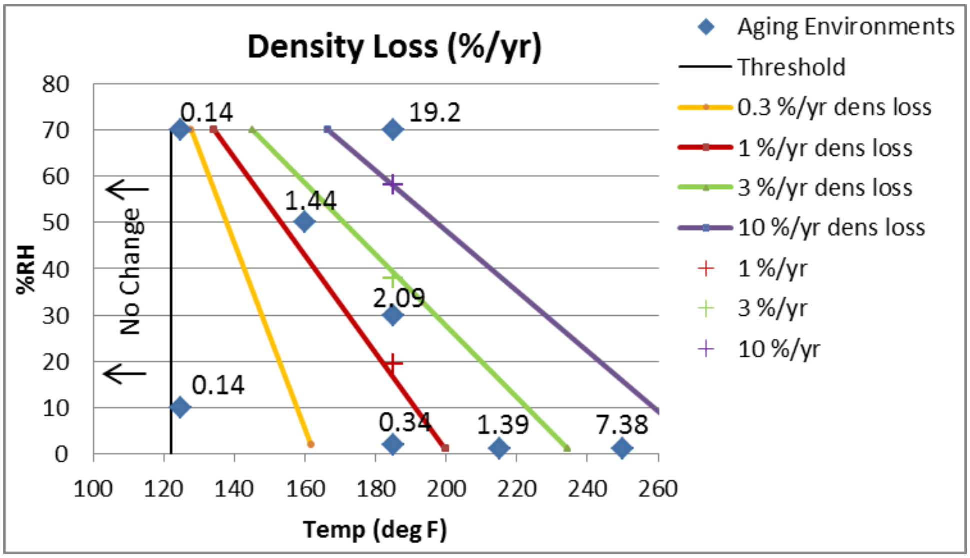


Figure 16. Fiberboard density loss model. Lines represent contours of equal rate of density decrease. Numerical values are the average degradation rates of aged samples.

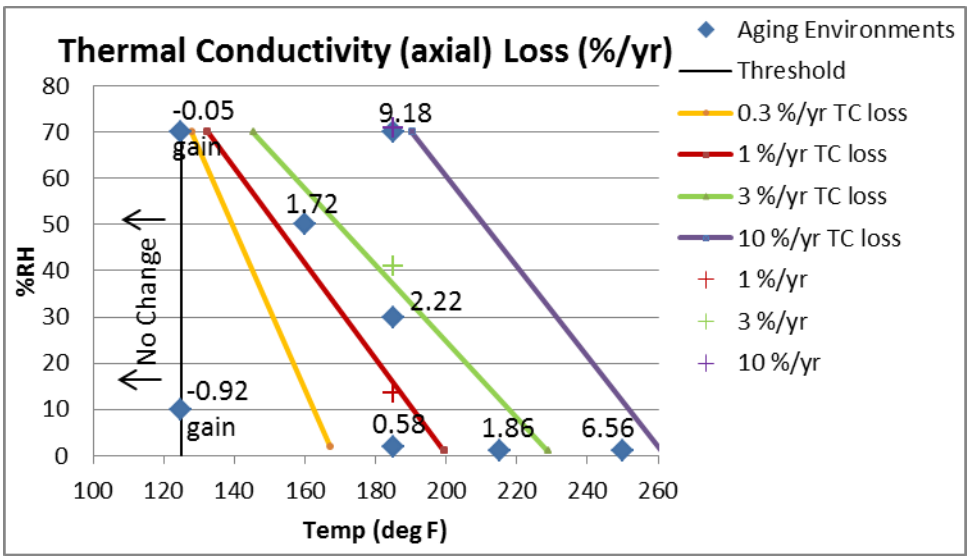


Figure 17. Fiberboard thermal conductivity, axial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the axial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in the 125 °F dry environment. This rate of change was not included in the modeling.

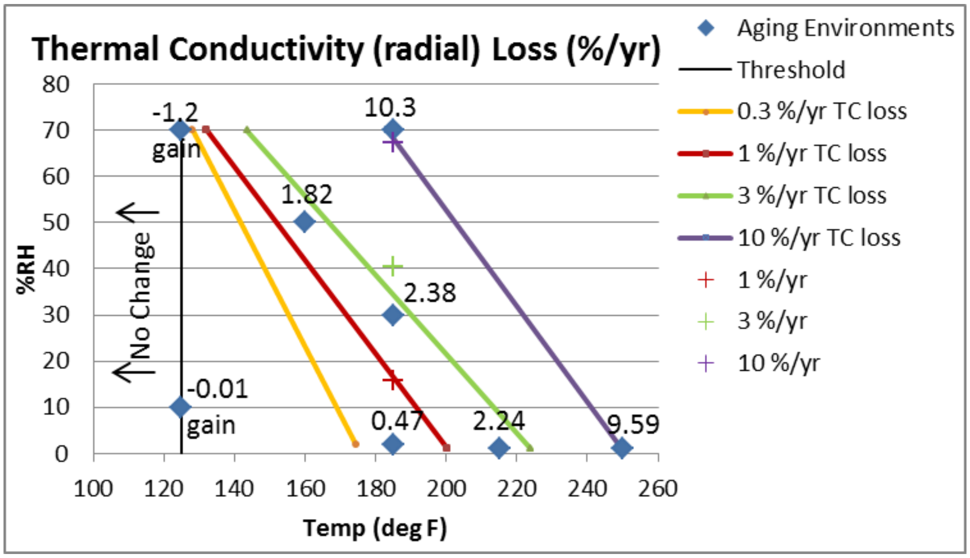


Figure 18. Fiberboard thermal conductivity, radial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the radial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in both 125 °F environments. To facilitate modeling, the 125 °F dry rate of change was not included, and the 125 °F 70%RH rate of change was adjusted to -0.0001 %/year.

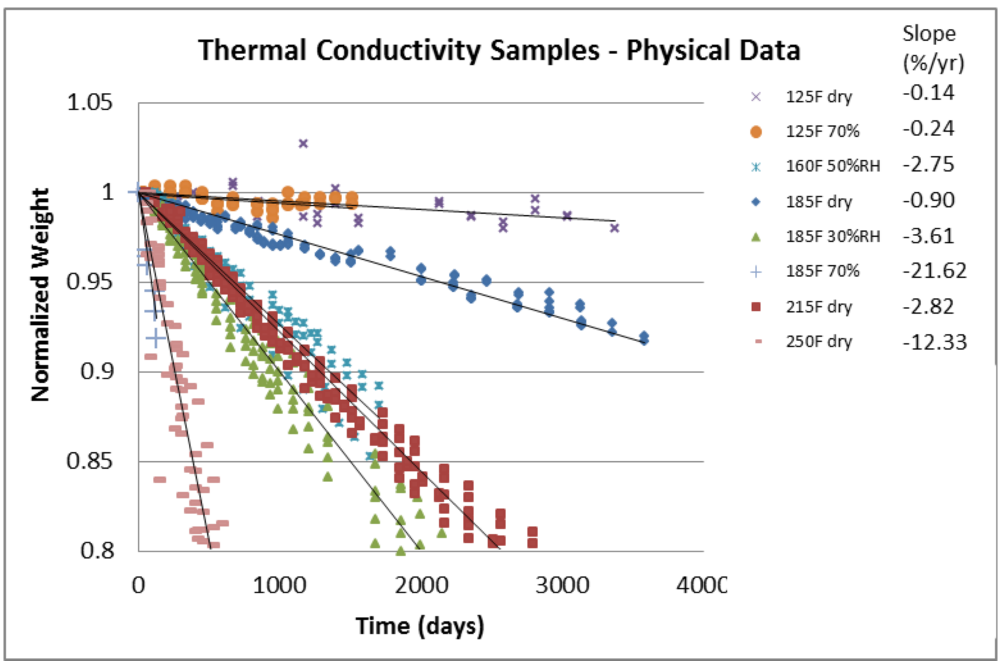


Figure 19. Physical data (weight change) trends from thermal conductivity samples

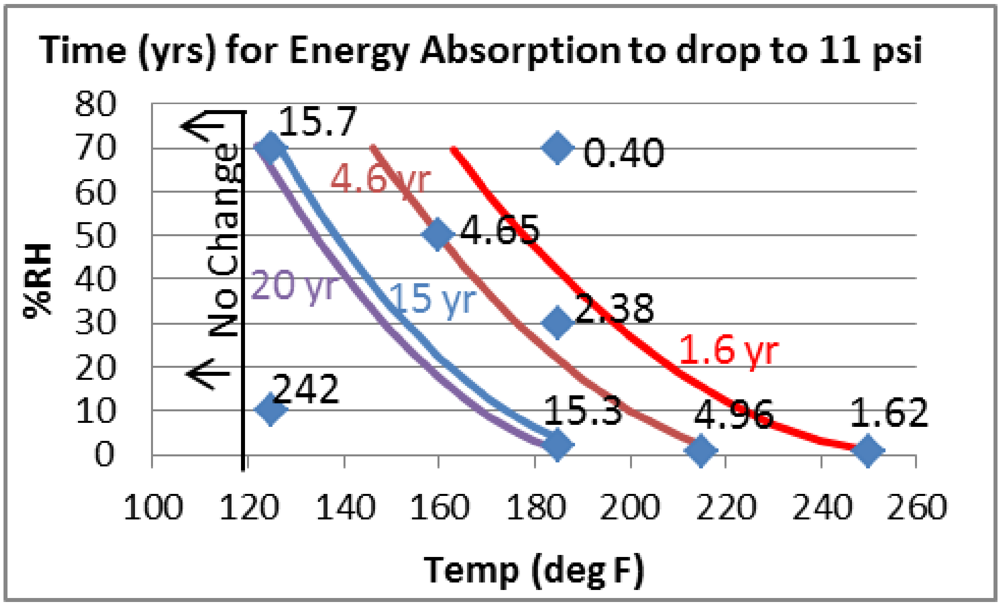


Figure 20. Model for energy absorption, based on compression test area under the stress-strain curve up to 40% strain. This graph shows contour lines describing environments for which energy absorption is predicted to drop to 11 psi over periods of 1.6, 4.6, 15 and 20 years. The numbers are the average lifetimes based on compression tests in the parallel orientation.

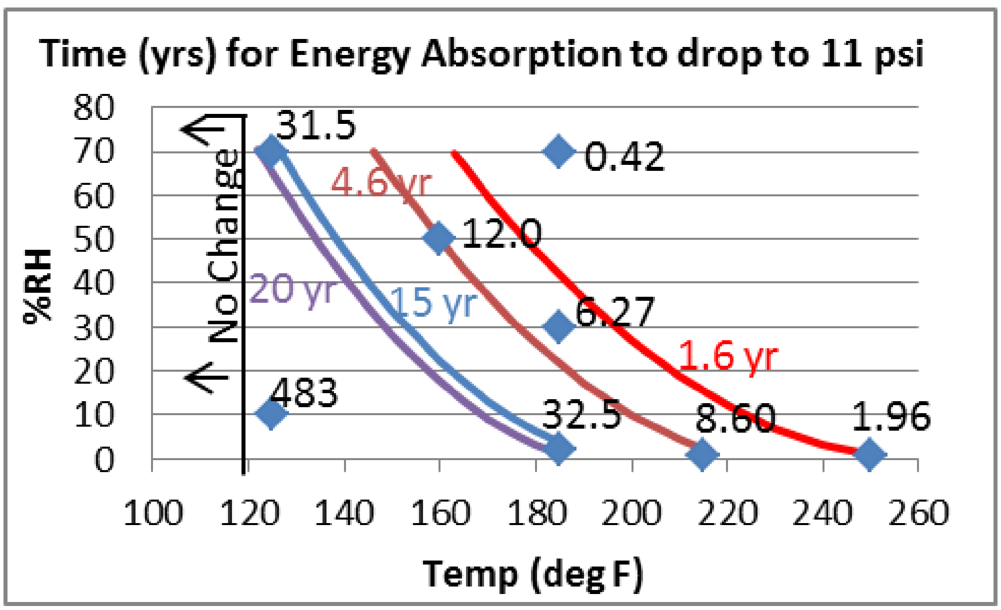


Figure 21. Alternate approach results for energy absorption, based on compression test area under the stress-strain curve up to 40% strain. This graph repeats the contour lines of constant degradation from Figure 23 (based on parallel orientation compression tests), and compares them to the lifetimes expected for each environment based on the averaged behavior of parallel and perpendicular orientation samples.

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