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

W. L. Daugherty

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Summary

Thermal, mechanical and physical properties have been measured on softwood fiberboard samples following accelerated aging for up to approximately 7 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 preliminary 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 acceptance criteria and an estimate of the actual conditions the fiberboard experiences in KAC, these models allow development of service life predictions.

Further work is needed 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 softwood fiberboard overpack assemblies. Efforts to address the behavior of cane fiberboard have been reported separately. 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]. In 2008, Knight-Celotex® softwood fiberboard was approved as an acceptable substitute for the previously approved cane fiberboard.

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 source packages, to provide data on package variability, although samples from some packages have not yet aged long enough to provide reliable trends. The package sources are as follows:

- SW – a new lower assembly provided by KAC. Samples began conditioning in limited environments in November 2008, with additional samples / environments added later.
- T4SW – lower assembly from training package T4. Samples began conditioning in limited environments in March 2014.
- T5SW – lower assembly from training package T5. Samples began conditioning in limited environments in March 2014.
- 6100 –package 9975-06100 following field surveillance and destructive examination. Samples began conditioning in September 2014.

Table 1 summarizes the maximum conditioning times for each environment through August 2015. Samples from the SW package have been aging in all environments. Samples from the other source packages have been aging in fewer environments, with the primary goal of showing package variation in typical environments.

Baseline and long-term testing of mechanical and thermal properties have been reported previously. Reference 4 summarized available data on softwood fiberboard through

February 2015. Additional data have since been collected, and the cumulative data set through August 2015 has been analyzed for the development of aging models. The conclusions of this report are specific to softwood fiberboard. Results for cane fiberboard have been reported separately. While the two materials behave similarly, they display enough difference in their aging behavior that the results for one material should not be assumed for the other without careful consideration.

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 on SW samples has been performed after aging in all environments. Compression samples from the other source packages have been aged in only 2 or 3 environments.

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 capacity 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, 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. 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 from the SW package are aging in seven of the environments, samples from the 6100 package are aging in five of the environments, and samples from the other two source packages are aging in two environments.

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. 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. Three specific heat capacity samples (from source package SW) are aged in each of two environments (185 ºF 30%RH and 250 ºF dry), and typically 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 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 the SW and 6100 source packages are conditioned in each environment. Samples from the other source packages are aging in four of the environments.

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 some of the samples aging at 250 ºF, and all of the samples aging at 185 ºF 70 %RH.

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 – 4 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

Only one package with softwood fiberboard has been removed from KAC for destructive examination (9975-06100). No significant degradation was observed in the fiberboard from this package following 5.4 years storage with a 12 watt internal heat load. 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.

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 158 ºF, based on the temperature profiles reported in Reference 5 for softwood fiberboard. The outer surfaces of the fiberboard would be up to ~40 ºF cooler or 118 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 9.2W internal heat load and 94 ºF ambient temperature.

A variety of temperature / humidity combinations should be considered in conjunction with understanding the range of conditions within KAC to adequately identify a limiting service life. For instance, the total moisture content will vary from package to package, but it might be assumed that the typical conforming package will have no more moisture than would be absorbed from the air at 75 °F and 100% RH. For an ambient temperature of 94 °F, the maximum softwood fiberboard temperature of ~158 °F will occur along the ID surface, in conjunction with relatively low moisture content. The higher moisture concentrations (corresponding to a relative humidity of ~75% or greater) will tend to occur along the OD surfaces which are much closer to ambient temperature. Other intermediate temperature / moisture combinations should also be considered, including the milder temperatures that would accompany heat loads less than 19 watts. 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].

Some efforts have been performed or are in progress to develop an improved understanding of the environment within the 9975 drum in storage. These efforts are addressing both cane and softwood fiberboard. 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, the humidity 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 to provide an initial survey of the range of humidity present. 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. 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 8 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 [8]. 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 6-8% (moisture loss), followed by an additional 10 – 15 %/year weight loss. At the higher temperature and humidity levels, the samples also darken, become more fragile, and may separate along the glue joints.

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, some of this initial moisture-related change might not occur in service, except as driven locally within the drum by a temperature gradient.

A control physical property softwood fiberboard sample has been maintained at ambient laboratory conditions, and measured periodically, to show if there is an overall bias in the data over time. The data from this control sample are shown in Figure 12. The control sample properties appear to show a slight decrease over time, but such changes are currently masked by the effect of seasonal moisture variation over the relatively short duration of testing. Based on data from cane fiberboard control samples, it is expected that the control sample will experience a gradual decrease in weight and dimensions due to handling. Until additional softwood fiberboard control sample data are available to average out the seasonal bias, the changes observed for cane fiberboard control samples will be assumed for the softwood fiberboard analysis. The cane fiberboard control sample variation rates will therefore be used to adjust the measured degradation rates of the aging softwood fiberboard 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 in cane fiberboard 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 [9]. 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) [10]. The specific impact of mold on fiberboard properties or package service life has not been examined, and is not addressed in this report.

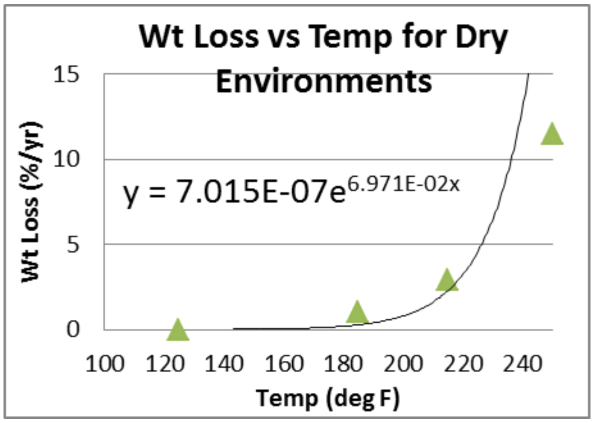
Degradation Models

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). These models are generally developed in the same manner used for cane fiberboard [11]. with minor variations where needed to better fit the data. At this time, these models have been developed for data from the SW source package only, since they comprise the most complete dataset with the longest aging periods.

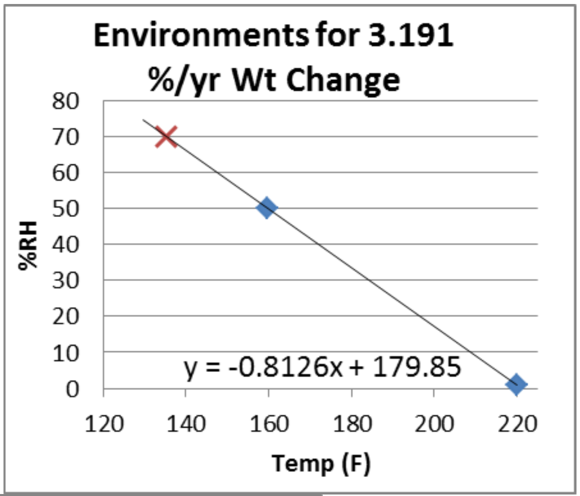
The following approach was used to model the change in fiberboard weight, dimensions, density, and thermal conductivity. Specific steps are illustrated for the change in weight

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

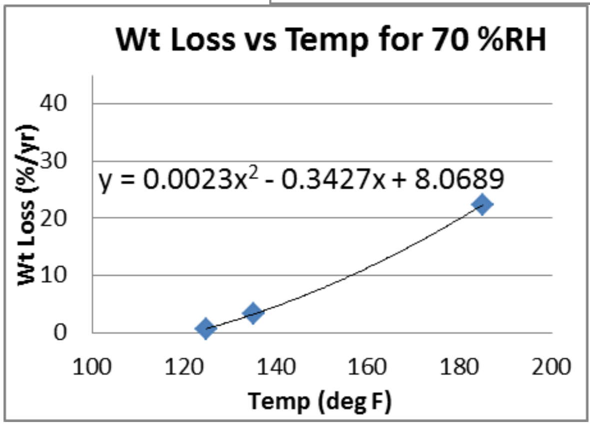
2. A curve is fit to rate of change vs temperature for 4 dry oven environments – 125, 185, 215 and 250 °F. An exponential relationship provides the best fit, and represents the variation with temperature at a low value of relative humidity (~1-10%).



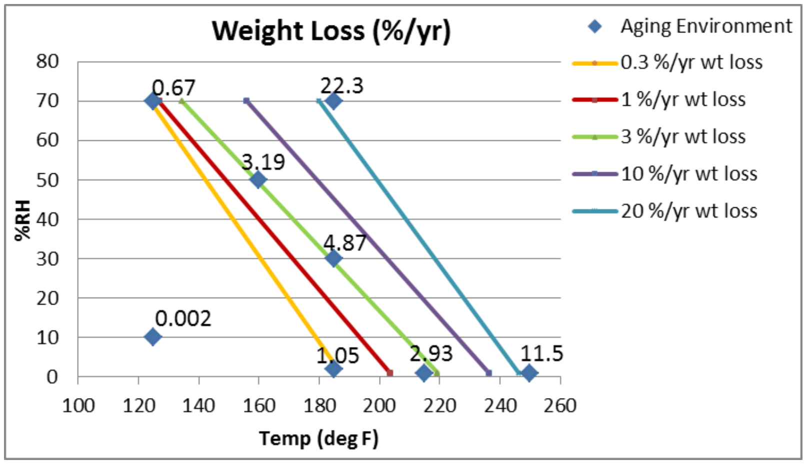
3. It is observed that similar rates of change occur for 215 °F dry, 185 °F 30%RH and 160 °F 50%RH environments, and that these 3 environments fall close to a common straight line in humidity – temperature space. This suggests a linear relationship would apply. The degradation rate for 160 °F 50%RH is 3.191 %/yr. From the curve fit to the dry environments, this same rate would be expected at 220.1 °F 1%RH. Extrapolating from these two environments, the same degradation rate is predicted for 135.2 °F 70%RH.



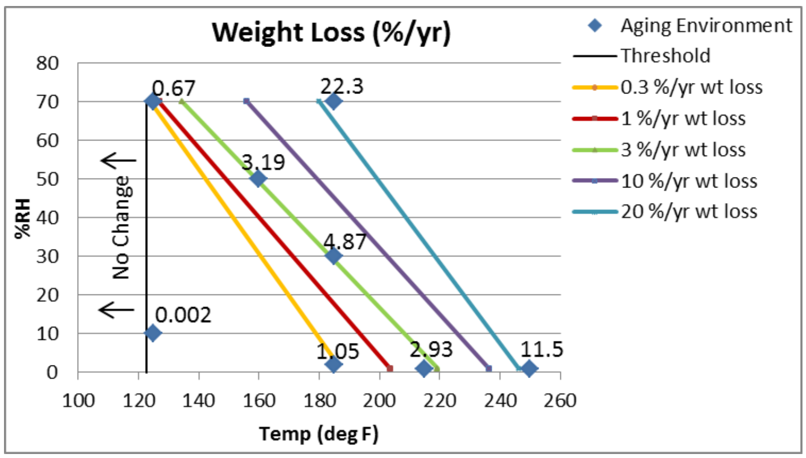
4. A curve is fit to rate of change vs temperature for 3 humid environments – 125 °F 70%RH, 135.2 °F 70%RH and 185 °F 70%RH. A binomial equation provides the best fit, and represents the variation with temperature at a constant relative humidity of 70%.



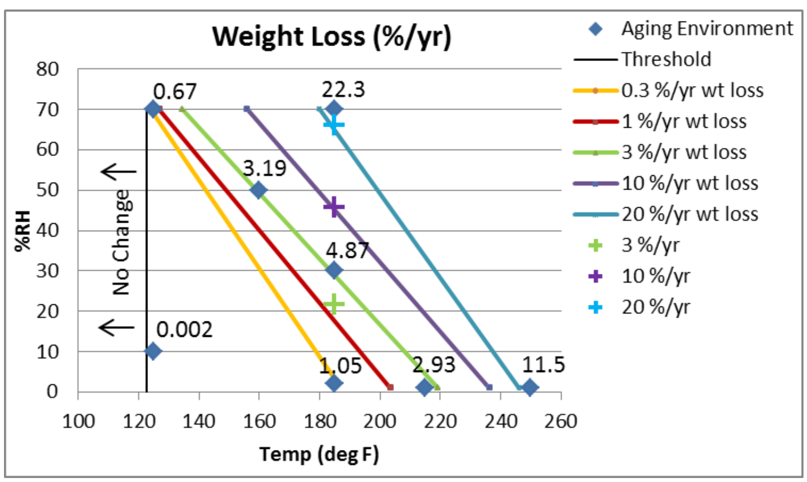
5. The two curve fits developed for the two relative humidity extremes are used to predict the temperatures at which specific rates of change will occur (e.g. a 1% rate of weight loss is predicted at 203.5 °F for low relative humidity, and at 126.9 °F for 70% RH).



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%). A binomial curve is fit to the rates of change from these 3 environments, and that curve is 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. In some cases, the form of one or more equations (binomial, exponential, etc.) providing the best fit to the data changes, but the process remains the same otherwise.

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. These samples are also handled much less often than the physical property samples, and therefore have less need to be corrected for weight loss caused by handling. 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 (Tables 3 and 4). Although only the SW source package is currently considered in developing this model, there is also variation from one source package to another.
- 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 cane 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 energy absorption.

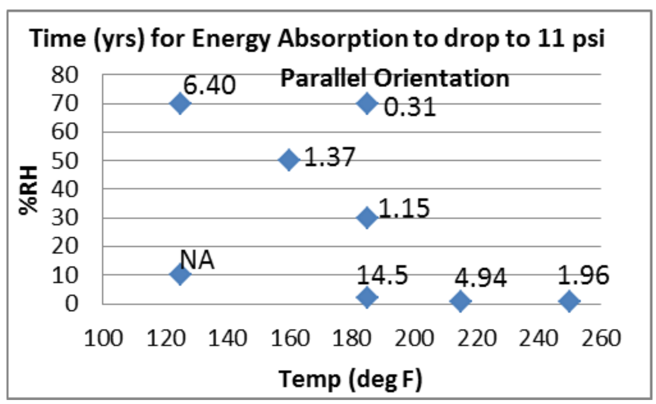
The forklift impact scenario primarily loads a local region of the fiberboard from the side (in a parallel orientation). Within a 9975 package, the drum and shield provide a degree of constraint to limit the motion of fiberboard under load. This constraint allows the load to re-distribute throughout 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)

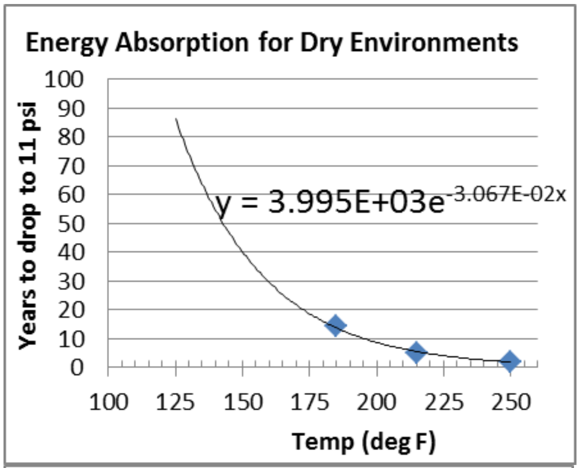
In this equation, the exponential factor “b” describes the rate of decrease of the area under the stress-strain curve. The time for the energy absorption of each source package in each environment to decrease to 11 psi is summarized in Table 8, although the degradation model is based on data from the SW source package only. With the “failure” times for source package SW in 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.



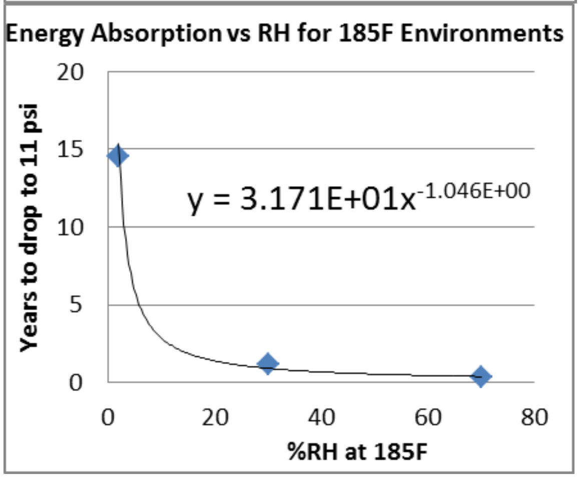
2. Fit an exponential curve to low humidity environments (185, 215 and 250 °F), and extrapolate to additional temperatures of interest. The 125 ºF data is excluded since the positive slope is not consistent with an exponential equation.

Prediction for 209.9 °F (dry) = 6.4 yrs
Prediction for 260.0 °F (dry) = 1.37 yrs
Prediction for 182.1 °F (dry) = 15 yrs



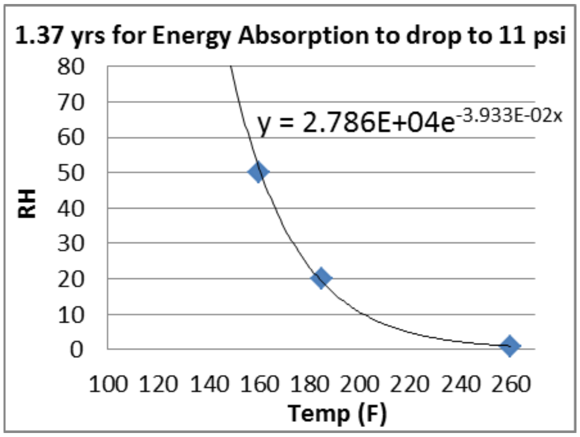
3. Fit a power law curve to 185 °F environments (dry, 30 and 70 %RH), and interpolate to additional humidity values of interest.

Prediction for 4.62 %RH = 6.4 yrs
Prediction for 20.1 %RH = 1.37 yrs
Prediction for 2 %RH = 15 yrs



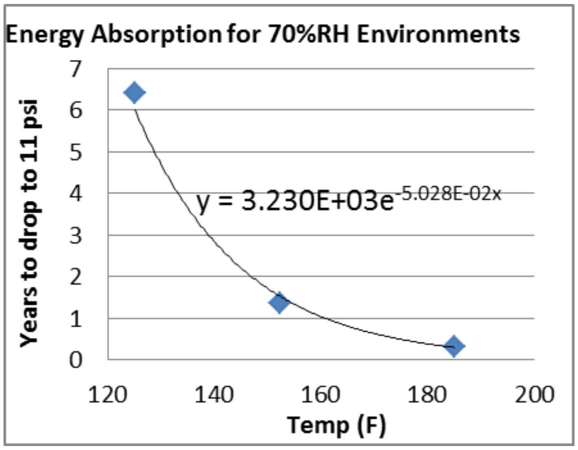
4. There are now 3 environments with an estimated decrease in energy absorption to 11 psi in 1.37 yrs – 260.0 °F dry, 160 °F 50 %RH, and 185 °F 20.1 %RH. Fit an exponential curve to these data to describe all environments which will produce a similar drop in energy absorption in 1.37 yrs.

Prediction for 152.2 °F = 70 %RH

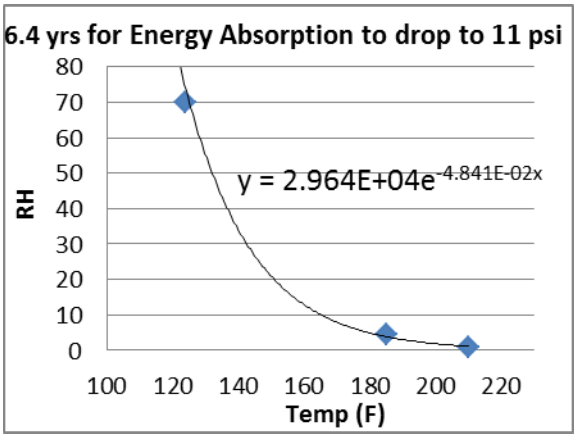


5. There are now 3 temperatures with estimated time for energy absorption to decrease to 11 psi at 70 %RH – 125 °F, 152.2 °F and 185 °F. Fit an exponential curve to these data, and interpolate to additional temperatures of interest.

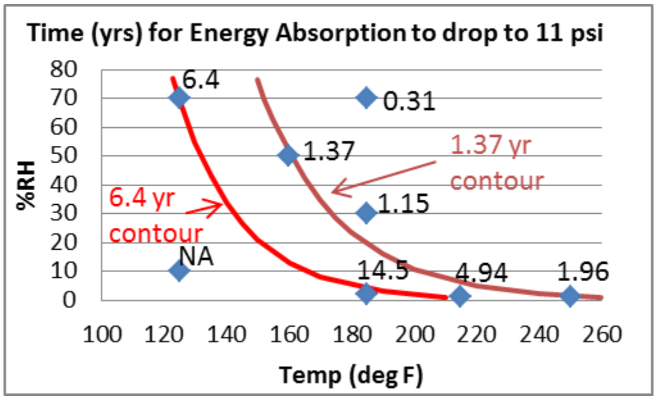
Prediction for 123.8 °F 70 %RH = 6.4 yrs
Prediction for 106.8 °F 70 %RH = 15 yrs



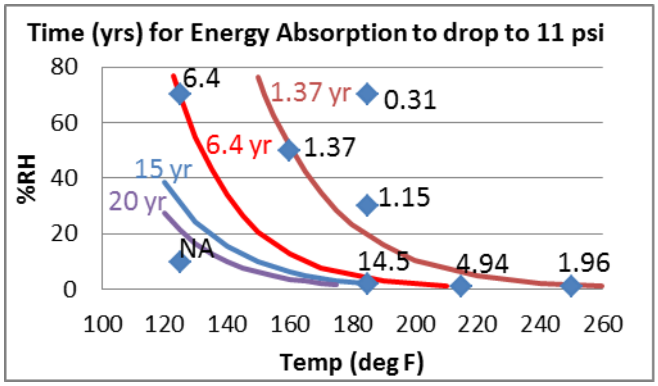
6. There are now 3 environments with energy absorption decrease to 11 psi in 6.4 yrs – 209.9 °F 1 %RH, 185 °F 4.62 %RH, and 123.8 °F 70 %RH. Fit an exponential curve to these environments to describe all environments which will produce a similar drop in energy absorption in 6.4 yrs.



7. The two exponential 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 1.37 yrs and 6.4 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 a similar 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, and the 15 and 20 year contour lines were not extended below this temperature. 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 contour curves calculated from these data. 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 up to twice as high 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 moister 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 with cane fiberboard 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. Table 9 compares density and thermal conductivity values from a softwood fiberboard package with averaged results from the 7 cane fiberboard packages. Except for thermal conductivity in the axial orientation, the softwood fiberboard properties fall within the 1 sigma range for the cane fiberboard properties. These data provide some indication of baseline properties that might be assumed in a service life estimate.

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 degradation models can be developed.

Softwood vs Cane Fiberboard

This report summarizes aging data for softwood fiberboard samples in a number of moderate to extreme environments, and develops degradation models from that data. A comparable effort has been performed for cane fiberboard samples. Previous reports [14] have cautioned against applying degradation models developed for cane fiberboard to softwood fiberboard. The comparability of degradation models can be compared for these two materials based on the most recent data for each material.

As the duration of test data increases, some differences between the two materials have decreased, but bias remains for some properties in some environments. These differences are relatively small, but estimated behaviors under storage conditions can be sufficiently different to warrant the continuation of separate degradation models. For that reason, it is still recommended that the two materials be treated separately as described by the degradation models in the two current reports. It is possible that service life estimates for storage in KAC will differ based on the type of fiberboard in a given package.

Conclusions and Recommendations

Thermal, mechanical and physical property data for softwood fiberboard samples have been summarized following aging in several environments (elevated temperature and/or humidity) for periods up to ~7 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. The predictive models are specific to a single softwood fiberboard assembly, and consider the effect of temperature, humidity and time.

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.

The analysis and predictions of this report should not be applied to packages with non-conforming conditions.

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Table 1. Summary of softwood fiberboard 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	201	230	177	176
215 ºF oven	334	--	63	344
185 ºF oven	32	--	221	354
185 ºF 30% RH	275	238	215	283
185 ºF 70% RH	75	--	51	43
160 ºF 50% RH	214	--	154	229
125 ºF oven	64	--	63	77
125 ºF 70% RH	217	--	114	225

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

Environ-ment	(wks)	SW	T4SW	T5SW	6100
Ambient	**0**	24.7	34.3	33.2	28.1
		25.0	31.1	25.8	23.6
		25.4	28.9	33.0	24.6
					24.0
125F	**8**	26.5			
Dry	**63**	24.1			
125F	**0.28**	16.5			
70%	**16**	18.8			
	32	19.2			
	64	17.8			
	114	15.6			
160F	**0.28**	21.5			22.6
50%	**16**	19.6			19.6
	32	17.1			
	64	14.0	13.3	12.8	
	105	11.7			
185F	**8**	19.0			
Dry	**32**	22.6			
	33	23.4			
	64	22.9			
	96	21.0			
185F	**0.28**	19.7			
30%	**8**	20.1			
	9	20.5			
	31	13.9			
	32	14.2			
	48	11.4			
	65	10.0			

Environ-ment	(wks)	SW	T4SW	T5SW	6100
185F	**0.28**	18.2			8.3
70%	**4**	14.0			7.3
	8	12.3			
	12				8.6
	16	7.8			
	20				6.6
	33	1.8			
	41	4.2			
	44				3.4
215F	**0.14**	21.3			
Dry	**8**	22.3			
	63	14.2			
250F	**0.28**	22.9			21.7
Dry	**8**	15.6	13.7	19.1	17.3
	8	17.3			
	16	10.7			
	18	14.7			
	32	13.3			12.2
	33	9.0			
	51		11.9	10.9	
	63	1.3			
	96	6.6			
	176	6.5			

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

Environ-ment	(wks)	SW	T4SW	T5SW	6100
Ambient	**0**	46.1	53.5	57.8	53.7
		50.8	50.9	50.0	42.1
		55.2	51.0	50.9	50.6
					43.1
125F	**8**	34.6			
Dry	**63**	39.6			
125F	**0.28**	37.1			
70%	**16**	39.0			
	32	37.3			
	64	30.8			
	114	25.3			
160F	**0.28**	44.9			45.6
50%	**16**	31.5			41.3
	32	19.7			
	64	9.8	20.7	20.9	
	105	7.0			
185F	**8**	28.2			
dry	**32**	15.1			
	33	34.7			
	64	18.8			
	96	25.9			
185F	**0.28**	37.1			
30%	**8**	30.5			
	9	32.7			
	31	15.3			
	32	14.1			
	48	18.4			
	65	10.3			

Environ-ment	(wks)	SW	T4SW	T5SW	6100
185F	**0.28**	4.0			13.9
70%	**4**	18.1			6.9
	8	14.6			
	12				7.9
	16	12.4			
	20				8.7
	33	2.1			
	41	4.1			
	44				3.7
215F	**0.14**	34.5			
Dry	**8**	36.6			
	63	26.8			
250F	**0.28**	30.3			28.6
Dry	**8**	13.8	24.3	23.1	10.6
		22.5			
	16	8.5			
	18	23.0			
	32	13.5			9.4
	33	16.2			
	51		9.5	11.1	
	63	15.4			
	96	10.1			
	176	8.1			

Column header group: Area under Curve (psi) for SW, T4SW, T5SW, 6100.

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

Environment	(wks)	SW	T4SW	T5SW	6100
		Area under Curve (psi) for			
Ambient	**0**	37.7	43.7	44.0	43.5
		40.4	42.4	41.8	44.1
		41.5	44.1	44.3	40.6
					40.4
125F	**8**	50.5			
Dry	**63**	47.8			
125F	**0.28**	32.2			
70%	**16**	29.3			
	32	32.2			
	64	32.0			
160F	**0.28**	37.5			39.2
50%	**16**	37.3			37.8
	32	37.1			
	64	34.4	30.5	28.8	
	154	25.0			
185F	**0.28**				44.3
Dry	**8**	48.2			
	16				45.9
	32	49.7			
	64	42.7			
	96	42.5			
	221	40.1			
185F	**8**	39.3			
30%	**9**	41.5			
	31	34.7			
	65	26.9			
	215	19.6			
185F	**0.28**	34.2			15.8
70%	**4**	33.2			14.2
	8	27.4			
	12				21.6
	16	14.7			
	20				16.0
	33	6.1			
	41	10.6			
	44				8.5
215F	**0.14**	47.3			
Dry	**8**	41.1			
250F	**0.28**				41.1
dry	**8**	41.4	33.7	36.6	38.6
		40.3			
	16	35.5			
	32	30.6			28.4
	33	30.4			
	51		24.1	24.1	
	63	26.1			
	96	18.9			
	177	7.9			

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.

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**		
SW 1R	8	0.0903	SW 2R	8	0.0934	6100-R	2	0.0952
6100-2R	2	0.0957						
T4SW-2R	4	0.0882						
T5SW-2R	4	0.0956						
185 ºF 30 %RH, radial orientation			**185 ºF 70 %RH, radial orientation**			**160 ºF 50 %RH, radial orientation**		
SW 3R	8	0.0975	SW 7R	4	0.0992	SW 4R	5	0.0998
6100-5R	2	0.1056	6100-4R	0.28	0.0954	6100-3R	2	0.0994
						T4SW-1R	4	0.0987
						T5SW-1R	4	0.1032
125 ºF oven, radial orientation			**125 ºF 70 %RH, radial orientation**					
SW 6R^8	8	0.0940	SW 5R	5	0.1054			
250 ºF oven, axial orientation			**215 ºF oven, axial orientation**			**185 ºF oven, axial orientation**		
SW 1A	8	0.0492				6100-A	2	0.0516
6100-2A	2	0.0505						
185 ºF 30 %RH, axial orientation			**185 ºF 70 %RH, axial orientation**			**160 ºF 50 %RH, axial orientation**		
SW 3A	8	0.0526	SW 7A	4	0.0548	SW 4A	5	0.0554
			6100-4A	0.28	0.0557	6100-3A	2	0.0546
125 ºF oven, axial orientation			**125 ºF 70 %RH, axial orientation**					
SW 6A	8	0.0544	SW 5A	5	0.0578			

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	6 – 8% decr	3 – 5% decr	2 - 3% decr	0 - 2% decr
215 ºF, dry oven	6 – 8% decr	4 – 5% decr	2 - 3% decr	< 1% (+ and -)
185 ºF, dry oven	7 – 8% decr	~4% decr	2 - 3% decr	< 1% decr
125 ºF, dry oven	4 – 5% decr	1 – 2% decr	1 - 2% decr	< 1% decr
185 ºF, 70%RH	~ 1% (+ and -)	0 – 3% decr	~1% incr	< 1% incr
185 ºF, 30%RH	2 – 4% decr	1 – 3% decr	0 - 1% decr	< 1% decr – 1% incr
160 ºF, 50%RH	2.4% decr - <1 incr	2% decr – ~1% incr	< 1% (+ and -)	< 1% (+ and -)
125 ºF, 70%RH	3% decr	~1% incr	1 - 2% incr	< 1% incr

Table 7. Comparison of weight changes for SW physical property and thermal conductivity samples to model predictions

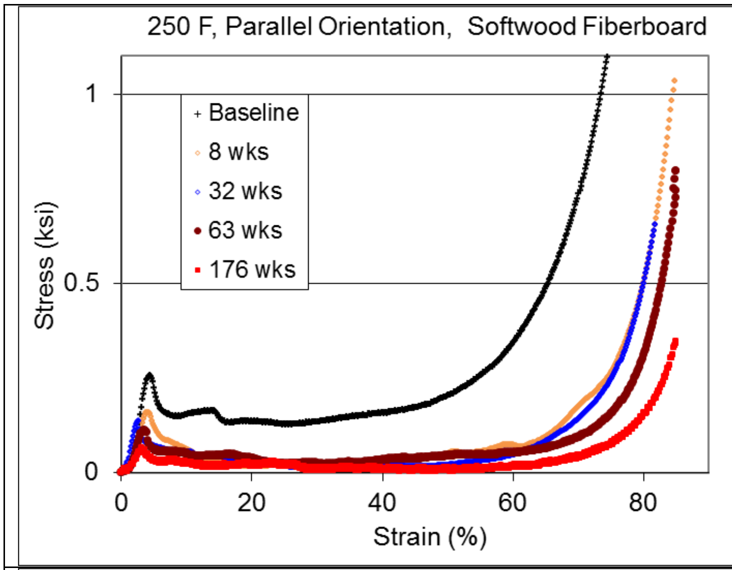
Environment	Model Prediction (%/yr)	Average Slope from Actual Data (%/yr) Physical Property Samples	Thermal Conductivity Samples
125 °F dry (5%)	-0.004	-0.002	-0.27
185 °F dry (2%)	-0.3	-1.05	NA
215 °F dry (1%)	-2.3	-2.93	-2.70
250 °F dry (1%)	-26.0	-11.5	-10.2
125 °F 70%	-1.2	-0.67	-0.50
160 °F 50%	-3.0	-3.19	-3.02
185 °F 30%	-3.5	-4.87	-4.18
185 °F 70%	-23.4	-22.3	-22.7

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

Environment	Source Package	Estimated Time to Fail (years)	Duration of Data used for Estimate	Estimated Time to Fail (years)	Duration of Data used for Estimate
		Parallel Orientation		**Perpendicular Orientation**	
125ºF dry	SW	**(pos. slope)**	63 weeks	**29.50**	63 weeks
	T4SW	NA			
	T5SW				
	6100 SW				
125ºF 70 %RH	SW	**6.40**	114 weeks	**(pos. slope)**	64 weeks
	T4SW				
	T5SW				
	6100 SW				
160ºF 50 %RH	SW	**1.37**	105 weeks	**8.83**	154 weeks
	T4SW	(only 1 datum)	64 weeks	(only 1 datum)	64 weeks
	T5SW	(only 1 datum)	64 weeks	(only 1 datum)	64 weeks
	6100 SW	0.29	16 weeks	10.58	16 weeks
185ºF dry	SW	**14.5**	96 weeks	**30.56**	221 weeks
	T4SW				
	T5SW				
	6100 SW	(pos. slope)	16 weeks	(pos. slope)	16 weeks
185ºF 30 %RH	SW	**1.15**	65 weeks	**7.15**	215 weeks
	T4SW				
	T5SW				
	6100 SW				
185ºF 70 %RH	SW	**0.31**	41 weeks	**0.56**	41 weeks
	T4SW				
	T5SW				
	6100 SW	0.69	44 weeks	0.69	44 weeks
215ºF dry	SW	**4.94**	63 weeks	**1.58**	8 weeks
	T4SW				
	T5SW				
	6100 SW				
250ºF dry	SW	**1.96**	176 weeks	**2.83**	177 weeks
	T4SW	0.85	51 weeks	2.92	51 weeks
	T5SW	0.10	51 weeks	2.54	51 weeks
	6100 SW	0.44	32 weeks	2.15	32 weeks

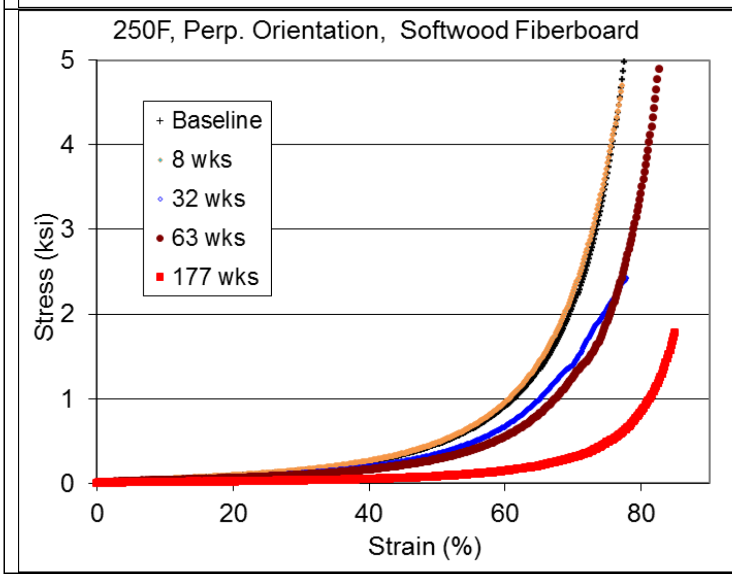
Table 9. Softwood fiberboard property values from 9975-06100 removed from storage in KAC for destructive examination. Comparison values from cane fiberboard packages are provided.

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)
06100 (softwood)	5.4 yrs	0.265	0.283	0.0574	0.1030
Avg +/- 1 sigma for 7 cane fiberboard packages [11]		0.269 +/- 0.019	0.291 +/- 0.008	0.0626 +/- 0.0009	0.1006 +/- 0.0053



(a) SW package, parallel orientation

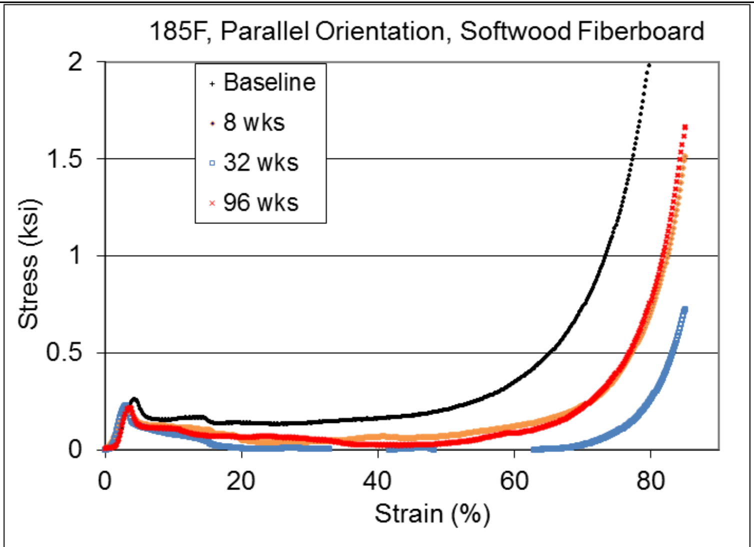
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.250	0.0508
8	0.156	0.0138
32	0.133	0.0135
63	0.113	0.0154
176	0.065	0.0081



(b) SW package, perpendicular orientation

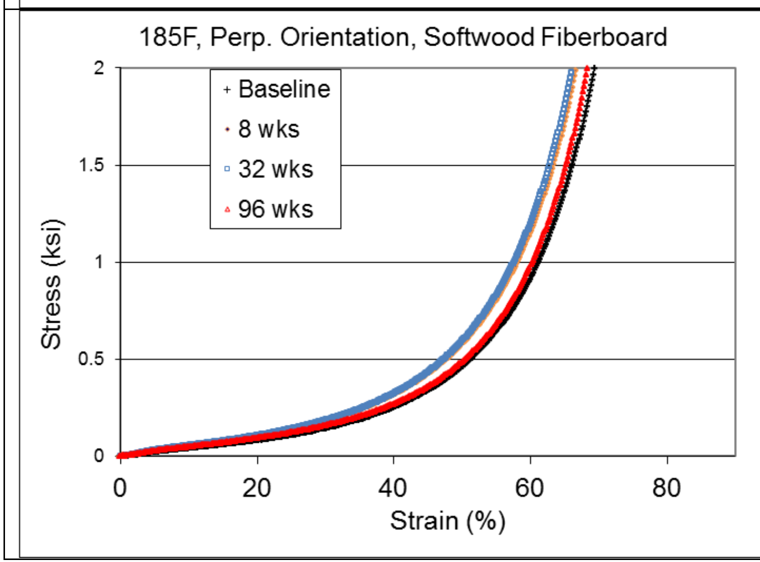
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0404
8	0.0414
32	0.0306
63	0.0261
177	0.0079

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



(a) SW package, parallel orientation

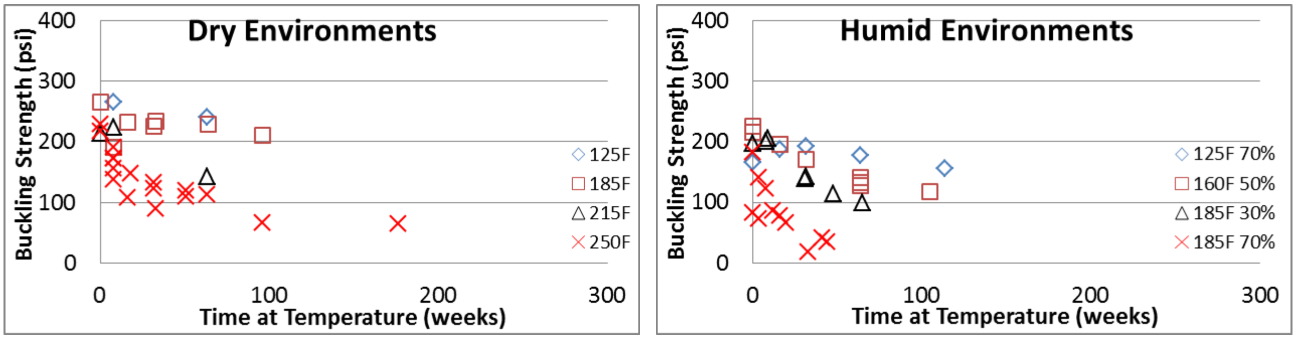
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.250	0.0508
8	0.190	0.0282
32	0.226	0.0151
96	0.210	0.0259



(b) SW package, perpendicular orientation

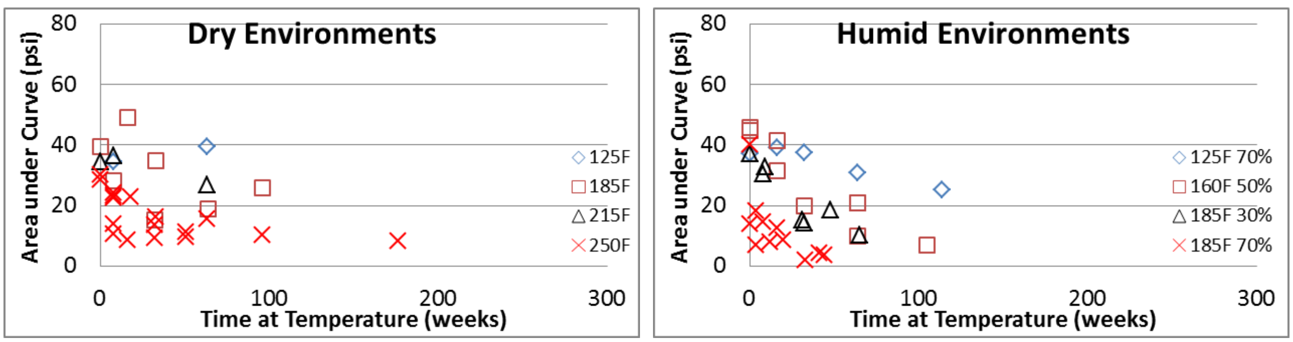
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0404
8	0.0482
32	0.0497
96	0.0425

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



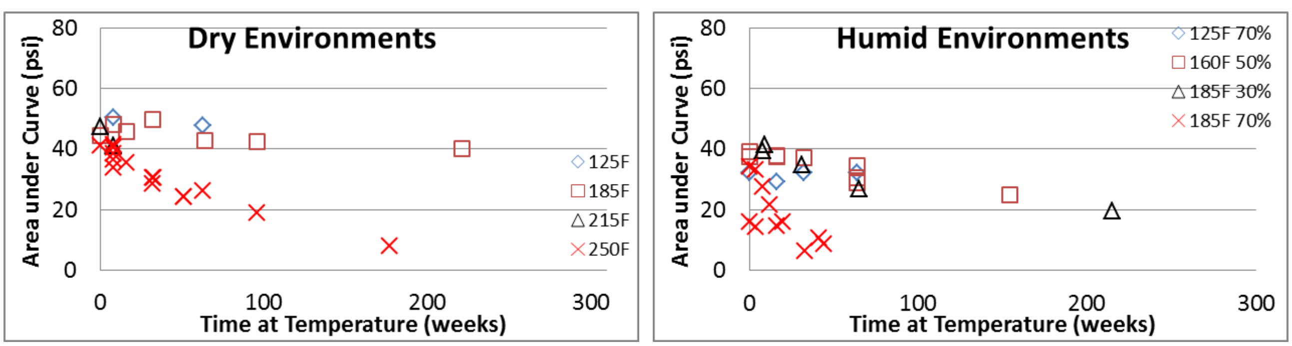
(a) (b)

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

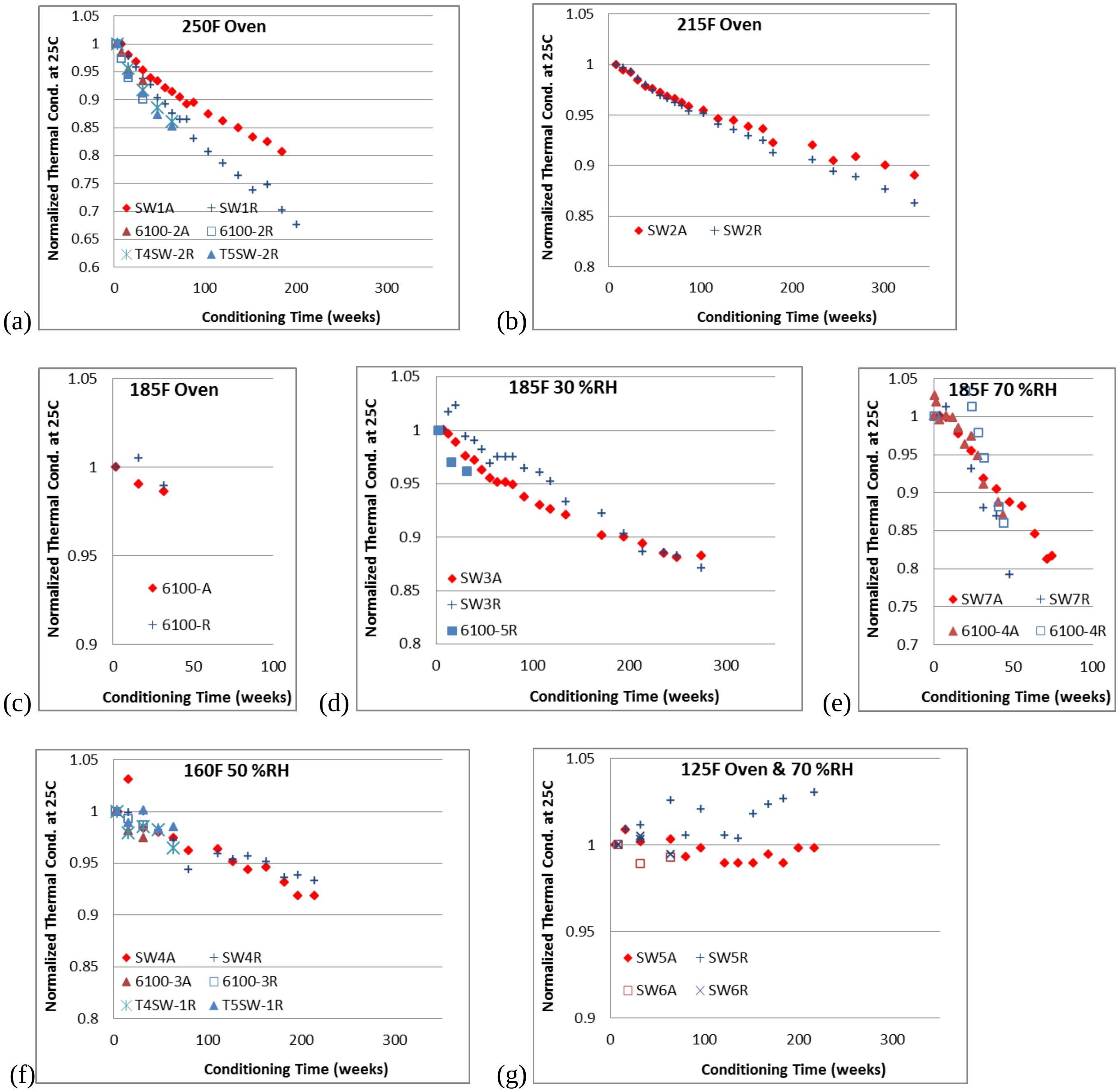


Figure 6. Thermal conductivity data measured at 25 ºC (77 ºF) mean temperature for each conditioning environment as noted. Data for each sample are normalized to the first conditioned value. The first conditioned value for each sample is identified in Table 5. Axial orientation samples are shown in red,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

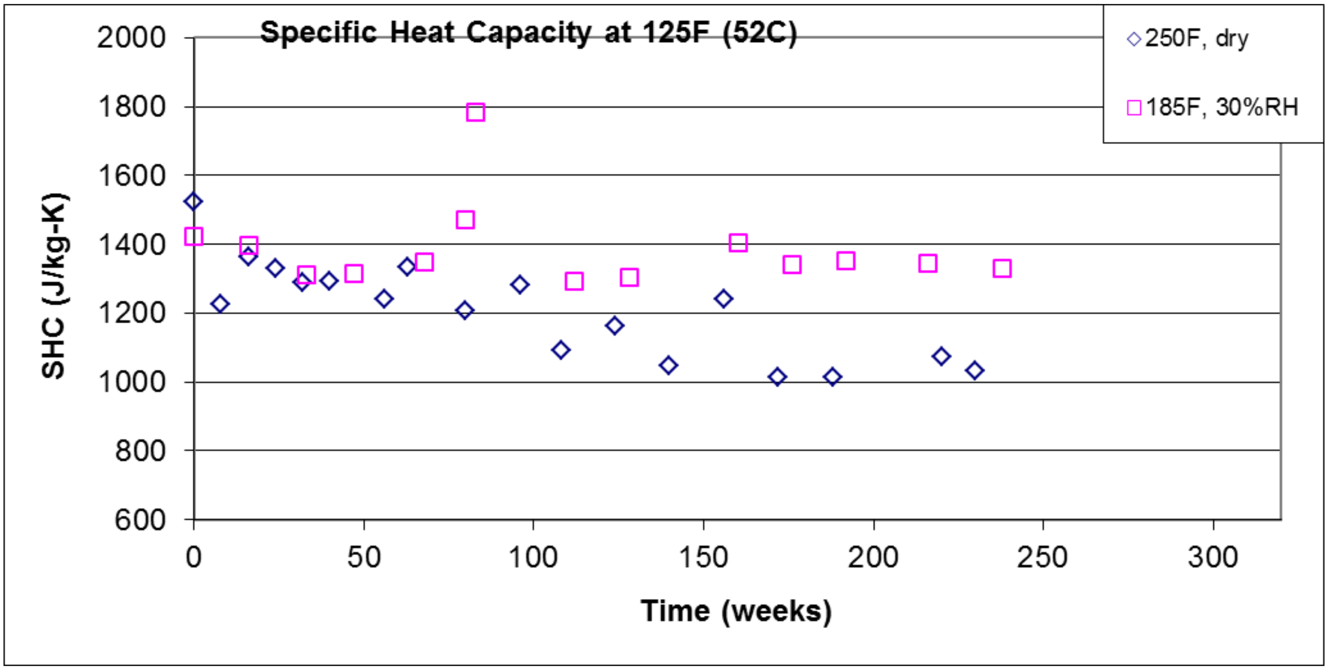
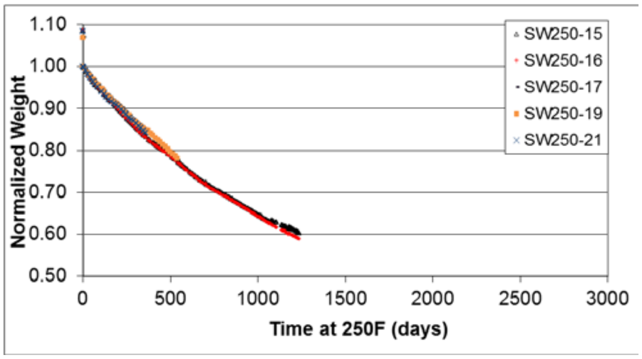
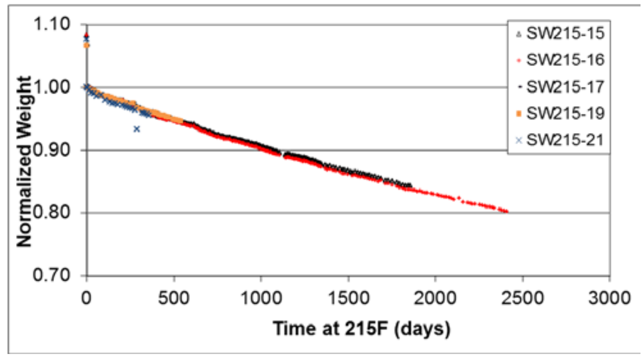


Figure 7. Specific heat capacity data at a mean temperature of 52 ºC (125 ºF) for each conditioning environment. A linear fit to the data for each environment produces the following trends:

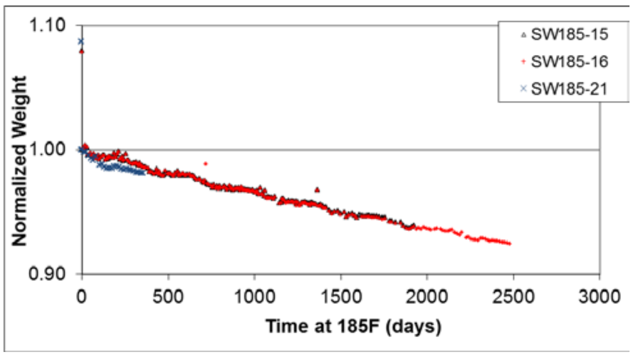
250 °F, dry	SHC (J/kg-K) = 1366.1 – 1.605 * time (weeks)
185 °F, 30%RH	SHC (J/kg-K) = 1422.6 – 0.320 * time (weeks)



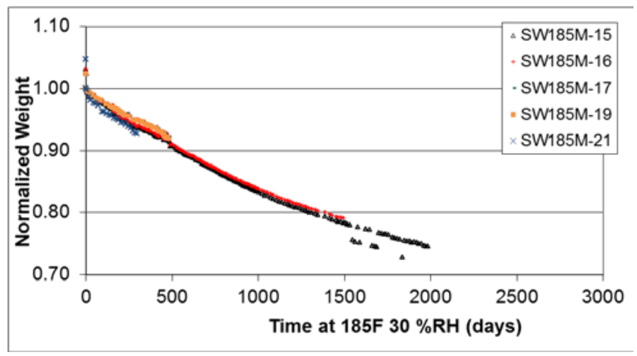
(a) 250 ºF, dry



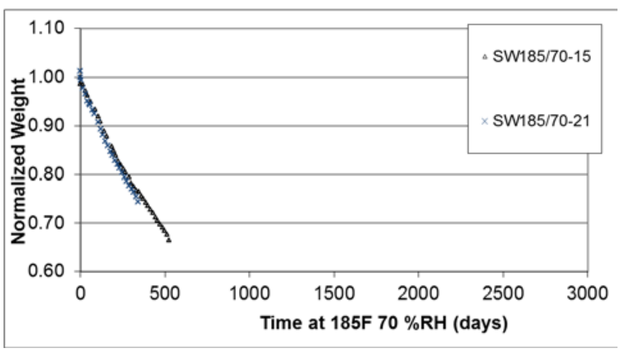
(b) 215 ºF, dry



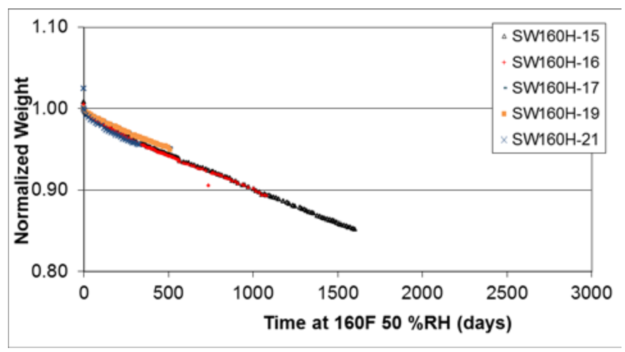
(c) 185 ºF, dry



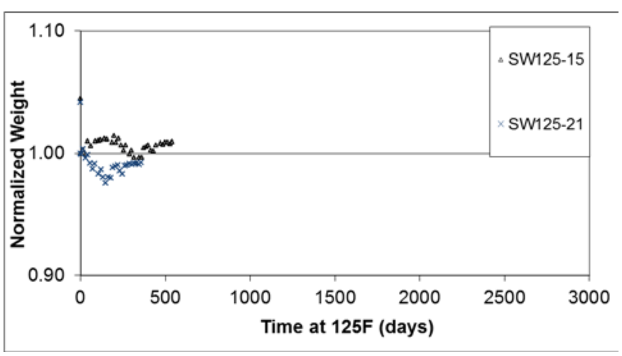
(e) 185 ºF, 30% RH



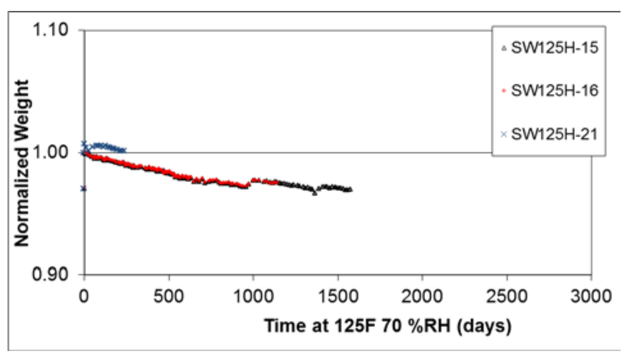
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

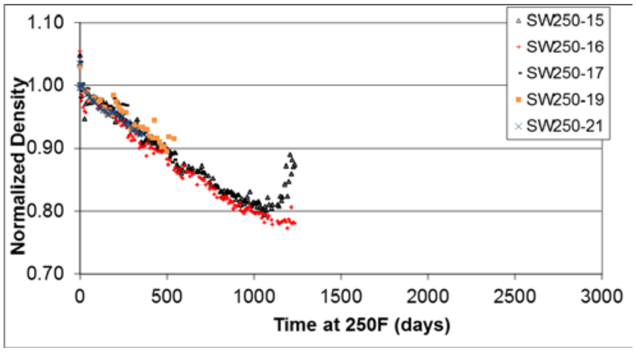


(g) 125 ºF, dry

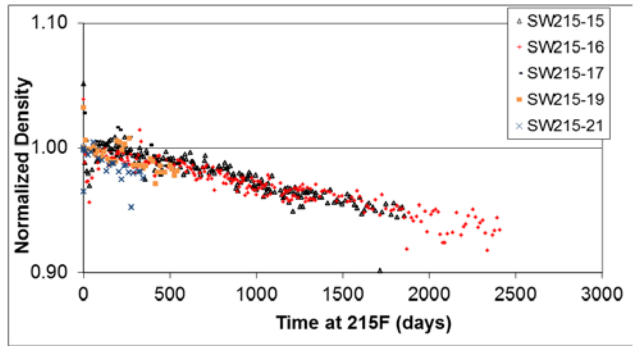


(h) 125 ºF, 70% RH

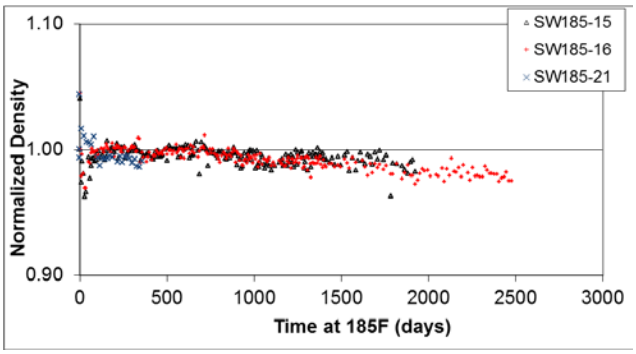
Figure 8. Weight data for physical property samples in the identified environments.



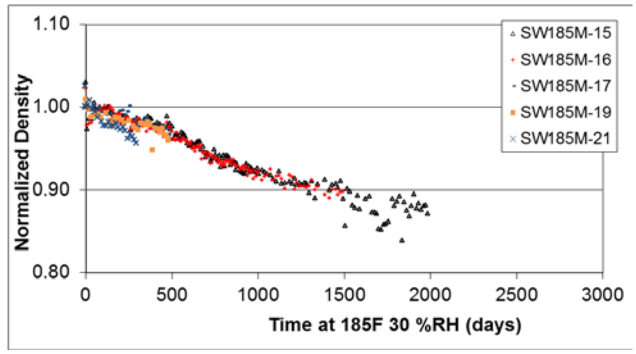
(a) 250 ºF, dry



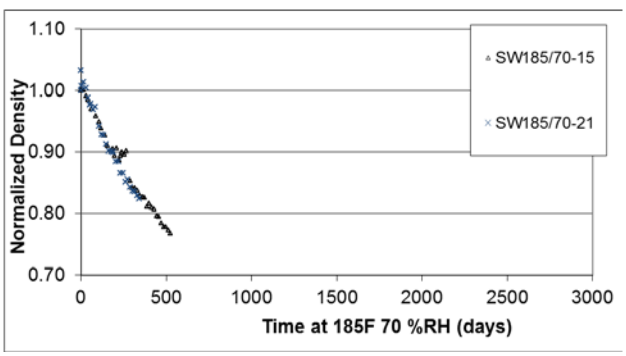
(b) 215 ºF, dry



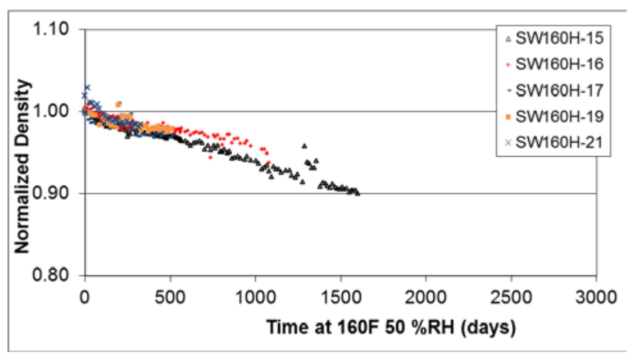
(c) 185 ºF, dry



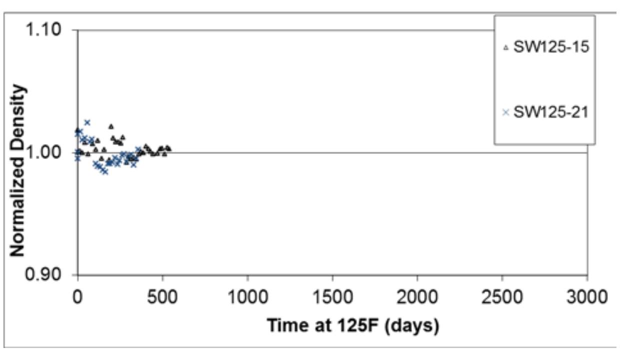
(e) 185 ºF, 30% RH



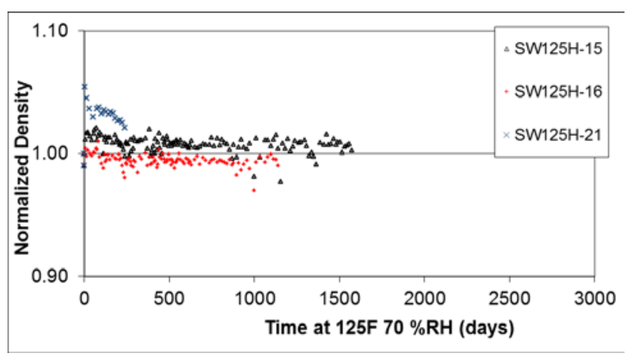
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

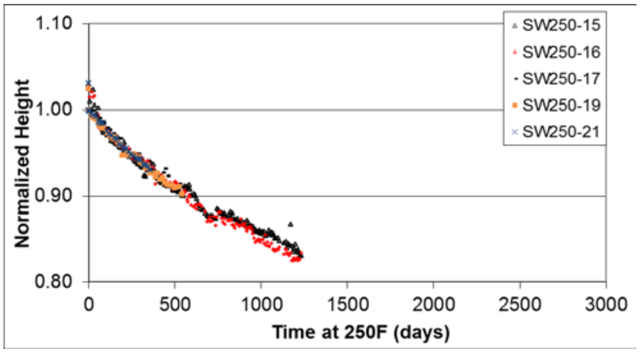


(g) 125 ºF, dry

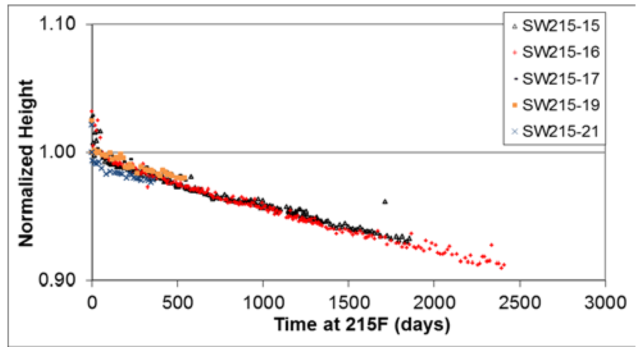


(h) 125 ºF, 70% RH

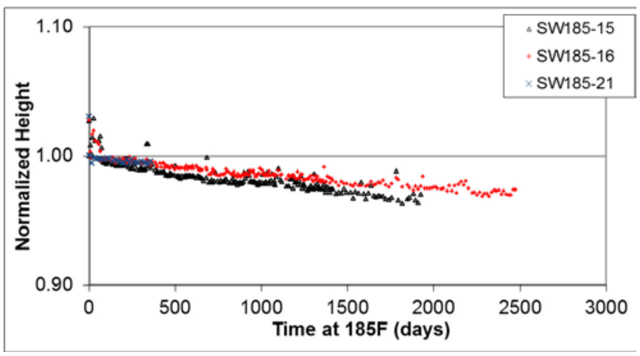
Figure 9. Density data for physical property samples in the identified environments



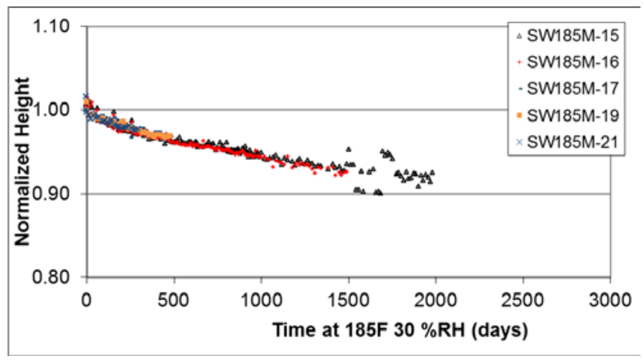
(a) 250 ºF, dry



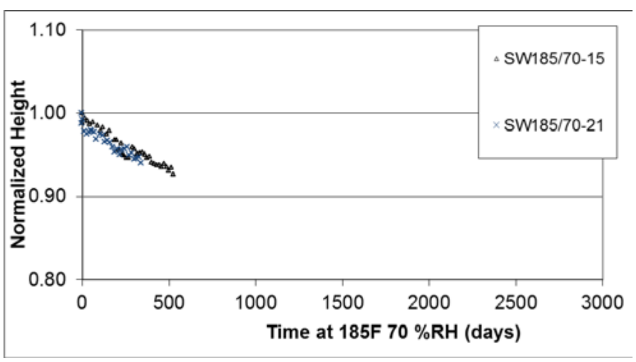
(b) 215 ºF, dry



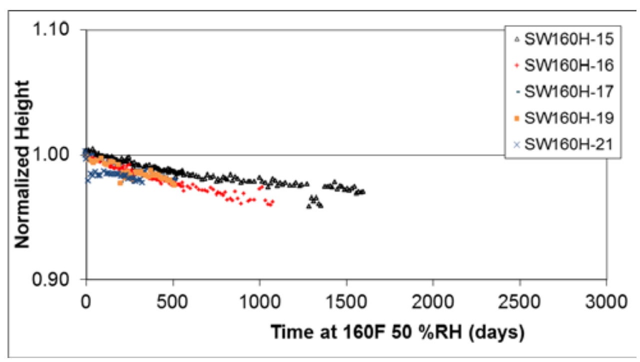
(c) 185 ºF, dry



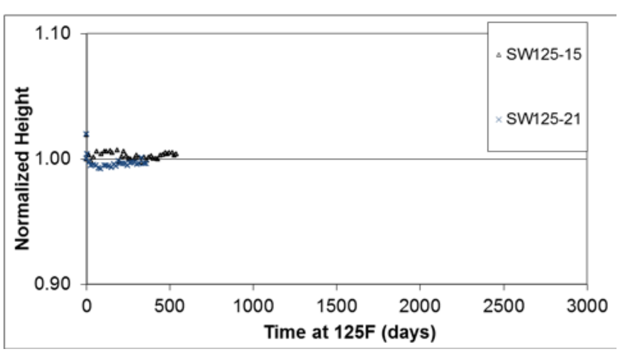
(e) 185 ºF, 30% RH



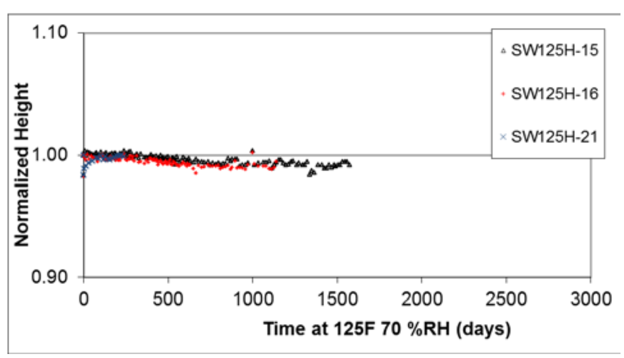
(e) 185 ºF, 70% RH



(f) 160 ºF, 50% RH

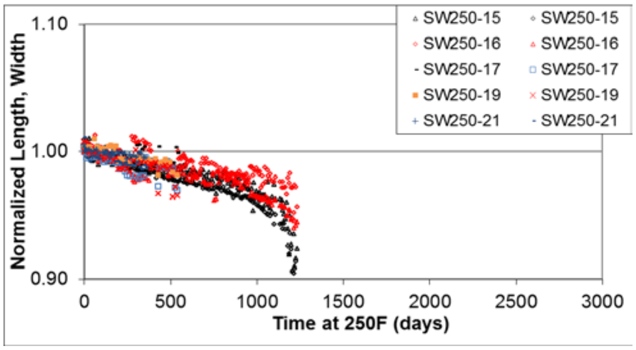


(g) 125 ºF, dry

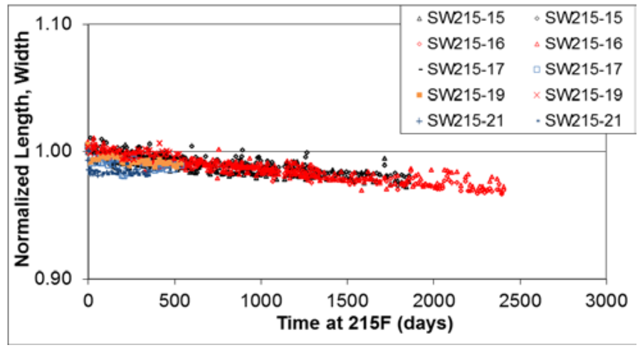


(h) 125 ºF, 70% RH

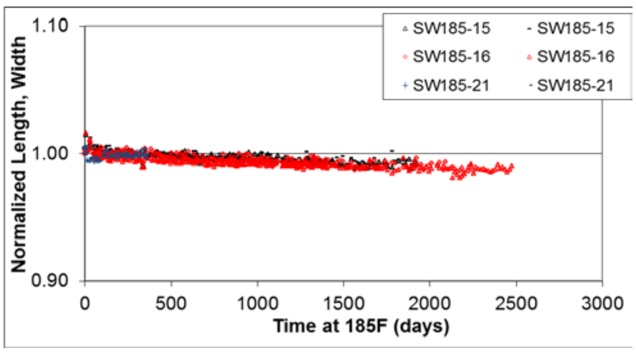
Figure 10. Height data for physical property samples in the identified environments



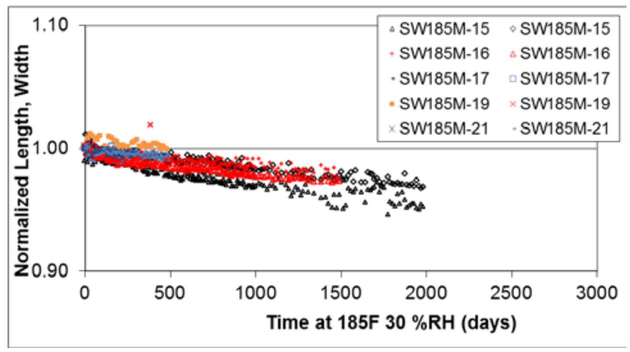
(a) 250 ºF, dry



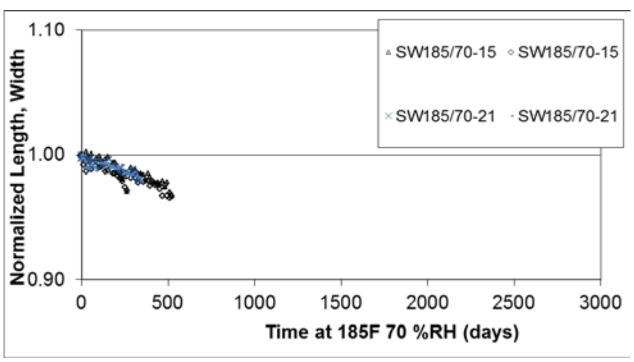
(b) 215 ºF, dry



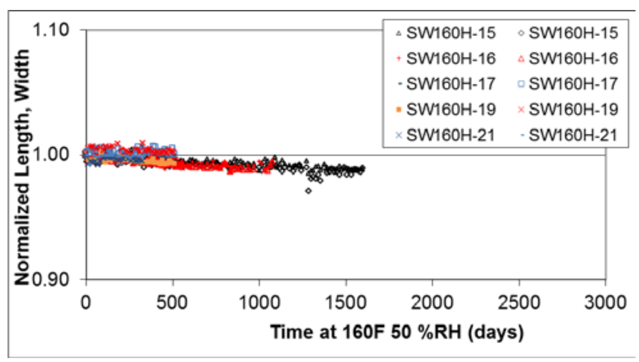
(c) 185 ºF, dry



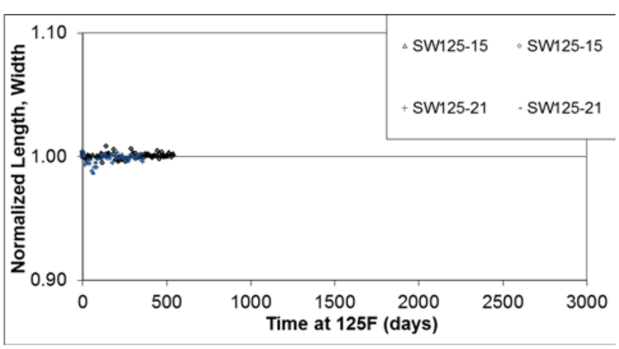
(e) 185 ºF, 30% RH



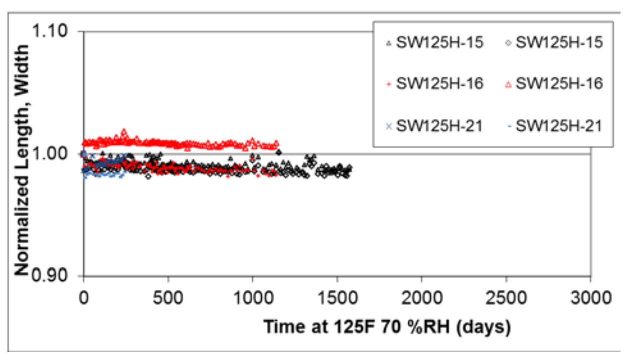
(e) 185 ºF, 70% RH



(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

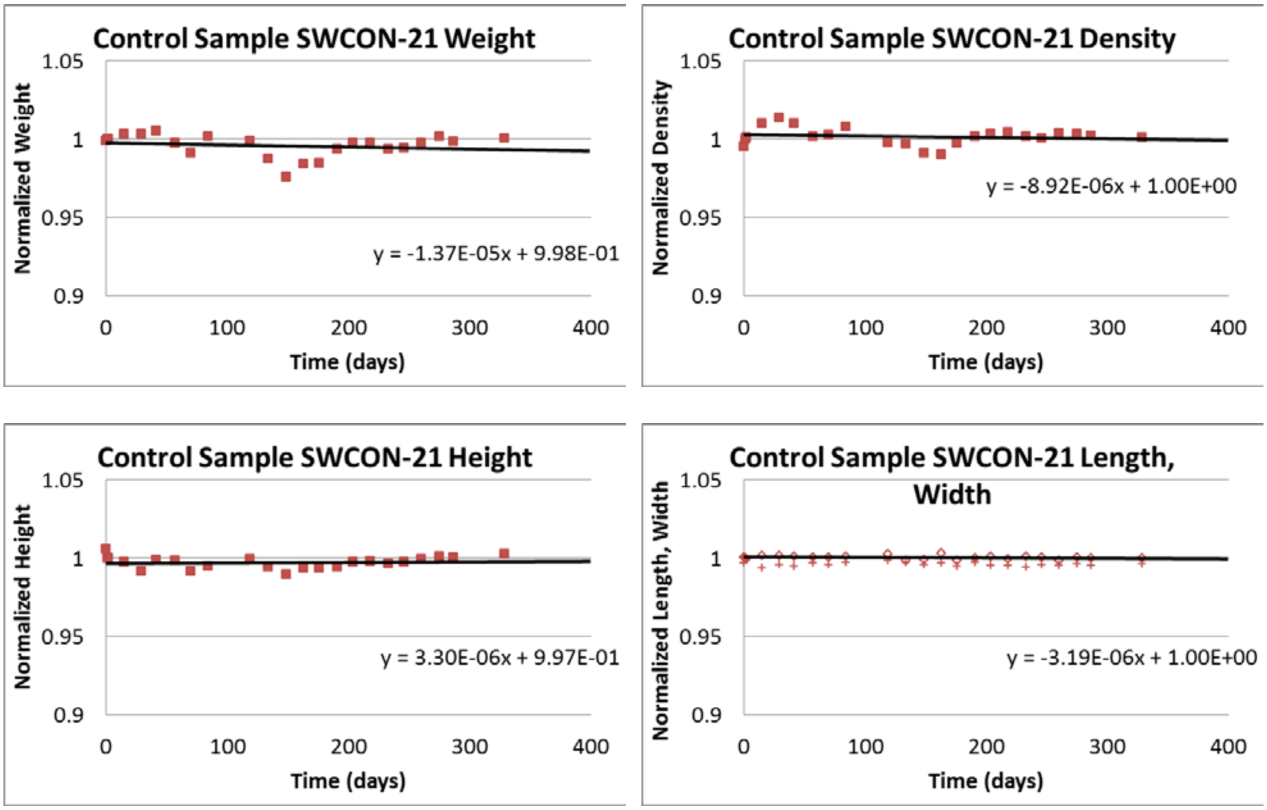


Figure 12. Physical property data for control sample SWCON-21.

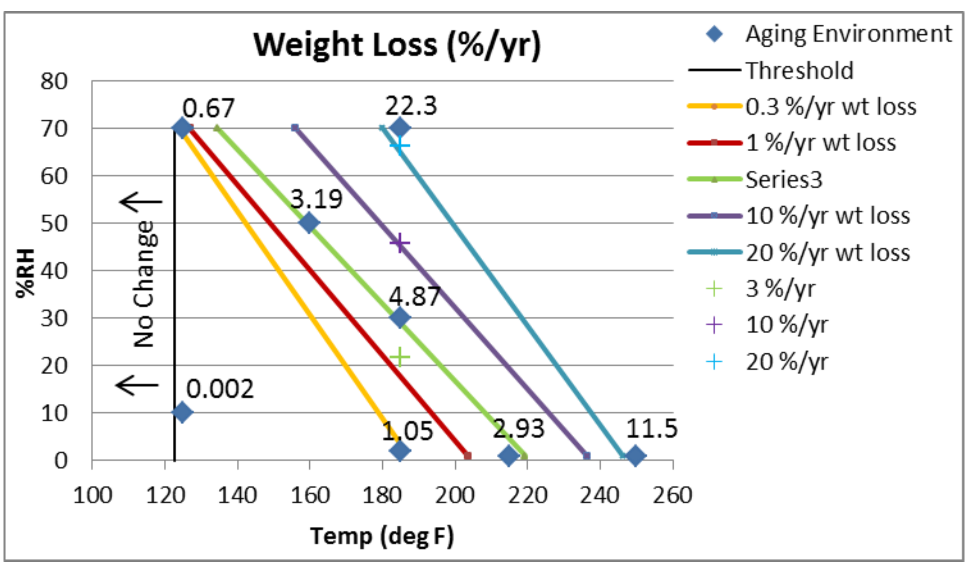


Figure 13. Softwood fiberboard weight loss model. Lines represent contours of equal rate of weight loss. Numerical values are the average degradation rates of aged samples.

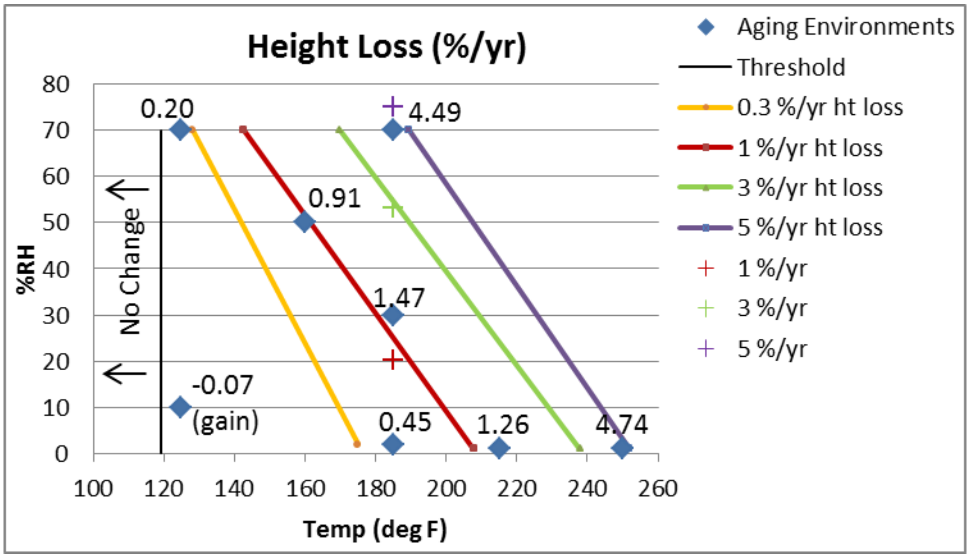


Figure 14. Softwood fiberboard height loss model. Lines represent contours of equal rate of height loss. Numerical values are the average degradation rates of aged samples.

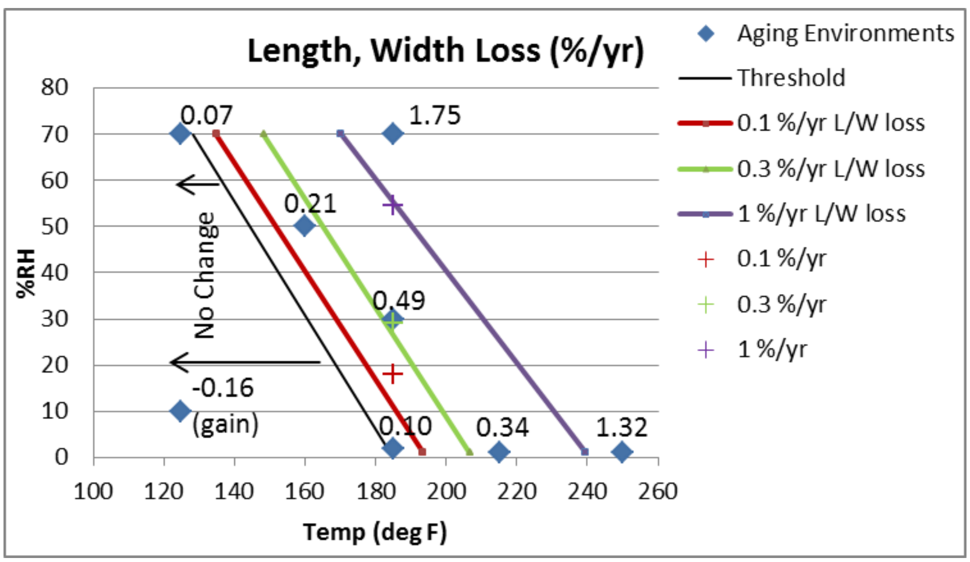


Figure 15. Softwood fiberboard length / width loss model. Lines represent contours of equal rate of length / width loss. Numerical values are the average degradation rates of aged samples.

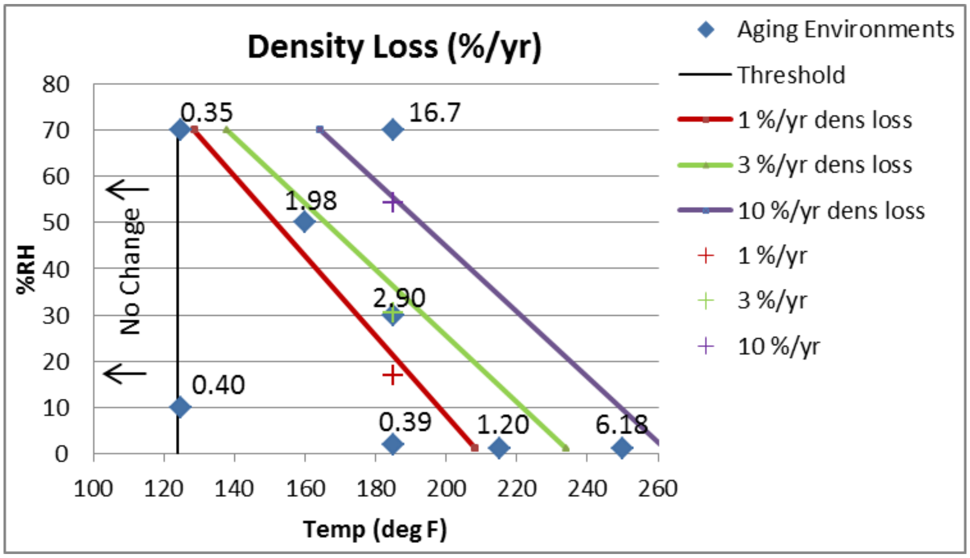


Figure 16. Softwood fiberboard density loss model. Lines represent contours of equal rate of density decrease. Numerical values are the average degradation rates of aged samples.

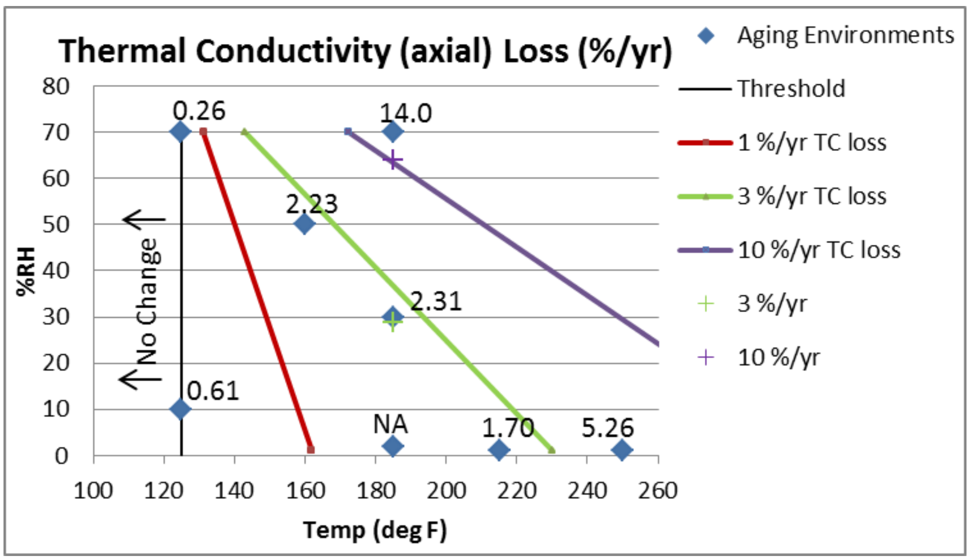


Figure 17. Softwood fiberboard thermal conductivity, axial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the axial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in the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

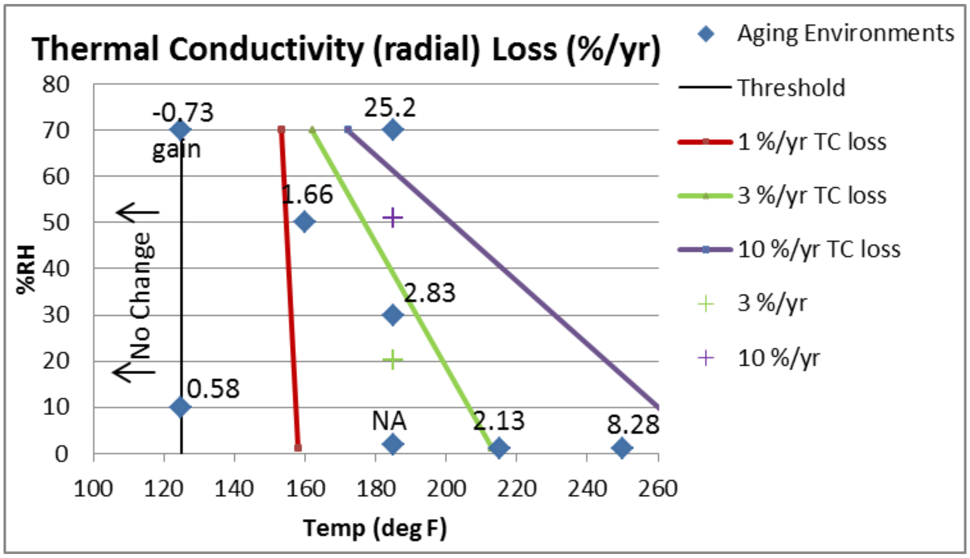


Figure 18. Softwood fiberboard thermal conductivity, radial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the radial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in 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.

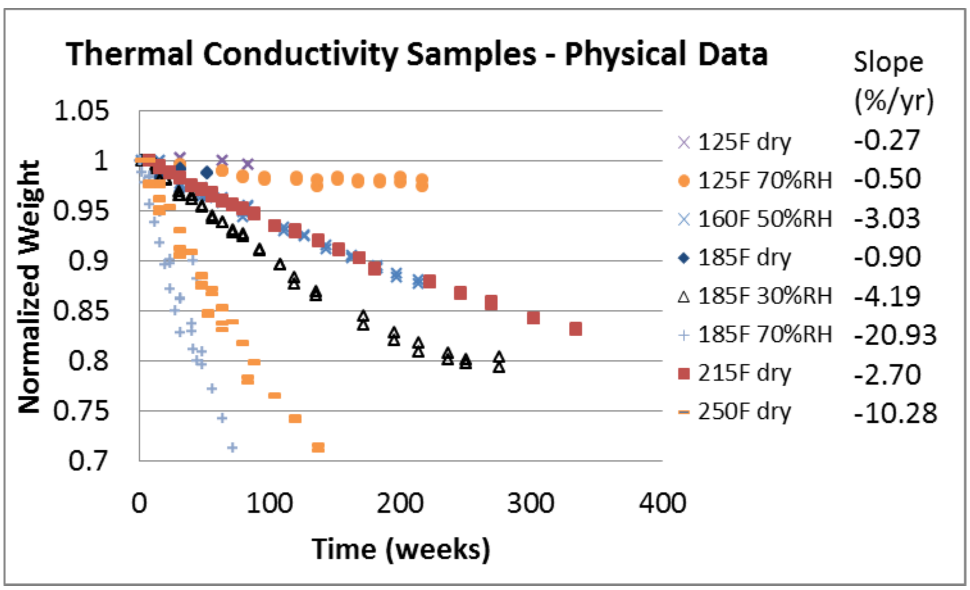


Figure 19. Physical data (weight change) trends from thermal conductivity samples

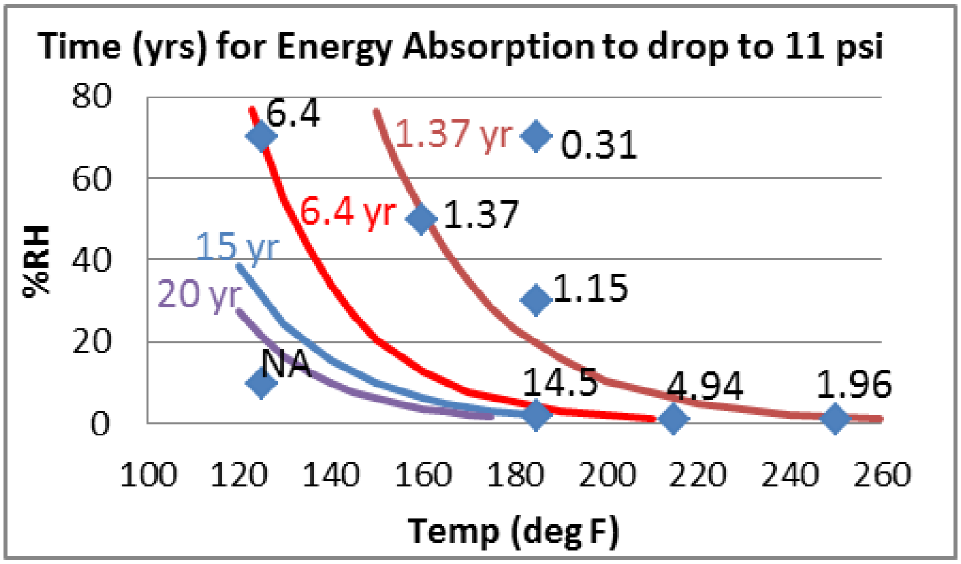


Figure 20. Model for energy absorption, based on compression test area under the stress-strain curve up to 40% strain. This graph shows contour lines describing environments for which energy absorption is predicted to drop to 11 psi over periods of 1.37, 6.4, 15 and 20 years. The numbers are the average lifetimes based on compression tests in the parallel orientation.

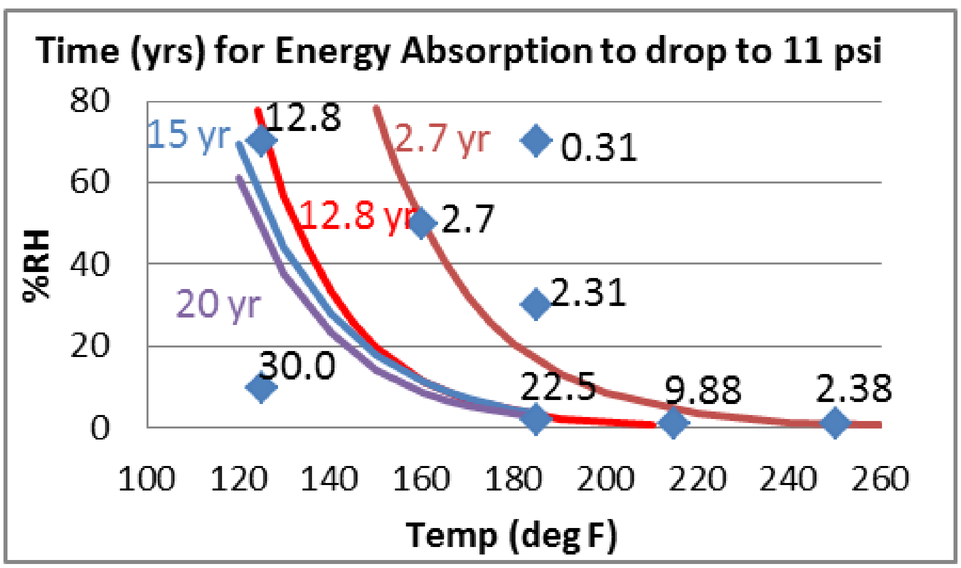


Figure 21. Alternate approach results for energy absorption, based on compression test area under the stress-strain curve up to 40% strain. This graph shows contour lines describing environments for which energy absorption is predicted to drop to 11 psi over periods of 2.7, 12.8, 15 and 20 years. The numbers are the average lifetimes based on the averaged behavior of parallel and perpendicular orientation samples.

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