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

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Summary

Thermal, mechanical and physical properties have been measured on cane 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 aging models fit to the data. Correlations relating several properties (thermal conductivity, energy absorption, weight loss and height decrease) to their rate of change in potential storage environments have been developed. Combined with an estimate of the actual conditions the fiberboard experiences in KAMS, these models allow development of service life predictions.

Some of the predicted degradation rates presented in this report are relatively extreme. However, these relate to environments that do not exist within KAMS, or would be postulated only as upset conditions that would not likely persist for an extended period. For a typical package 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. Little or no degradation of the fiberboard is expected for typical storage conditions. It should be noted that the ultimate 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 KAMS. Additional data continue to be collected to permit future refinements to the models and assumptions.

For developing service life predictions, the ambient conditions within KAMS 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. While the outer drum does not provide an air-tight seal, it does greatly restrict the gain or loss of moisture in the fiberboard. 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, and anomalous humidity changes could be avoided.

Further work should be performed to better define KAMS 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.

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 bounding estimate of the range of environments which fiberboard in KAMS can experience is illustrated in Figure 1. Also shown in this figure is the range of fiberboard environments under loss of ventilation (including natural convection) conditions.

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 [2]. Thermal tests are performed to measure thermal conductivity and specific heat capacity. The thermal conductivity is measured on two sample orientations; the axial orientation measures the conductivity of heat perpendicular to the fiberboard layers (axial heat flow within the package), and the radial orientation measures the conductivity of heat parallel to the fiberboard layers (radial heat flow within the package). Compression test samples are tested in either of two orientations, with the applied load either parallel or perpendicular to the fiberboard layers. Physical measurements are made for small samples (~2 inch cubes) in each conditioning environment as well as for full sized upper fiberboard assemblies. The upper assemblies are maintained in an ambient environment and track seasonal variation in 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 years in storage.
- 2234, 826 – lower assemblies removed from packages following several years service in KAMS and subsequent surveillance activities.
- 826U, 600U – upper assemblies removed from packages following several years service in KAMS 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 September 2012. 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 environmental chambers have been available for conditioning samples.

Baseline and long-term testing of mechanical and thermal properties through fiscal year 2010 has been reported previously [3, 4]. Additional data have since been collected, and the cumulative data set through September 2012 has been analyzed for the development of an aging model. All the data considered herein have been collected on cane fiberboard samples. Recently, the use of softwood fiberboard in 9975 packages has been approved. A separate effort is in progress to demonstrate the degree to which the two materials are comparable in regards to aging behavior. At this point, the conclusions of this report are applicable only to cane fiberboard.

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.

Typical compression stress-strain curves are shown in Figures 2-3 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 (LD1, LD2, MSC, New and KT2).

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, and representative groupings of these data are presented in Figures 4-6.

Several trends in the compression test data can be summarized as follows:

- The buckling strength (for parallel orientation) and the area under the curve to 40% strain (for both orientations) decrease with increasing exposure time at 250 ºF. A similar trend might exist at 215 ºF, but is weaker and less consistent. No significant change over time is observed at lower temperature dry environments.

- The buckling strength (for parallel orientation) and the area under the curve to 40% strain (for both orientations) is significantly lower after conditioning at 100% relative humidity (RH) (regardless of the temperature) compared to samples conditioned at lower humidity levels. To a lesser extent, the buckling strength and area under the curve to 40% strain (for parallel orientation samples) are lower at 70% RH than for lower humidity levels, and tend to decrease over time. There are insufficient data for perpendicular orientation samples to identify whether such a trend exists for them as well.
- Mechanical properties vary from one package to another. For example, samples from the New package tend to have the highest buckling strength and the highest area under the curve to 40% strain for each conditioning environment in which they were tested. Samples from the LD2 package tend to have the lowest buckling strength for each conditioning environment in which they were tested.

Thermal Tests
Thermal conductivity data for each environment are summarized in Figure 7. 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. Several trends are summarized as follows:

- In the 250, 215 and 185 ºF dry environments, the thermal conductivity decreases with increasing conditioning time. The rate of change increases with temperature. No significant change over time is observed in a 125 ºF dry environment.
- At 185 ºF, the thermal conductivity decreases faster as the humidity level increases. The rate of decrease at 185 ºF 70% RH is greater than in a 250 ºF dry environment. This effect of humidity is not seen at 125 ºF comparing a dry oven with 70% RH.
- A similar rate of decrease in thermal conductivity is seen in the 160 ºF 50% RH, 185 ºF 30% RH and 215 ºF dry environments.

The thermal conductivity samples conditioned at 250 ºF were moved from one oven to another after 56 weeks. It was subsequently noted that a temperature gradient within the first oven caused each thermal conductivity sample to have been at a different temperature. The actual temperatures were subsequently estimated to range from 242 to 279 ºF [5].

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 8. In general, an increase in humidity (and in sample moisture content) results in an increase in specific heat capacity.

The measured specific heat capacity has decreased by about 24% while conditioning at 250 ºF over ~5 years. This may reflect an actual property change, or it may be an artifact resulting from sample shrinkage, which has been significant over this period. A smaller sample produces a loose fit in the brass capsule that is used to measure specific heat capacity, and may impede the conduction of heat from the sample. This in turn may reduce the measured specific heat capacity. Testing of samples that were progressively reduced in size (without conditioning) was inconclusive in demonstrating the extent of this effect.

The nominal decrease in specific heat capacity is shown under Figure 8 by the coefficient in each equation that was fit to the data for each environment. The highest rate of decrease is seen for 160 ºF 50 %RH and 250 ºF dry environments. The high rate for 160 °F 50 %RH likely reflects the very limited data (4 points) and the degree of scatter in the data, and is expected to decrease with the accumulation of additional data.

Physical Tests

The weight and density of samples in each environment have been tracked. 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.

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 values of these samples are summarized in Figures 9-12. 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 were added subsequently.

For samples conditioned at temperatures of $\geq$160 ºF, a continuous weight loss (beyond an initial change due to moisture loss / gain) is observed. The rate of weight loss is greater with higher temperatures and with increased humidity. In the 125 ºF dry environment, a slight decrease in weight is observed, superimposed on a stronger seasonal variation. No significant change in weight was observed at low temperatures (50, 15 ºF). Samples from the different material sources behave similarly, with about the same rate of weight loss in a given environment.

In Figure 9 (a), the MSC sample shows a change in weight loss rate after approximately 330 days at 250 ºF. This was attributed to temperature gradients within the oven initially used to condition those samples [5]. Analysis of the available data suggests that these physical property samples were at a location within the oven with an actual temperature of approximately 236 ºF. The samples were subsequently moved to a different oven with a more consistent temperature profile, and the weight loss rate has since been consistent with that for the other samples subsequently added at this temperature. This same effect is also seen in the density (Figure 10(a)) and height (Figure 11(a)) data.

Density data for the physical property samples are shown in Figure 10. For samples conditioned in dry ovens at 215 and 250 ºF, a continuous decrease in density is observed. Within each of the humid environments at 160 and 185 ºF, a continuous density decrease is observed. At 125 ºF 70% RH, there is no significant change in density over time. Above 125 ºF, the rate of density loss is greater for higher temperatures and higher humidity levels. Comparable rates of density loss are observed for the various material sources within each environment. Qualitatively, dimensional changes in each environment follow those described for density. The change in height tends to be significantly greater than the change in length or width for a given environment.

Three fiberboard upper subassemblies have been weighed and measured periodically (see Figure 13). Following the accumulation of greater than 12 months data, and establishing the seasonal variation in these measurements, several incremental changes were made in the exposure of these assemblies, as follows.

- Each upper subassembly was initially exposed to ambient environment, in a room that experiences some degree of temperature and humidity fluctuation.
- One upper subassembly was placed back inside its drum in October 2005 (Figure 13, point 1) and removed only for weekly (initially) or monthly measurement. The lid was loosely placed on the drum. This provides a lower bound estimate of the degree of isolation provided by the drum.
- A second upper subassembly was placed back inside its drum in June 2006 (Figure 13, point 2) and removed for measurement at intervals of several months duration. The lid was loosely placed on the drum. By varying the opening frequency for these two drums, but observing the same weight changes, it was shown that opening the drums to weigh the subassemblies did not influence the weight change.
- The lid for the second upper subassembly in its drum was bolted tight in August 2007 (Figure 13, point 3). This provides a more realistic estimate of the degree of isolation provided by the drum in service.

Comparing the range of seasonal weight change for subassemblies in and out of a drum shows a significant degree of isolation is provided by the drum, even with the lid only loosely placed. Over the 1 year period from 8/07 to 8/08, the open subassembly experienced a total weight variation of 178g (or 1.5% of its total weight). During the same period, the subassembly in a drum with the lid loosely placed experienced a weight variation of 21g (0.18 wt%), and the subassembly in a drum with the lid bolted in place experienced a weight variation of 4g (0.034 wt%).

Termination of 250 ºF Aging Environment Samples

All of the original cane fiberboard samples aging at 250 °F have been terminated, as described below. Samples conditioning in other environments will also be considered for termination as similar circumstances arise.

Compression Test Samples

The area under the stress-strain curve up to a strain of 40% has been adopted as a metric for relative comparison of compressive behavior between different samples. Finite element analysis has been performed to demonstrate that the 9975 package in KAMS will survive a forklift impact scenario even if the nominal fiberboard compression strength is reduced by 80%. [6] 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 6 calculation uses a fiberboard stress-strain curve for sample "16pkg", reported in Reference 7. 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.

Since the forklift impact scenario loads the fiberboard primarily from the side, the compression test metric (area under the stress-strain curve up to 40% strain) for samples tested with the load applied in the parallel orientation will be considered. At 250 °F, this metric had dropped to 11 psi or less within 64 weeks of conditioning, and remained under this limit (see Figure 14). For package source NEW, no compression test data is available beyond 32 weeks conditioning, but the available data extrapolate to a similar conclusion – that the metric would be less than 11 psi after 64 weeks conditioning at 250 °F. In January 2009, the few remaining compression samples conditioning at 250 °F were tested, with a total conditioning time of 193 weeks. All data from samples conditioned beyond 64 weeks support the conclusion that the fiberboard will not perform its energy absorption function after 64 weeks at 250 °F.

Compression samples that are tested in the lab are done so without lateral constraint, allowing the sample to shift or bow sideways under load. With this arrangement, the area under the stress-strain curve tends to be reduced relative to that for a constrained sample, and the degradation indicated by the metric will conservatively under-predict the energy absorption capacity of the fiberboard. This conservatism is greater in the drier (hotter) environments, since the dry samples have a greater tendency to slip sideways under load. In contrast, the fiberboard in a 9975 package experiences some degree of lateral constraint, with side motion limited after the air gaps around the fiberboard assembly have been filled by shifting fiberboard. In this configuration, the degree of strain experienced by most regions of the fiberboard assembly is limited as the material starts to compress locally and the stress re-distributes to adjacent less-compressed fiberboard regions. As the fiberboard shifts within the drum, the peak fiberboard strains are limited. By considering the energy absorbed by the fiberboard only up to 40% strain, the increased energy absorption capacity at higher strains (see for example, the significant increase in compression strength above 60% strain in Figure 2), is conservatively excluded.

Physical Property Samples

The physical property samples were removed from conditioning at 250 ºF in January 2011, following up to 275 weeks in that environment. All samples had experienced greater than 50% decrease in weight. They were also significantly darkened and fragile (Figure 15) and prone to breakage during handling. The relative change in the physical properties at the time testing was discontinued is summarized in Table 6.

Reference 8 recommends limits on fiberboard density and dimensions based on the values assumed in the nuclear criticality safety evaluation. This evaluation assumed a 2.5 inch radial and 4.0 inch axial fiberboard dimensional loss, and density of 0.20 g/cc. Response limits were recommended that are conservative to these assumed values – 0.5 inch dimensional loss (in either direction) and 0.21 g/cc density. At the time of removal, the physical property samples had experienced the following:

- height loss of ~20-30%, corresponding to ~7 – 10 inches loss in a full fiberboard assembly. This greatly exceeds the assumed loss and the response limit.

- length / width loss of ~8-14%, corresponding to ~0.4 – 0.7 inches radial loss in a fiberboard assembly. This equals or exceeds the response limit for most samples.
- density loss of 23-32%. Fiberboard assembly density measured on destructive examination (DE) packages ranges from 0.24 to 0.30 g/cc. For an average density of 0.27 g/cc, the observed losses correspond to final densities of 0.18 to 0.20 g/cc, which is equal to or less than the value used in the nuclear criticality safety analysis.

Thermal Samples
Most of the thermal conductivity sample and all of the specific heat capacity samples were removed from the 250 ºF dry environment in September 2010. The thermal conductivity samples had been aging for up to 272 weeks, and had last been tested following a maximum 255 weeks exposure. The specific heat capacity samples had been aging for 268 weeks, and had last been tested following 258 weeks exposure. The two remaining thermal conductivity samples began conditioning later than the rest, and were removed in August 2012 following 180 weeks aging.

These samples showed extreme degradation, discoloration and darkening, and fragility at the time of removal (Figure 16). Breakage during handling was occurring with increasing frequency. (One exception is that two low density thermal conductivity samples remained in the oven since they began conditioning significantly later than the other samples.) Specific acceptance criteria for thermal properties to define an end-of-life condition have not yet been identified.

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 KAMS. The typical package stored in KAMS 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 KAMS can vary seasonally, or due to changes in HVAC status. The normal ambient temperature in KAMS is less than 90 °F, even in the summer. However, with loss of ventilation, the maximum ambient temperature increases to 137 °F [10], and the corresponding shield temperature is 196 °F [11] with 19 watts internal heat load. The maximum fiberboard temperature is assumed to be similar to this shield temperature. With normal ventilation conditions, the fiberboard temperature should generally remain below ~150 °F for all packages. For a typical ambient temperature of ~85 ºF and an internal heat load of 10 watts or less, the maximum fiberboard temperature is expected to be about 115 ºF.

To date, all 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 KAMS 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 KAMS.

The 9975 SARP notes that the package does not provide an air- or water-tight seal. However, upper fiberboard subassembly testing described above 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.

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.

An 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 outside and bottom.

Data have been collected comparing the moisture content of fiberboard samples with the equilibrium relative humidity of the surrounding air [9]. These data suggest that moisture content between 8 and 18 %WME (a typical range for many packages) corresponds to an equilibrium relative humidity between approximately 40 and 75% at room temperature. At a moisture content of 22 %WME, these data suggest the equilibrium relative humidity would be >80%. Additional effort is required to demonstrate how this information scales up to a 9975 package with an internal heat source. For example, the Reference 9 data indicate that the relative humidity in air surrounding the fiberboard increases at elevated temperature (up to ~160 °F) for the same fiberboard moisture content, indicating a decrease in the fiberboard moisture content with elevated temperature. These data indicate that the humidity within packages in storage could be significant, especially around the OD and bottom.

A variety of temperature / humidity combinations should be considered in conjunction with understanding the range of conditions within KAMS to adequately identify a limiting service life. For instance, for an ambient temperature of 90 °F, the maximum fiberboard temperature of ~150 °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 close in temperature to the ambient value of ~90 °F or less. Other intermediate temperature / moisture combinations should also be considered, including the milder temperatures that would accompany heat loads less than 19 watts.

In the laboratory testing, there are two contributions to property changes – immediate, reversible changes due to change in moisture content, and irreversible changes due to degradation. When a sample 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 [12] 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.
- Specific heat capacity will decrease as moisture content decreases. This effect is reported in the literature [12] 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 7 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%. These data also indicate several temperature – humidity combinations which do not produce a significant weight change (i.e. a moisture content close to 10 wt% is the equilibrium condition for these environments. These environments include 185 ºF 70%RH, 160 ºF 50%RH and 15 ºF 60%RH. These same environments have somewhat varying effects on the other physical properties.

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 [13]. In addition to water vapor, compounds from pyrolysis are evolved at temperatures as low as 95 ºC (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 degradation rates. They do not include the 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 weight and density data for two of these control samples are shown in Figure 17. In addition, the overall rate of change in weight and density is indicated. Both of these samples show a slight decrease in weight over time (~0.1 – 0.2 %/year), with 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.

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.

Mold has been observed in 8 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 [14]. An extreme example of mold was observed in another 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) [15]. 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

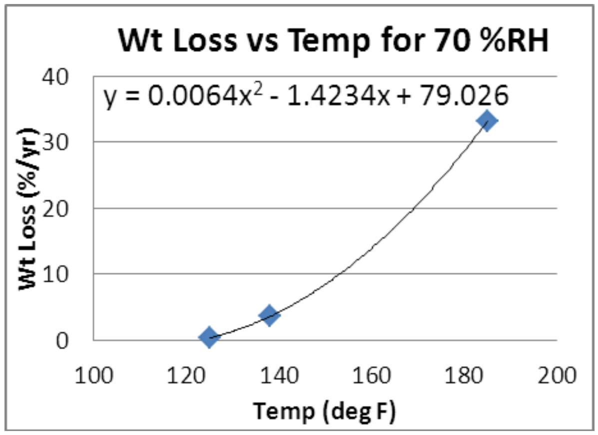
Aging models have been constructed based on the observed changes in several fiberboard properties. These include weight, height, thermal conductivity (axial and radial) and energy absorption (area under the stress-strain curve to 40% strain). Most of the models are based on the average behavior of all samples, and do not reflect any variation among packages or samples. The following approach was used to model the change in fiberboard weight, height, and thermal conductivity (axial and radial orientations). 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 9 for normalized weight change).

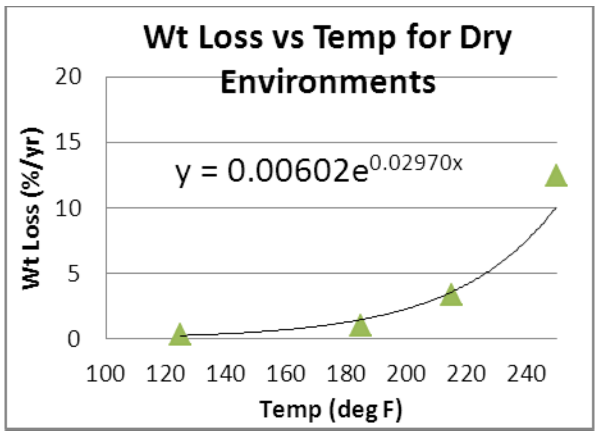
2. It is observed that very similar rates of change occur for 215 °F dry, 185 °F 30%RH and 160 °F 50%RH environments, and that these 3 environments fall close to a common straight line in humidity – temperature space. This same line includes the environment of 138 °F 70%RH. It is assumed that the average of the rates for these 3 environments (3.6 %/year

decrease in weight) is also valid for an environment of 138 °F 70%RH.

3. A curve is fit to rate of change vs temperature for 3 environments – 125 °F 70%RH, 138 °F 70%RH and 185 °F 70%RH. A binomial provides the best fit, and represents the variation with temperature at a constant relative humidity of 70%.

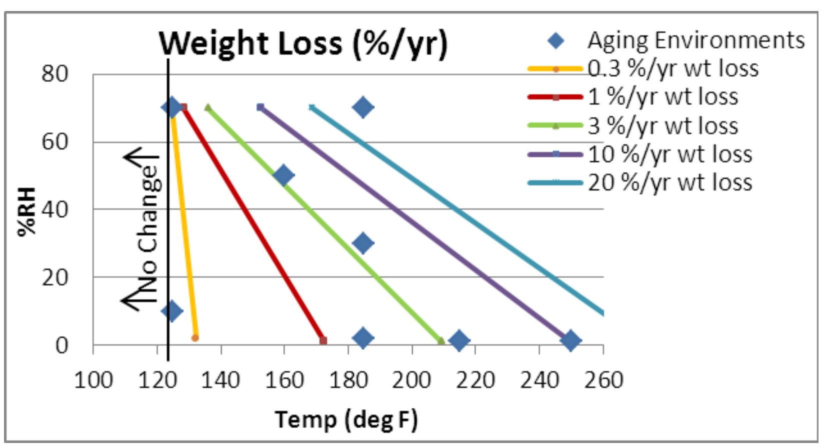


4. A curve is fit to rate of change vs temperature for 4 dry environments – 125 °F dry, 185 °F dry, 215 °F dry and 250 °F dry. An exponential relationship provides the best fit, and represents the variation with temperature at a low value of relative humidity (~1-10%).

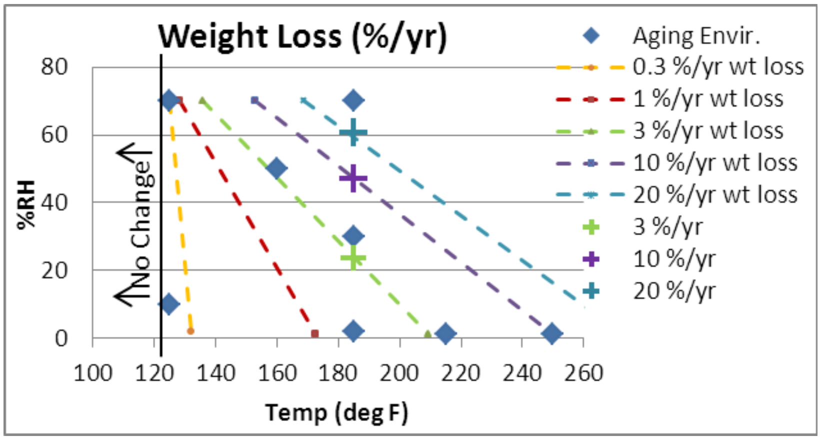


5. The two curve fits developed for the two relative humidity extremes are used to predict the temperatures at which specific rates of change will occur (e.g. a 1% rate of weight loss is predicted at 172.5 °F for low relative humidity, and at 128.4 °F for 70% RH).

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. Based on the very low rates of weight loss at 125 °F dry and 125 °F 70 %RH, it is assumed that there is no change in weight at lower temperature environments.



7. 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.



8. For a given combination of temperature and relative humidity within the envelope provided by the data, the graphs provide an estimate of the rate of change for the properties considered.

The aging models are shown graphically in Figures 18 – 21 for weight, height, 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 22 and Table 8.

A slightly 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 (Table 3).
- 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.

As described above, a strength criterion limiting the area under the stress-strain curve to at least 20% of that for the nominal stress-strain curve (i.e. 11 psi) is adopted for this analysis. Since the forklift impact scenario primarily loads the fiberboard in a parallel orientation, test data from that orientation are used in model development.

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)

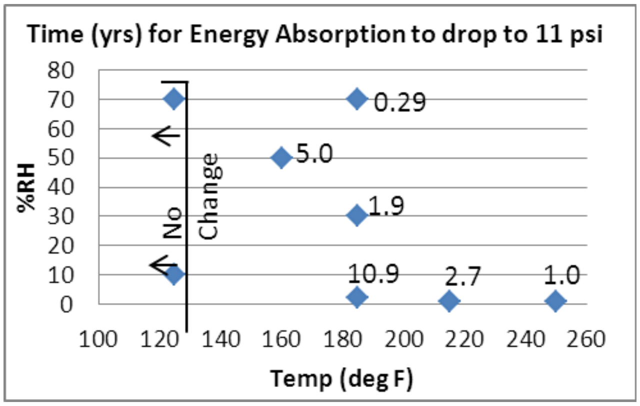
In this equation, the exponential factor "b" describes the rate of decrease of the area under the stress-strain curve.

It is observed from Table 3, that baseline values for area under the stress-strain curve up to 40% strain vary significantly, but tend to average close to 55 psi (0.055 ksi), consistent with the data used in the forklift impact calculation. However, given the variation observed between source packages, combining (or averaging) the data from multiple packages may be non-conservative. Rather, the exponential fit is applied separately to data from each source package in each environment, and the time for the energy absorption of that source package to decrease to 11 psi is calculated from the curve fit. For each environment, the source package with the shortest time to decrease to 11 psi is conservatively used, with two exceptions:

- In the 160F 50%RH environment, samples from 4 of the 5 source packages were aged and tested through 8 weeks only, and scatter in these limited data lead to a positive increase in energy absorption over time. Only New package material shows a decrease with time.
- In the 125F 70%RH environment, samples from 2 of the 4 source packages show a positive increase in energy absorption over time. Since these two source packages (LD1 and New) also experienced the longer aging times (16 and 64 weeks, respectively), it is judged on average that there is no net degradation in this environment.

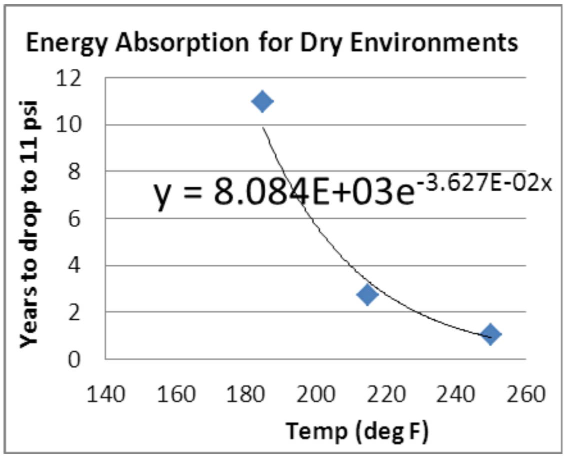
With these minimum "failure" times for each environment, the following approach was used to extrapolate these data to other environments.

1. The initial data are characterized in terms of the minimum time for the area under the stress-strain curve to a strain of 40% to decrease to 11 psi. No significant change in energy absorption is observed for 125 °F dry and 125 °F 70 %RH environments.



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

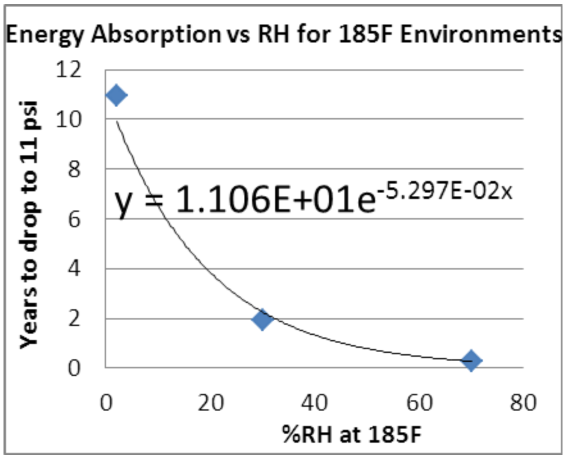
Prediction for 160 °F (dry) = 24 yrs
Prediction for 125 °F (dry) = 87 yrs (consistent with observation of very little change at 125 °F)
Prediction for 173 °F (dry) = 15 yrs
Prediction for 204 °F (dry) = 4.9 yrs



3. Assume 125 °F 70 %RH environment will decrease to 11 psi in half the time as 125 °F dry, e.g. 43.5 yrs.

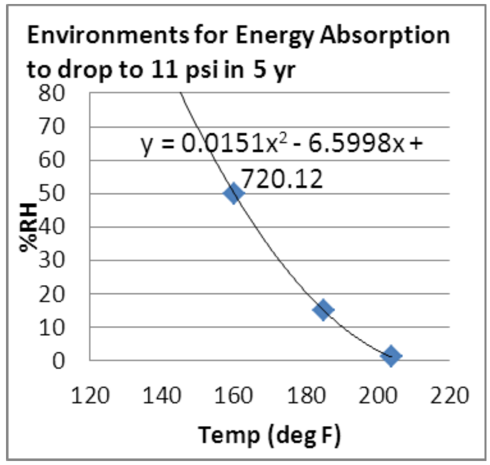
4. Fit an exponential curve to 185 °F environments (dry, 30 and 70 %RH), and interpolate to additional humidity values of interest.

Prediction for 15 %RH = 5 yrs



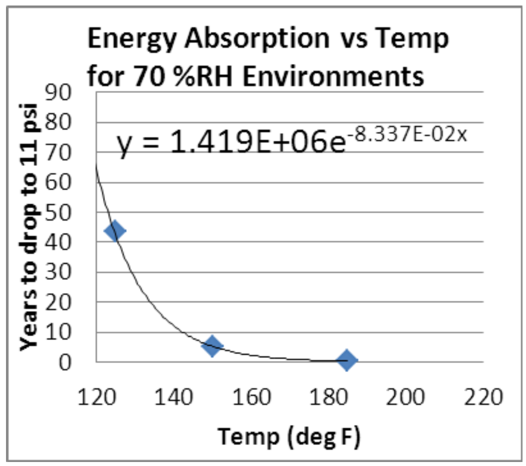
5. There are now 3 environments with an estimated decrease in energy absorption to 11 psi in ~5 yrs – 204 °F dry, 160 °F 50 %RH, and 185 °F 15 %RH. Fit a binomial curve to these data to describe all environments which will produce a similar drop in energy absorption in ~5 yrs.

Prediction – 5 yrs energy absorption to decrease to 11 psi at 150 °F 70 %RH



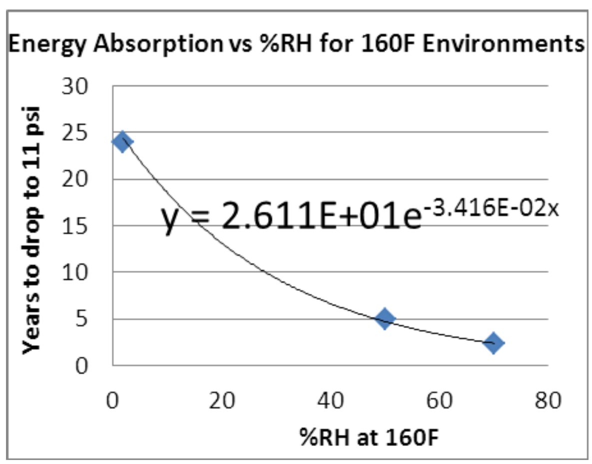
6. There are now 3 temperatures with estimated time for energy absorption to decrease to 11 psi at 70 %RH – 125 °F, 150 °F and 185 °F. Fit an exponential curve to these data, and interpolate to additional temperatures of interest.

Prediction for 160 °F 70 %RH = 2.3 yrs
Prediction for 137.4 °F 70 %RH = 15 yrs

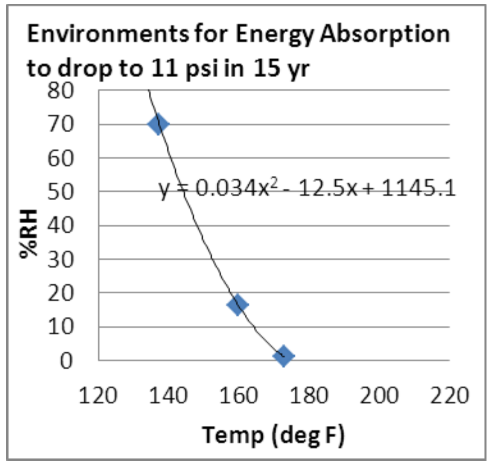


7. There are now 3 RH values with estimated time for energy absorption to decrease to 11 psi at 160 °F – dry (2 %RH), 50 %RH and 70 %RH. Fit an exponential curve to these data, and interpolate to additional humidity levels of interest.

Prediction for 160 °F 16.2 %RH = 15 yrs



8. There are now 3 environments with energy absorption decrease to 11 psi in ~15 yrs – 173 °F dry, 160 °F 16.2 %RH, and 137.4 °F 70 %RH. Fit a binomial curve to these environments to describe all environments which will produce a similar drop in energy absorption in ~15 yrs.



9. The two binomial curve fits developed in steps 5 and 8 provide contour lines describing environments which lead to energy absorption decrease to 11 psi in periods of ~5 yrs and 15 yrs. These are shown in Figure 23, and identify the environmental ranges within which energy absorption will remain above ~11 psi for storage periods of ~5 years or ~15 years. A similar process could be used to identify environmental ranges corresponding to other storage periods.

As noted above, the limited data from several source packages were not used in identifying the minimum degradation rates for the 125F 70%RH and 160F 50%RH environments. Due to the limited aging time and scatter of the results, a curve fit to data from several source packages showed a positive increase over time, although such behavior is not expected to actually occur. This includes samples from source package LD2, which are typically among the weakest samples tested after aging in other environments. Therefore, it is noted that having insufficient data to demonstrate realistic behavior for this source package may represent a potential non-conservative aspect of the above model. To address this situation, additional compression samples from the LD1 and LD2 source packages will be added to the 125F 70%RH and 160F 50%RH environments.

A further consideration in the implementation of any acceptance criterion is that degradation will not occur uniformly throughout the fiberboard. The temperature gradient across the side wall of the fiberboard assembly is modest. For a 19 watt load in a 3013 container, the maximum steady state temperature difference across the fiberboard and drum (in the radial direction) is 47 ºF [16]. Coincident with this thermal gradient, there will tend to be a moisture gradient in the opposite direction (higher moisture content in the lower temperature regions). Since degradation rates are typically dependent on the temperature and moisture content, any gradient in these conditions within the fiberboard assembly will produce a corresponding gradient in the degradation rate. In some cases, the opposite effects of these two gradients may offset each other. More likely, there will be a partial offset, but a net difference in degradation rate across the fiberboard.

The fiberboard environment within the 9975 packages stored in KAMS will vary. The temperature and temperature gradient within a package will vary with the ambient temperature and internal heat load. The moisture content of the fiberboard will largely be determined by the initial fiberboard condition (barring significant water intrusion during service), and the distribution of that moisture will be driven by the temperature gradient.

With an ambient temperature of 85 °F and a maximum internal heat load, the maximum fiberboard temperature will be ~135 °F (along the ID surface) [17]. Based on data from instrumented packages, the temperature along the fiberboard OD is ~40 °F cooler than the ID, or ~95 °F for an ambient temperature of 85 °F. The total moisture content will vary from package to package, but it might be assumed that the typical package will have no more moisture than would be absorbed from the air at 75 °F and 100% RH. Without any redistribution of moisture, the elevated service temperatures would reduce the relative humidity inside the package to ~55% along the fiberboard OD surface and ~17% along the fiberboard ID surface. These are two environments that might exist along the OD or ID surfaces of 9975 packages. The intermediate fiberboard regions would be at intermediate environments. The overall degradation rate would be an average over a continuum of local behaviors for a range of intermediate environments.

In reality, moisture within the package will re-distribute. Moisture levels near the ID surface will be further reduced, while the OD surfaces will become wetter. In addition, there will likely be a net transfer of moisture from the central elevations to the bottom of the fiberboard if a significant heat load is present. In local regions where the moisture level increases further (e.g. above 55% RH), fiberboard weight, density, compressive strength and axial thermal conductivity are expected to decrease at a faster rate.

These changes will have a local (near-surface) effect only, since the moisture extremes will be local. The property limits are developed as bulk average properties. It is judged that even with local surface regions degrading at a significant rate, the overall average rate of change in the bulk fiberboard property will still be low. This judgement is supported by observation of packages removed from service after up to 7 years storage in KAMS. 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 exterior surface compared to the rest of the assembly.

The limiting need for fiberboard compressive strength is the postulated forklift impact event in KAMS. 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.

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.

An improved understanding of the environment within the 9975 drum in storage should be developed. KAMS 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). Further efforts to define moisture content and relative humidity within the packages in storage should provide for a more realistic application of the models.

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 ~7 years. Most of the aging environments are bounding to the conditions expected within the 9975 shipping package during storage in KAMS. Initial models have been developed from this data to provide estimates of degradation rate and/or service life under potential storage conditions for several fiberboard properties, including thermal conductivity, energy absorption, weight loss and height change. 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. This includes placing additional compression test samples from the LD1 and LD2 source packages in the 125 ºF 70 %RH and 160 ºF 50 %RH environments.

The prediction of service life for packages stored in KAMS 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. This process needs to continue 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 KAMS. 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. 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. Further efforts will help understand some of these extreme conditions and provide more realistic predictions.

The assumptions and inputs behind the predictions in this report should be well understood before attempting to identify an actual service life in KAMS. 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 were 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.

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Table 1. Summary of maximum sample exposure times prior to testing, for data through September 2012.

	Maximum exposure time (weeks) through September 2012			
Environment	Thermal Conductivity	Specific Heat Capacity	Compression Strength	Physical Properties
250 ºF oven	255 [1]	258	193	275 [1]
215 ºF oven	304	—	200	334
185 ºF oven	337	368	211	367
185 ºF 30% RH	192	196	98	210
185 ºF 70% RH	22	22	23 [2]	19
160 ºF 50% RH	112	32	64	114
125 ºF oven	337	379 [3]	133 [4]	312
125 ºF 70% RH	80	17	64	90
77 ºF 70% RH	—	—	8	—
50 ºF refrigerator	—	—	—	288
15 ºF freezer	—	—	—	288
Other environments			[5]	

[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 at 70 %RH for the stated period, but also include additional aging time at the same temperature in a dry oven. No significant degradation is observed for samples at these temperatures (125, 185 ºF) in a dry oven.

[3] Exposure time for these SHC samples is through November 2012.

[4] 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 and 70 %RH. No significant degradation has been observed from the aging periods at 125 ºF 70 %RH.

[5] 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

Environment	(wks)	LD1	LD2	MSC	New	KT2
Ambient	**0**	0.228	0.185	0.164	0.393	0.295
		0.200	0.171	0.242	0.410	0.265
		0.192	0.189	0.180	0.357	0.286
			0.152		0.288	0.252
77F 70%	**2**	0.214	0.156			
	8	0.193	0.129			
125F Dry	**2**	0.242	0.152	0.246		0.275
		0.223**	0.173	0.248		
			0.151**	0.238		
				0.231		
				0.266		
	4	0.289	0.158	0.264		
		0.255**				
	7		0.208	0.234		
	8	0.202	0.189	0.270		
	16	0.258	0.206	0.279		
			0.172			
	21			0.262**		
	32		0.160	0.257		
	35	0.204**	0.176**			
	48	0.228**	0.191**			
				0.259**		
	53			0.234**		
	64		0.183	0.193		
	122			0.217**		
125F 40%	**2**			0.248		0.263
				0.256		
				0.240		
125F 70%	**2**	0.173	0.136	0.184		
	4	0.178	0.136	0.186		
	6	0.165*	0.079*			
		0.183	0.136	0.170	0.197	
	8	0.146*	0.146*			
	10	0.185*	0.120*			
	16	0.175	0.102		0.197	
	32				0.217	
	64				0.214	
125F 100 %	**2**			0.031		0.062
				0.026		
				0.030		
160F 50%	**2**	0.243	0.126	0.203		0.148
		0.218		0.220		
	4	0.181				0.240
		0.257				
	8	0.184	0.113	0.201	0.245	0.198
		0.216		0.231		0.215
	16				0.275	
	32				0.260	
	64				0.168	
185F dry	**2**	0.196	0.170	0.187	0.308	
	4	0.240	0.196	0.148		
	8	0.212	0.155	0.196		
	16	0.206	0.089			
	32	0.227	0.080	0.222	0.346	
					0.348	

Environment	(wks)	LD1	LD2	MSC	New	KT2
185F dry (cont.)	**64**	0.269	0.184	0.217		
	96	0.168	0.148	0.231		
	139	0.206	0.123	0.203		
	179	0.209		0.206		
	211			0.204		
185F 30%	**2**	0.200		0.214	0.283	
	8	0.269		0.226	0.314	
	16	0.284		0.226	0.294	
	32	0.229		0.201	0.290	
	75	0.100		0.109	0.224	
	98	0.098		0.114	0.212	
185F 70%	**2**	0.187	0.123	0.182		
		0.184	0.146			
	4	0.150	0.053	0.159		
	6	0.113*	0.110*			
	8	0.124	0.112	0.130		
	12	0.142	0.093			
	23			0.032*		
215F dry	**2**	0.222	0.147	0.223		
		0.306		0.207		
	8	0.296	0.115	0.200		
	16	0.209	0.153	0.201		
		0.255		0.206		
	32	0.199	0.152	0.185		
	64	0.146	0.111	0.147		
		0.219				
	96	0.194	0.116	0.130		
	148	0.157		0.109		
	200	0.146		0.098		
250F dry	**2**	0.214	0.212	0.288		
		0.187				
	4	0.173				
	7			0.222		
	8	0.125	0.132		0.255	
					0.257	
	16	0.109	0.121			
	32		0.095	0.094	0.135	
	47			0.058		
	64		0.071	0.049		
	96	0.074				
	134		0.024	0.029		
	153	0.044				
	193		0.012	0.033		

Additional Environments

Environment	(wks)	KT2	Environment	(wks)	KT2	Environment	(wks)	KT2
77F dry	**2**	0.264	**195F dry**	**2**	0.172	**195F 100%**	**2**	0.025
		0.269			0.264			0.028
		0.248			0.221			0.027
		0.331			0.239			0.041
77F 100%	**2**	0.072	**195F 40%**	**2**	0.273			
		0.062						
		0.068						

* 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 for stated period, but also include additional time at 125 ºF 70 %RH.

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

Environ-		Area under Curve (ksi) for				
ment	(wks)	LD1	LD2	MSC	New	KT2
Ambient	**0**	0.0359	0.0424	0.0458	0.0698	0.0732
		0.0584	0.0476	0.0600	0.0782	0.0648
		0.0460	0.0490	0.0419	0.0779	0.0673
			0.0378		0.0595	0.0713
77F	**2**	0.0463	0.0419			
70%	**8**	0.0419	0.0367			
125F	**2**	0.0462	0.0378	0.0410		0.0731
Dry		0.0512**	0.0427	0.0472		
			0.0305**	0.0618		
				0.0631		
				0.0682		
	4	0.0558	0.0460	0.0568		
		0.0450**	0.0451**			
	7		0.0435	0.0374		
	8	0.0359	0.0449	0.0583		
	16	0.0404	0.0416	0.0404		
			0.0363			
	21			0.0457**		
	32		0.0418	0.0348		
	35	0.0380**	0.0411**			
	48	0.0395**	0.0413**			
	53			0.0590**		
				0.0404**		
	64		0.0486	0.0516		
	122			0.0444**		
125F	**2**			0.0720		0.0639
40%				0.0576		
				0.0633		
125F	**2**	0.0438	0.0283	0.0417		
70%	**4**	0.0373	0.0371	0.0436		
	6	0.0344*	0.0256*			
	8	0.0373	0.0372	0.0380	0.0443	
		0.0503	0.0362			
	10	0.0334*	0.0345*			
	16	0.0453	0.0255		0.0467	
	32				0.0562	
	64				0.0480	
125F	**2**			0.0084		0.0168
100%				0.0079		
				0.0078		
160F	**2**	0.0571	0.0318	0.0365		0.0248
50%		0.0524		0.0410		
	4	0.0334				0.0433
		0.0506				
	8	0.0565	0.0365	0.0466	0.0551	0.0597
		0.0519		0.0626		0.0425
	16				0.0524	
	32				0.0508	
	64				0.0381	
185F	**2**	0.0353	0.0349	0.0332	0.0470	
dry	**4**	0.0311	0.0459	0.0248		
	8	0.0380	0.0366	0.0374		
	16	0.0457	0.0251			
	32	0.0312	0.0190	0.0458	0.0673	
					0.0653	
	64	0.0243	0.0362	0.0462		
185F	**96**	0.0295	0.0291	0.0386		
dry	**139**	0.0330	0.0298	0.0382		
(cont.)	**179**	0.0228		0.0325		
	211			0.0325		
185F	**2**	0.0504		0.0485	0.0688	
30%	**8**	0.0273		0.0398	0.0671	
	16	0.0248		0.0321	0.0514	
	32	0.0276		0.0431	0.0418	
	75	0.0167		0.0148	0.0283	
	98	0.0105		0.0117	0.0255	
185F	**2**	0.0499	0.0276			
70%		0.0402*	0.0298*	0.0433		
	4	0.0367	0.0180	0.0242		
	6	0.0214*	0.0271*			
	8	0.0181	0.0248	0.0253		
	12	0.0180	0.0215			
	23			0.0060*		
215F	**2**	0.0493	0.0258	0.0398		
dry		0.0416		0.0354		
	8	0.0335	0.0287	0.0188		
	16	0.0418	0.0280	0.0264		
		0.0342		0.0374		
	32	0.0302	0.0291	0.0286		
	64	0.0327	0.0313	0.0237		
		0.0316				
	96	0.0168	0.0195	0.0141		
	148	0.0150		0.0136		
	200	0.0164		0.0058		
250F	**2**	0.0399		0.0472	0.0522	
dry		0.0507				
	4	0.0273				
	7			0.0410		
	8	0.0112	0.0199		0.0400	
					0.0356	
	16	0.0113	0.0178			
	32		0.0159	0.0158	0.0206	
	47			0.0069		
	64		0.0110	0.0092		
	96	0.0090				
	134		0.0034	0.0063		
	153	0.0066				
	193		0.0018	0.0050		

Additional Environments

		KT2			KT2			KT2
77F	**2**	0.0688	**195F**	**2**	0.0453	**195F**	**2**	0.0064
dry		0.0654	**dry**		0.0484	**100%**		0.0075
		0.0619			0.0589			0.0078
		0.0607			0.0461			0.0095
77F	**2**	0.0189	**195F**	**2**	0.0482			
100%		0.0188	**40%**					
		0.0171						

* 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 for stated period, but also include additional time at 125 ºF 70 %RH.

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

Environment	(wks)	Area under Curve (ksi) for LD1	LD2	MSC	New	KT2
Ambient	**0**	0.0461	0.0308	0.0331	0.0527	0.0493
		0.0368	0.0297	0.0294	0.0517	0.0594
			0.0253			0.0528
						0.0536
77F	**2**	0.0420	0.0263			
70%	**8**	0.0381				
125F	**2**	0.0575	0.0252	0.0539		0.0626
Dry		0.0575**	0.0348**	0.0420		
				0.0376		
				0.0409		
	4	0.0541**	0.0345**			
	8	0.0559				
		0.0557				
	16	0.0582				
		0.0565				
	21			0.0363**		
	32			0.0554		
	35	0.0537**	0.0395**			
	48	0.0492**	0.0320**			
	53			0.0566**		
	64			0.0400		
	112			0.0578**		
125F	**2**			0.0345		
40%				0.0365		
				0.0403		
125F	**2**	0.0393	0.0216	0.0279		
70%	**6**	0.0388*	0.0231*			
	8	0.0323				
		0.0363				
	10	0.0334*	0.0236*			
	16	0.0349				
	32					
	64					
125F	**2**			0.0038		
100%				0.0055		
				0.0090		
160F	**2**	0.0446	0.3033	0.0472		0.0454
50%		0.0493		0.0332		
	8	0.0409			0.0528	0.0485
		0.0359				
	16				0.0593	
	32				0.0477	
	64				0.0556	
185F	**2**	0.0480	0.0325	0.0372	0.0690	
dry	**8**	0.0555				
		0.0536				
	16	0.0471				
		0.0429				
185F	**32**			0.0401		
dry	**64**	0.0573	0.0326	0.0458		
(cont.)	**96**	0.0494	0.0242	0.0475		
	139	0.0457	0.0350	0.0470		
185F	**2**	0.0494		0.0399	0.0576	
30%	**8**	0.0480		0.0497	0.0530	
	16	0.0539		0.0479	0.0568	
	32	0.0429		0.0282	0.0563	
185F	**2**	0.0362	0.0267	0.0277		
70%		0.0344*	0.0265*			
	6	0.0358*	0.0235*			
	8	0.0355				
		0.0344				
	23			0.0110*		
215F	**2**	0.0536	0.0333	0.0329		
dry	**16**	0.0530	0.0311	0.0319		
	32	0.0487	0.0304	0.0351		
	64	0.0479	0.0274	0.0315		
		0.0460				
	96	0.0410	0.0262	0.0317		
	148	0.0341		0.0211		
	200	0.0249		0.0300		
250F	**2**	0.0488		0.0522	0.0650	
dry		0.0459				
	7			0.0520		
	8	0.0426			0.0538	
		0.0445				
	16	0.0265				
		0.0217				
	32		0.0235	0.0205	0.0398	
	47			0.0123		
	64			0.0160	0.0153	
	96	0.0158				
	193	0.0096	0.0016	0.0050		

Additional Environments

Environment	(wks)	KT2	Environment	(wks)	KT2	Environment	(wks)	KT2
77F	**2**	0.0519	**195F**	**2**	0.0567	**195F**	**2**	0.0061
dry		0.0519	**dry**		0.0564	**100%**		0.0073
		0.0547			0.0618			0.0067
					0.0573			0.0058
77F	**2**	0.0128	**195F**	**2**	0.0469			
100%		0.0134	**40%**					

* 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 for stated period, but also include 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			
			MSC-1A	5	0.0639			

Table 6. Summary of thermal and physical property changes upon termination of 250 °F conditioning

Property	Duration of Conditioning at 250 °F, at time of last test	Final Property Value, Normalized*
Thermal cond. @ 25 °C, radial	199 – 255 wks	60.1 – 64.1% (4 samples)
Thermal cond. @ 25 °C, axial	199 – 255 wks	72.2 – 73.8% (3 samples)
Specific heat capacity @ 52 °C	258 wks	75.0% **
Physical properties (8 samples)	225 – 275 wks	41.6 – 48.3% (weight)
		72.1 – 82.4% (height)
		68.0 – 76.8% (density)

* Values are reported as a percentage of the value measured after the first nominal conditioning period.
** Due to data scatter, this value is the average change based on a linear curve fit to all the data.

Table 7 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
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 8. 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%)	< -0.3	-0.30	-0.17
185 °F dry (2%)	-1.4	-1.04	-0.92
215 °F dry (1%)	-3.5	-3.35	-2.93
250 °F dry (1%)	-10	-12.47	-14.2
15 °F 60%	0	+0.02	NA
50 °F 10%	0	-0.13	NA
125 °F 70%	-0.5	-0.38	-0.17
160 °F 50%	-3.3	-3.62	-2.69
185 °F 30%	-3.8	-3.99	-3.74
185 °F 70%	-24	-33.16	-21.62

Table 9. Compression stress-strain data used in the forklift impact calculation [6]

True strain [1]	True stress (psi) [2]		Engineering strain [3]	Engineering stress (psi) [3]
0.000	0		0.000	0
-0.001	25		-0.001	25
-0.057	35		-0.055	35
-0.115	61		-0.109	61
-0.178	89		-0.163	89
-0.246	124		-0.218	124
-0.318	171		-0.272	171
-0.399	238		-0.329	238
-0.477	323		-0.380	323
-0.511 [4]	363 [4]		-0.400 [4]	363 [4]
-0.574	454		-0.437	454
-0.681	643		-0.494	643
-0.793	905		-0.548	905
-0.923	1327		-0.603	1327
-1.055	1978		-0.652	1978
-1.232	3312		-0.708	3312
-1.309	4200		-0.730	4200
-1.386	5327		-0.750	5327

1. True strain (ε) is converted from engineering strain (e) by: $\varepsilon = \ln(1 + e)$
2. True stress (σ) is numerically equal to engineering stress (s) since the material compresses with essentially no change in cross section area.
3. Engineering stress and strain values are generated by the control computer during testing.
4. These values (corresponding to an engineering strain of 40%) were not used in the forklift impact calculation, but have been added to the table for reference.

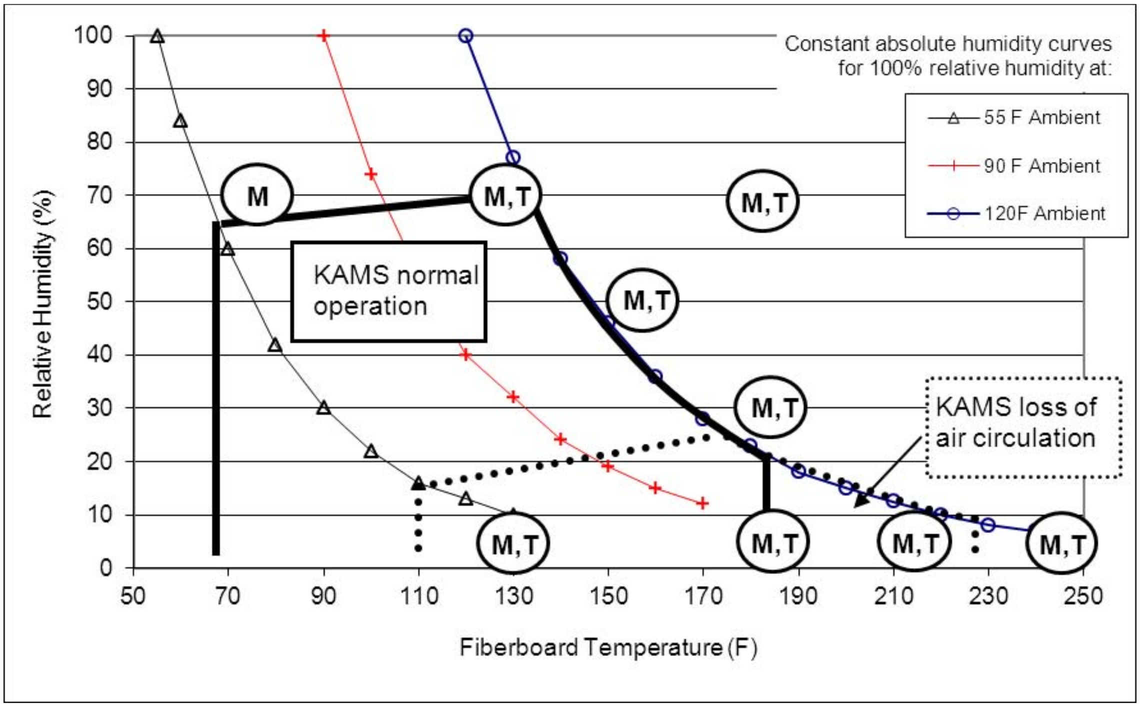
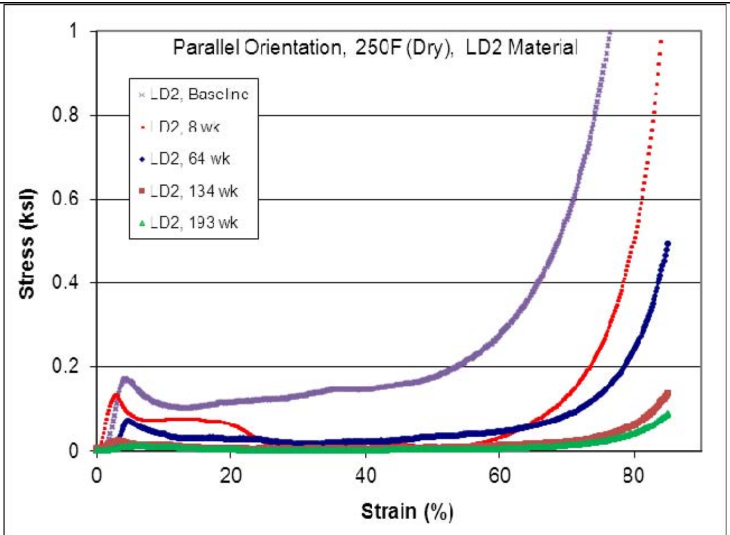
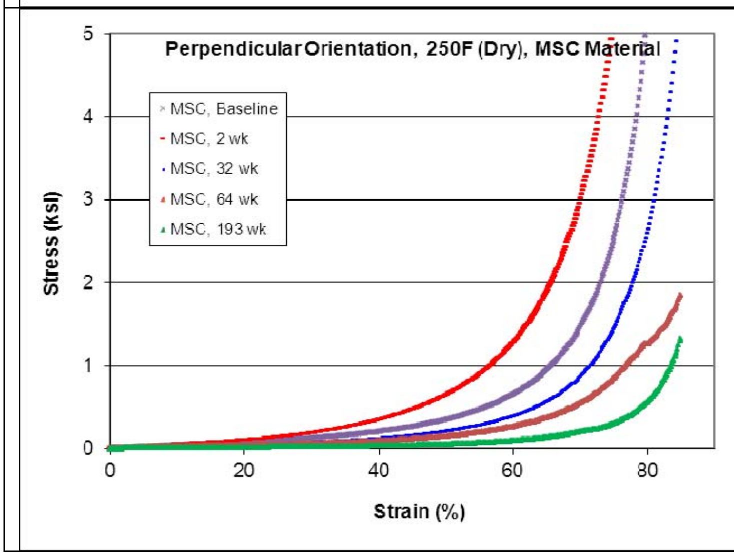


Figure 1. Bounding estimate of the range of environments which fiberboard in KAMS can experience under normal operation and under loss of air circulation (both ventilation and natural convection). Also shown are the environments for longer-term aging and testing (circles). "M" denotes mechanical testing. "T" denotes thermal and physical property testing. Physical property testing (only) has also been conducted following aging at 15 and 50 °F.



(a) LD2 material, parallel orientation

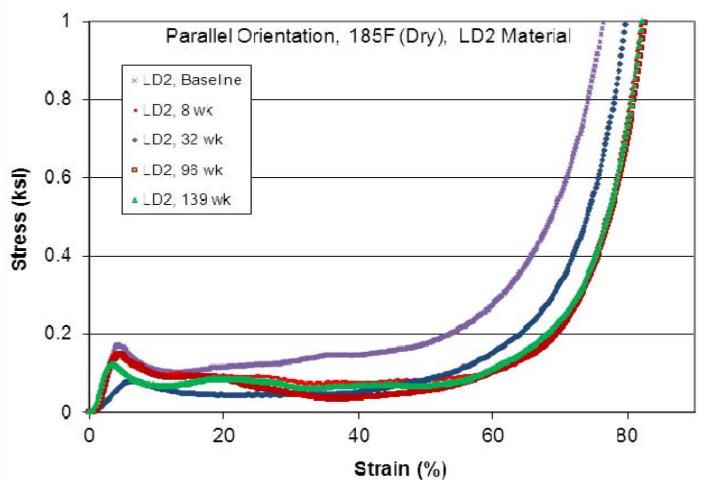
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.171	0.0476
8	0.132	0.0199
64	0.071	0.0110
134	0.024	0.0034
193	0.012	0.0018



(b) MSC material, perpendicular orientation

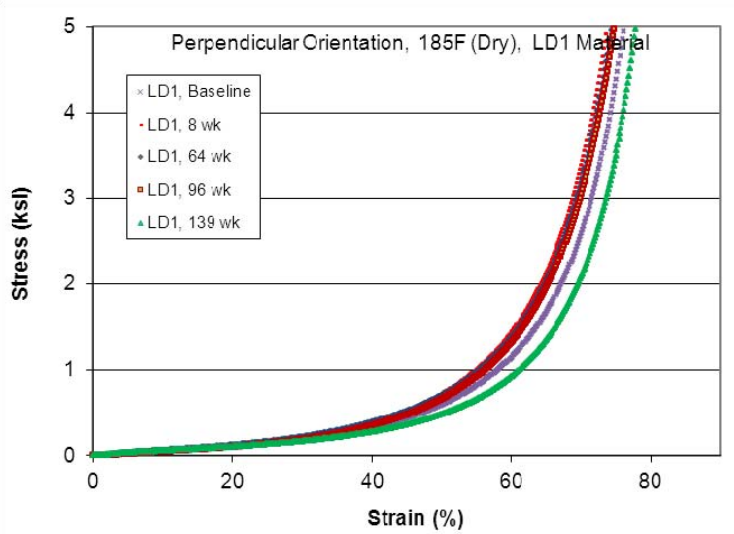
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0338
2	0.0522
32	0.0205
64	0.0160
193	0.0050

Figure 2. Engineering stress-strain compression curves for select fiberboard samples conditioned and tested at 250 ºF



(a) LD2 material, parallel orientation

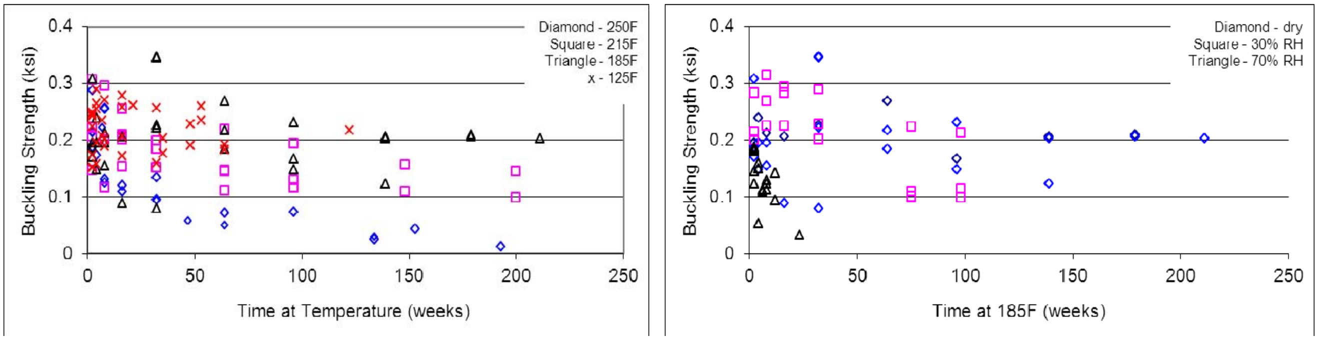
Conditioning Period (wks)	Buckling Strength (ksi)	Area under Curve to 40% Strain (ksi)
0	0.171	0.0476
8	0.155	0.0366
32	0.080	0.0190
96	0.148	0.0291
139	0.123	0.0298



(b) LD1 material, perpendicular orientation

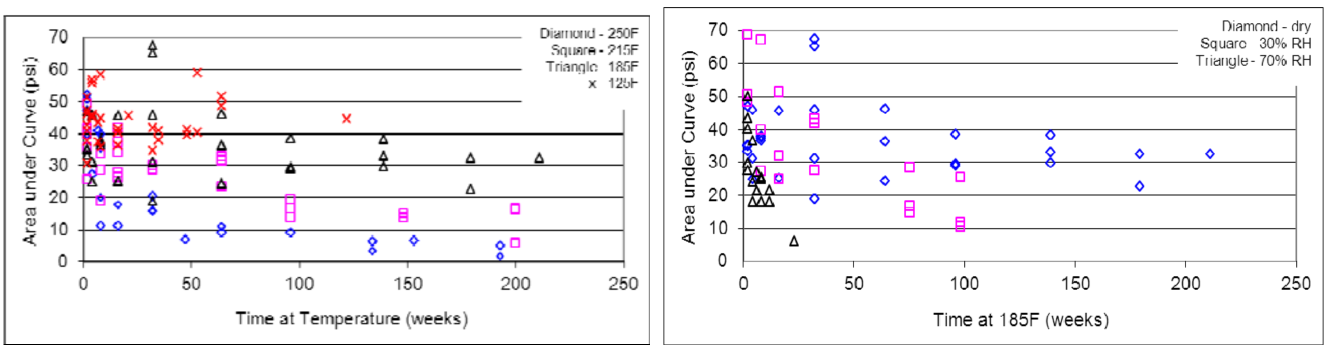
Conditioning Period (wks)	Area under Curve to 40% Strain (ksi)
0	0.0461
8	0.0555
64	0.0573
96	0.0494
139	0.0457

Figure 3. Engineering stress-strain compression curves for select fiberboard samples conditioned and tested at 185 °F



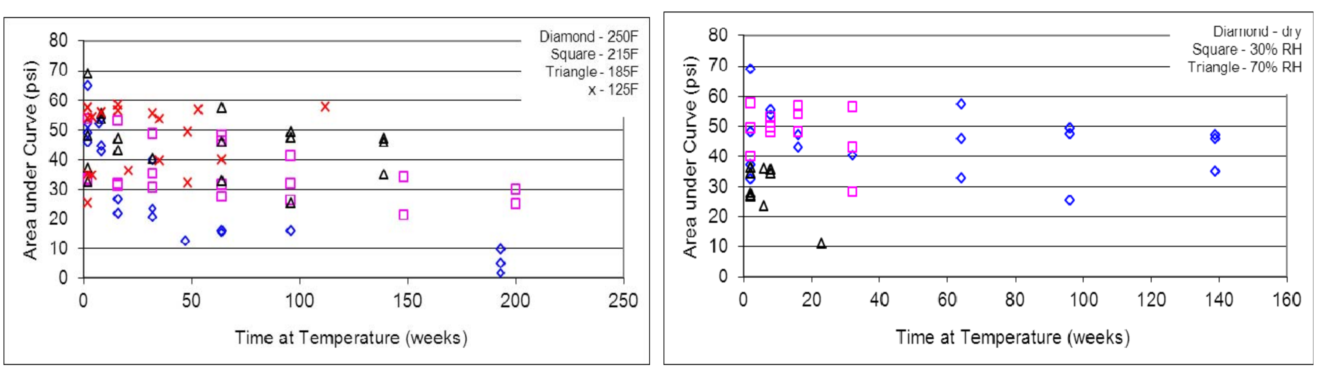
(a) (b)

Figure 4. Buckling strength (ksi) for compression samples, parallel orientation. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned at 185 ºF, at the humidity levels noted.



(a) (b)

Figure 5. Area under the stress-strain curve up to 40% strain, for parallel orientation samples. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned at 185 ºF, at the humidity levels noted.



(a) (b)

Figure 6. Area under the stress-strain curve up to 40% strain, for perpendicular orientation samples. Samples in (a) were conditioned in dry environments, at the temperatures noted. Samples in (b) were conditioned at 185 ºF, at the humidity levels noted.

(a) (b) (c) (d) (e) (f) (g)

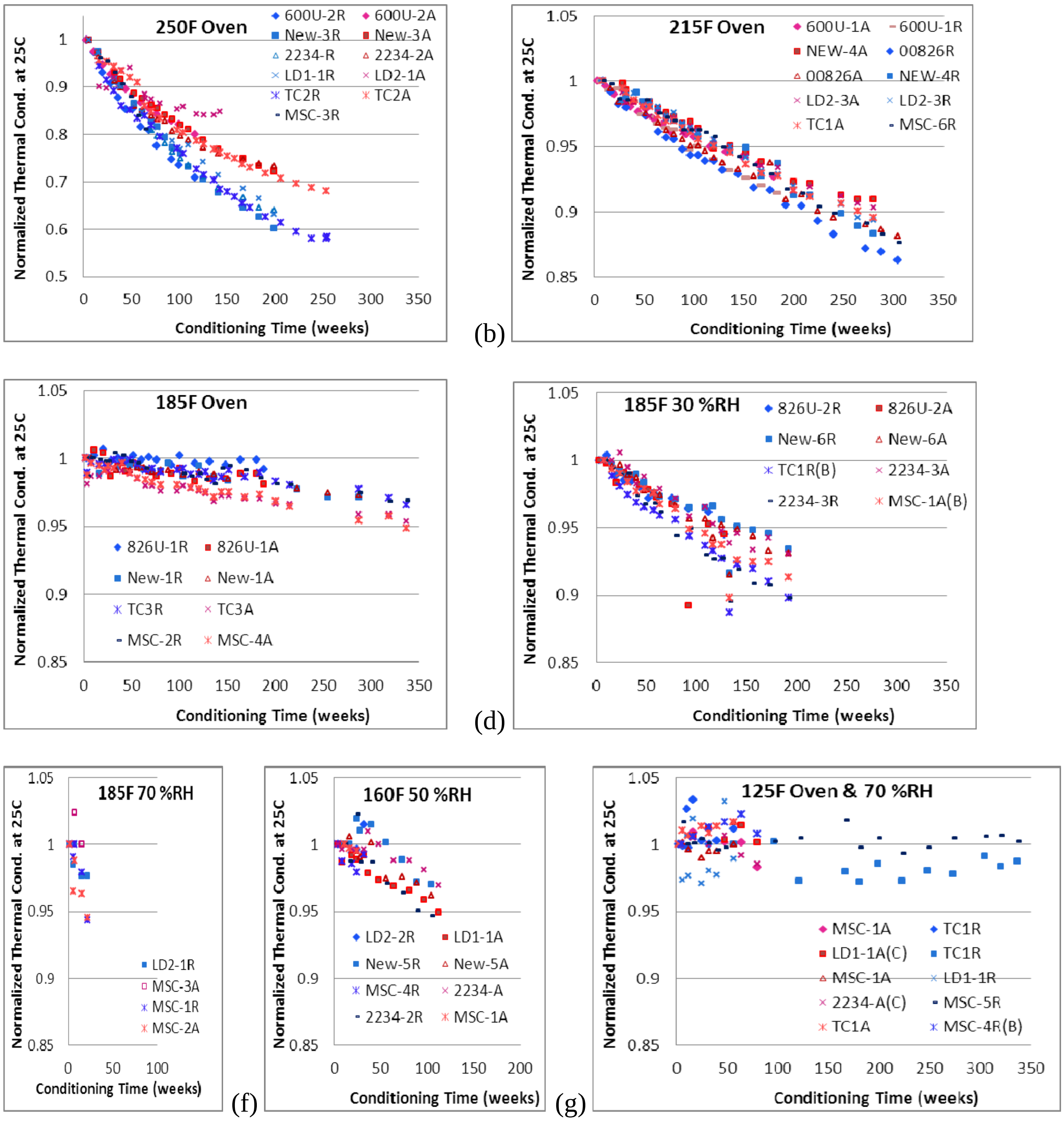


Figure 7. Thermal conductivity data measured at 25 ºC (77 ºF) mean temperature for each conditioning environment as noted. Data for each sample are normalized to the first conditioned value. The first conditioned value for each sample is identified in Table 5. Axial orientation samples are shown in red, and radial orientation samples are shown in blue.

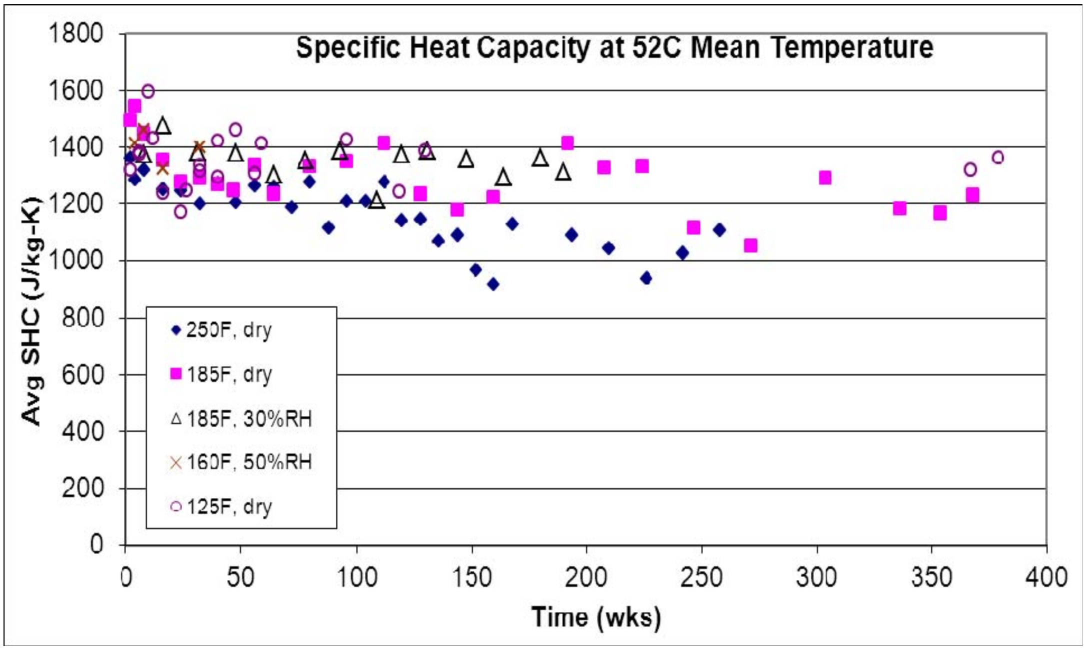
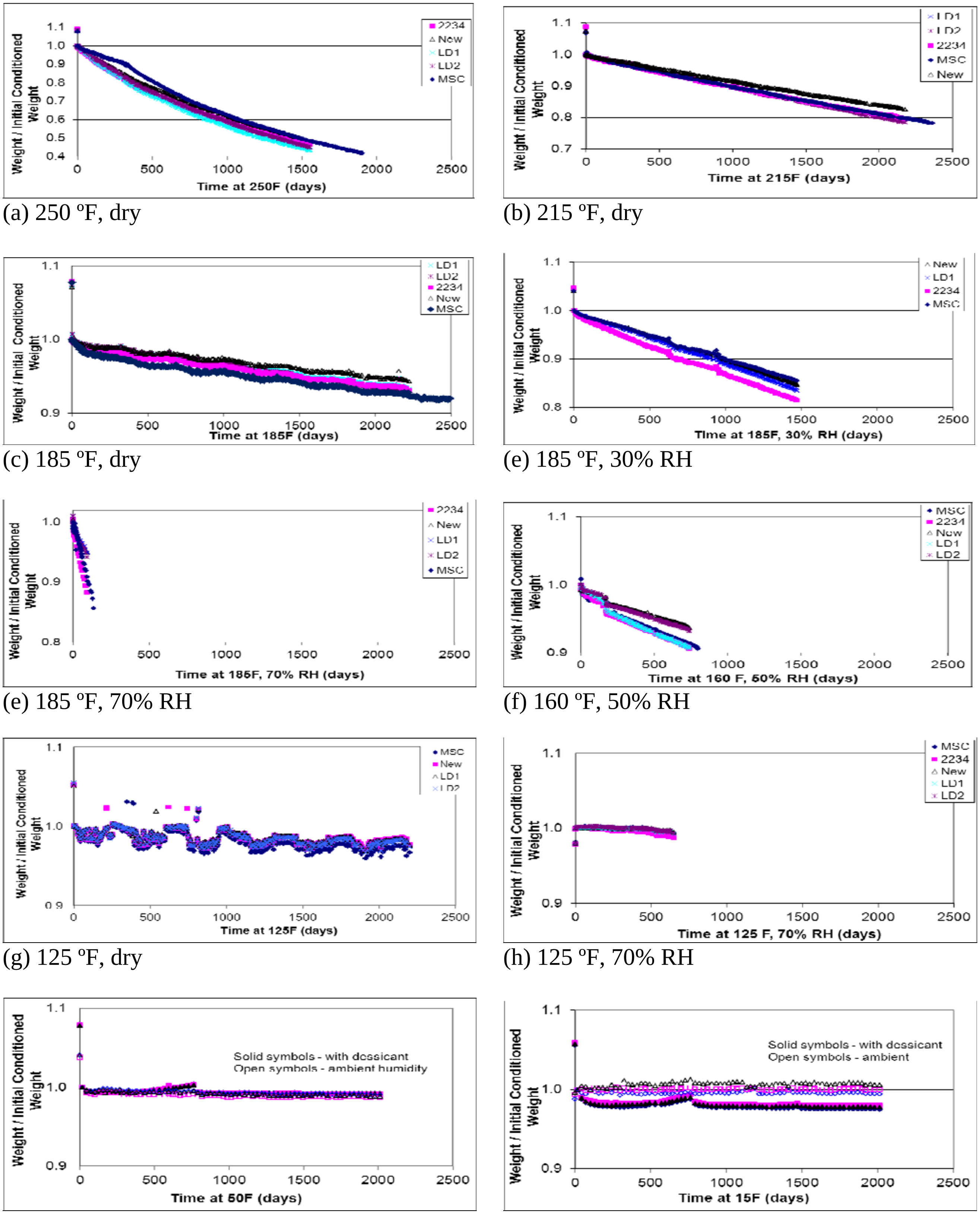


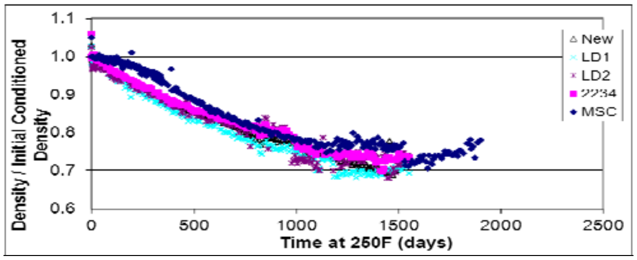
Figure 8. Specific heat capacity data at a mean temperature of 52 ºC (125 ºF) for each conditioning environment. A linear fit to the data for each environment produces the following trends:

250 °F, dry	SHC (J/kg-K) = 1299.4 – 1.263 * time (weeks)
185 °F, dry	SHC (J/kg-K) = 1373.6 – 0.567 * time (weeks)
125 °F, dry	SHC (J/kg-K) = 1355.6 – 0.047 * time (weeks)
185 °F, 30%RH	SHC (J/kg-K) = 1396.1 – 0.422 * time (weeks)
160 °F, 50%RH	SHC (J/kg-K) = 1421.3 – 1.450 * time (weeks)

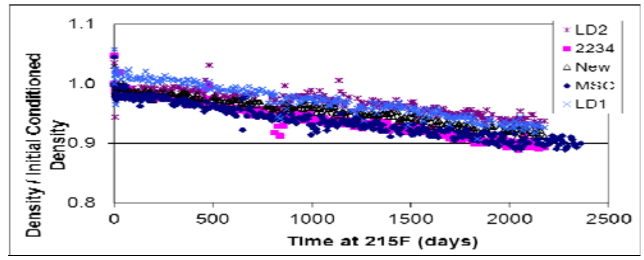


(a) 250 ºF, dry
(b) 215 ºF, dry
(c) 185 ºF, dry
(e) 185 ºF, 30% RH
(e) 185 ºF, 70% RH
(f) 160 ºF, 50% RH
(g) 125 ºF, dry
(h) 125 ºF, 70% RH
(i) 50 ºF
(j) 15 ºF

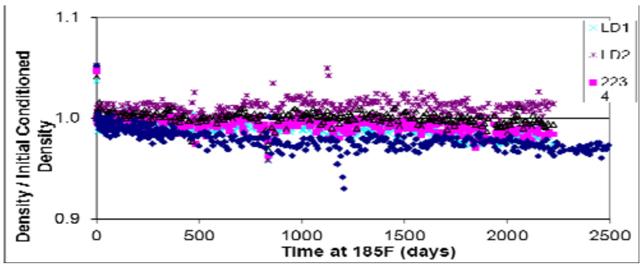
Figure 9. Weight data for physical property samples in the identified environments.



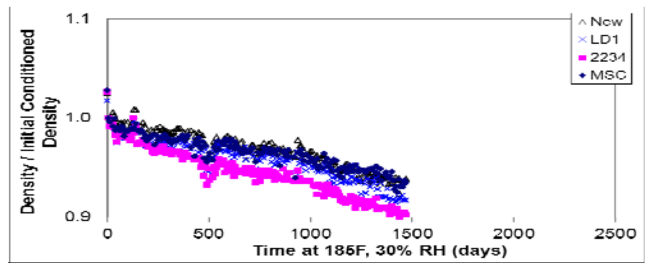
(a) 250 ºF, dry



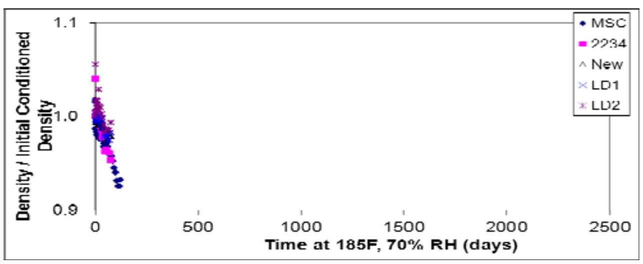
(b) 215 ºF, dry



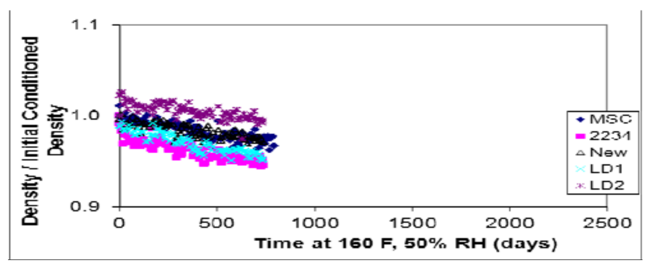
(c) 185 ºF, dry



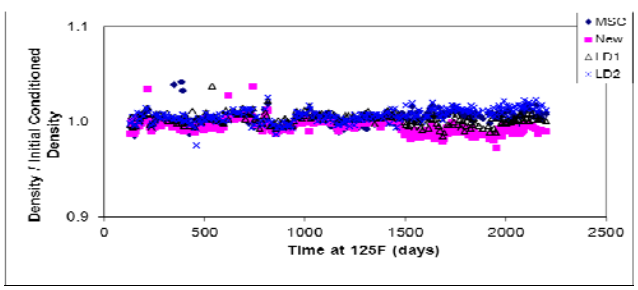
(e) 185 ºF, 30% RH



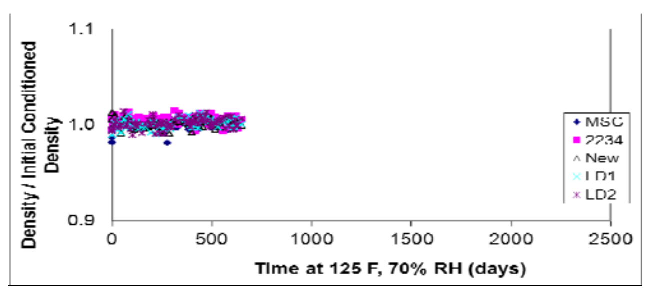
(e) 185 ºF, 70% RH



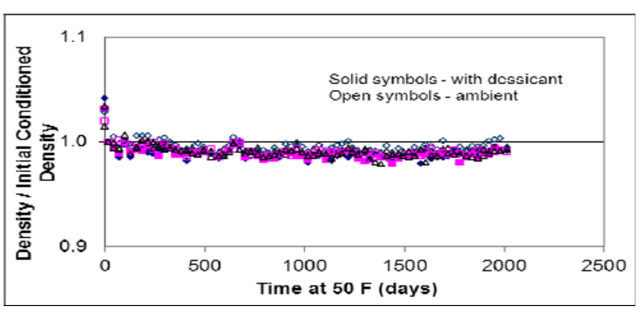
(f) 160 ºF, 50% RH



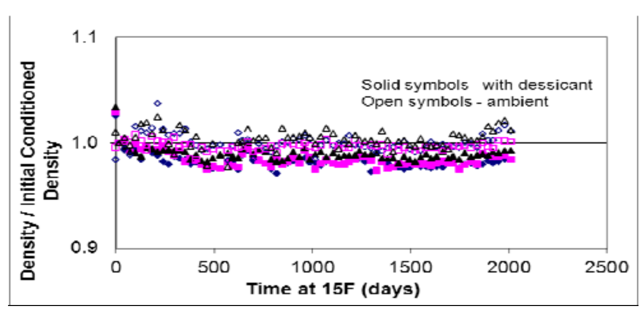
(g) 125 ºF, dry



(h) 125 ºF, 70% RH

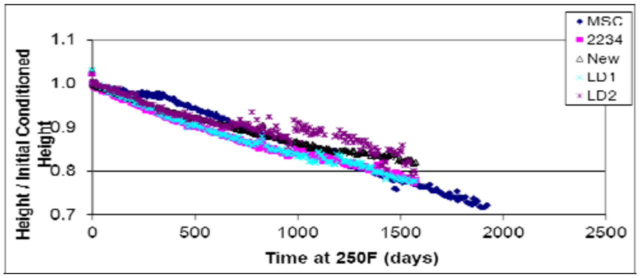


(i) 50 ºF

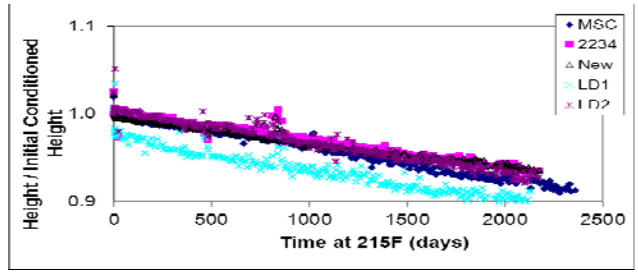


(j) 15 ºF

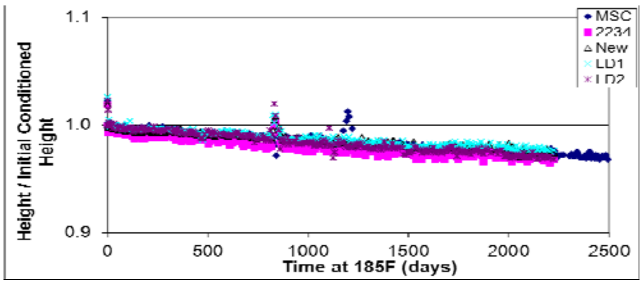
Figure 10. Density data for physical property samples in the identified environments



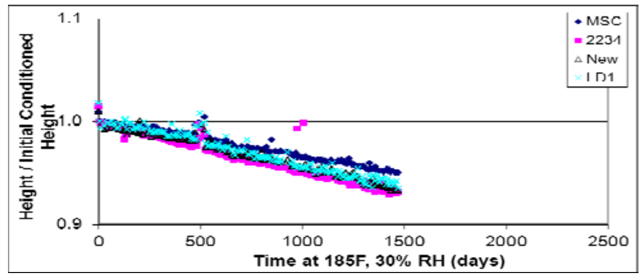
(a) 250 ºF, dry



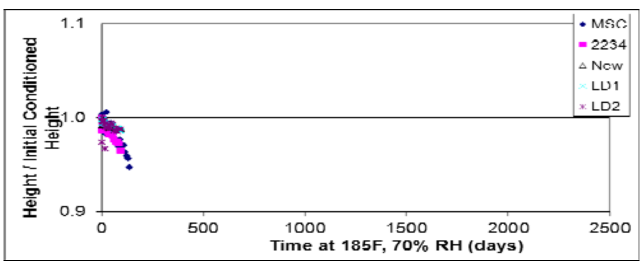
(b) 215 ºF, dry



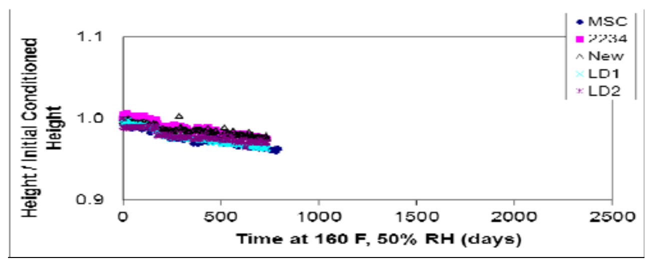
(c) 185 ºF, dry



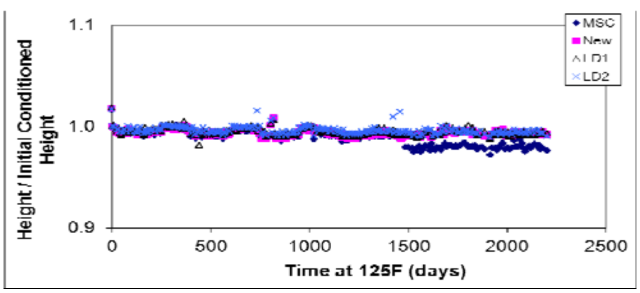
(e) 185 ºF, 30% RH



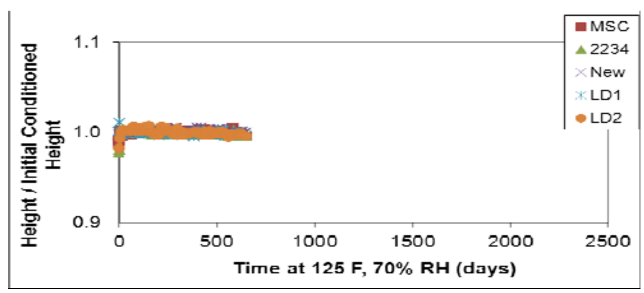
(e) 185 ºF, 70% RH



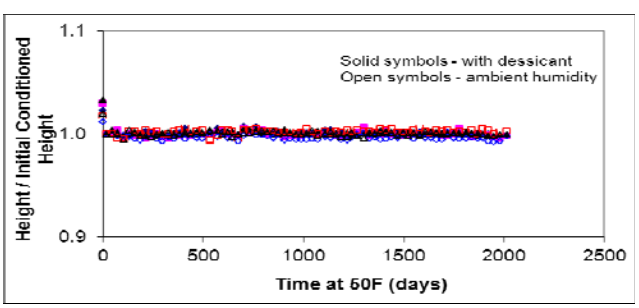
(f) 160 ºF, 50% RH



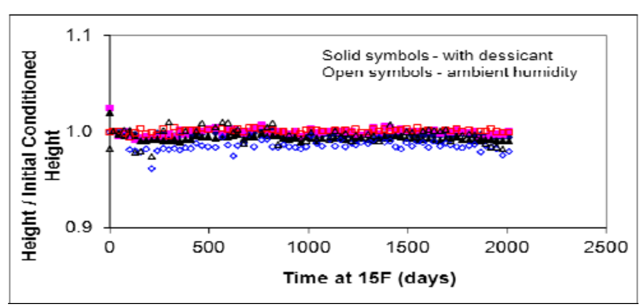
(g) 125 ºF, dry



(h) 125 ºF, 70% RH

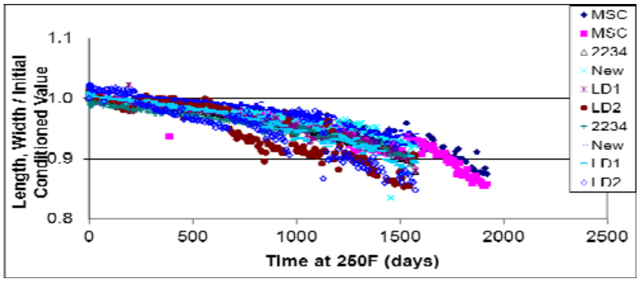


(i) 50 ºF

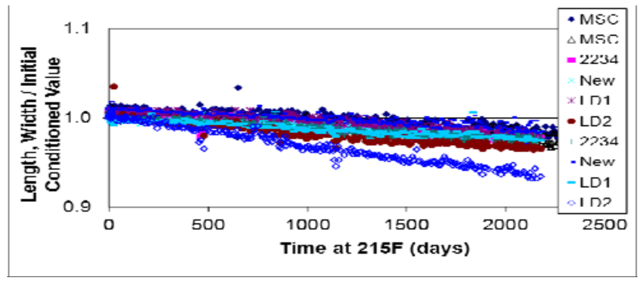


(j) 15 ºF

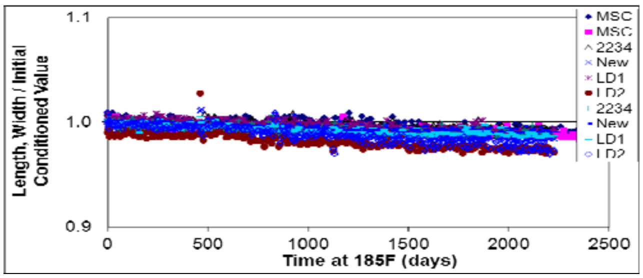
Figure 11. Height data for physical property samples in the identified environments



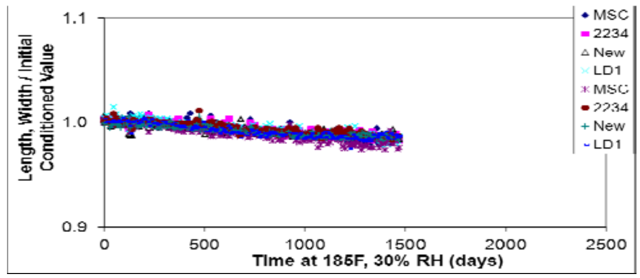
(a) 250 ºF, dry



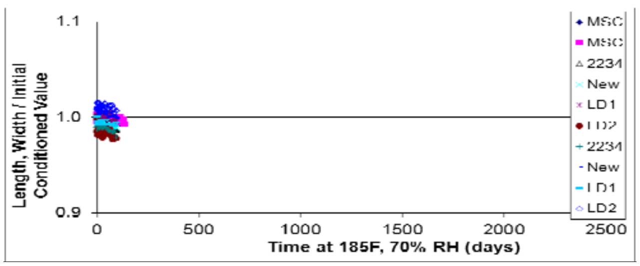
(b) 215 ºF, dry



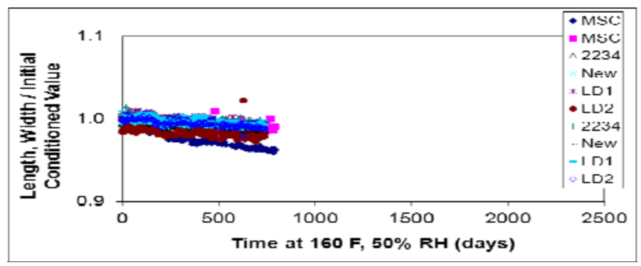
(c) 185 ºF, dry



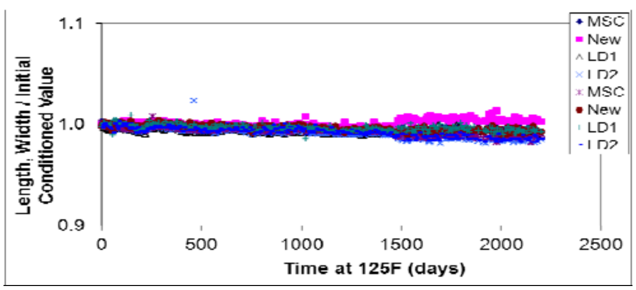
(e) 185 ºF, 30% RH



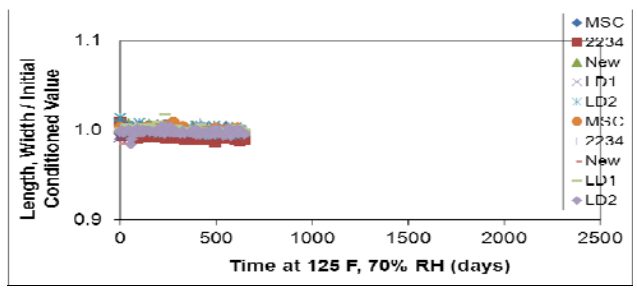
(e) 185 ºF, 70% RH



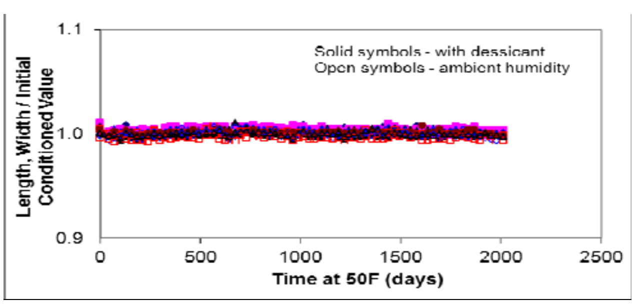
(f) 160 ºF, 50% RH



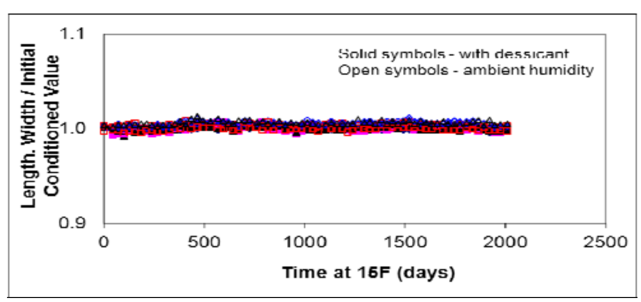
(g) 125 ºF, dry



(h) 125 ºF, 70% RH



(i) 50 ºF



(j) 15 ºF

Figure 12. Length & width data for physical property samples in the identified environments

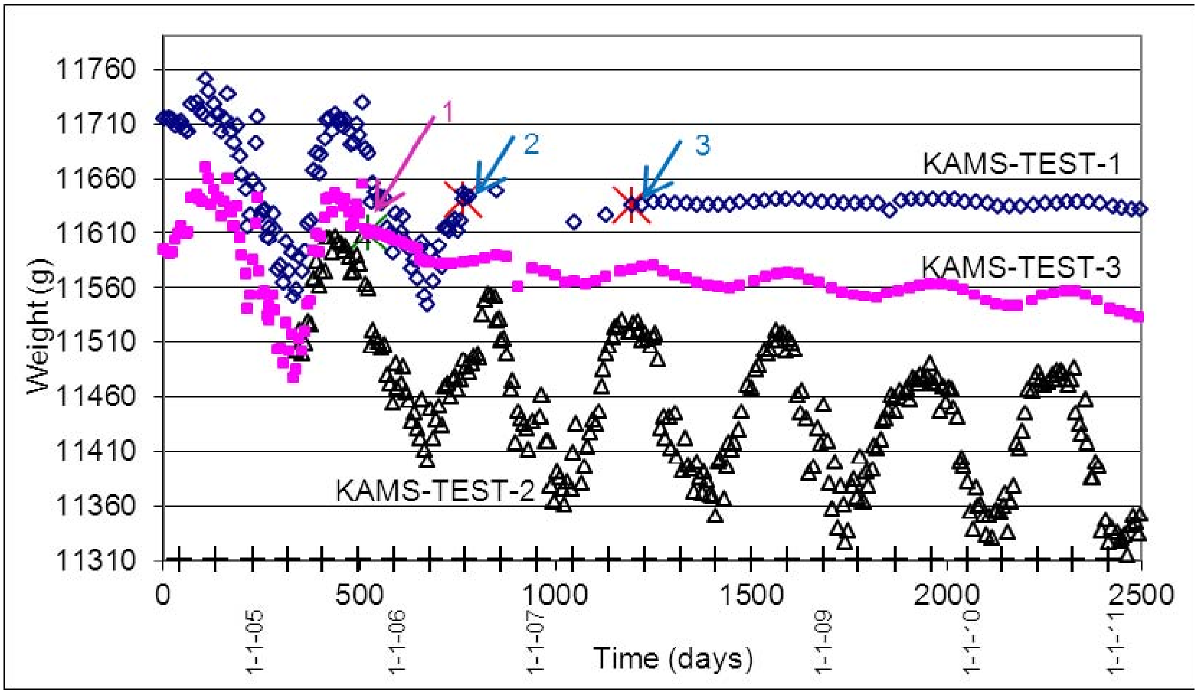


Figure 13. Seasonal weight variation of 3 upper fiberboard subassemblies. All 3 subassemblies were initially exposed to ambient conditions. At point (1), subassembly 3 was returned to its drum with the lid loosely in place. At point (2), subassembly 1 was returned to its drum with the lid loosely in place, and at point (3) the lid for subassembly 1 was bolted tight.

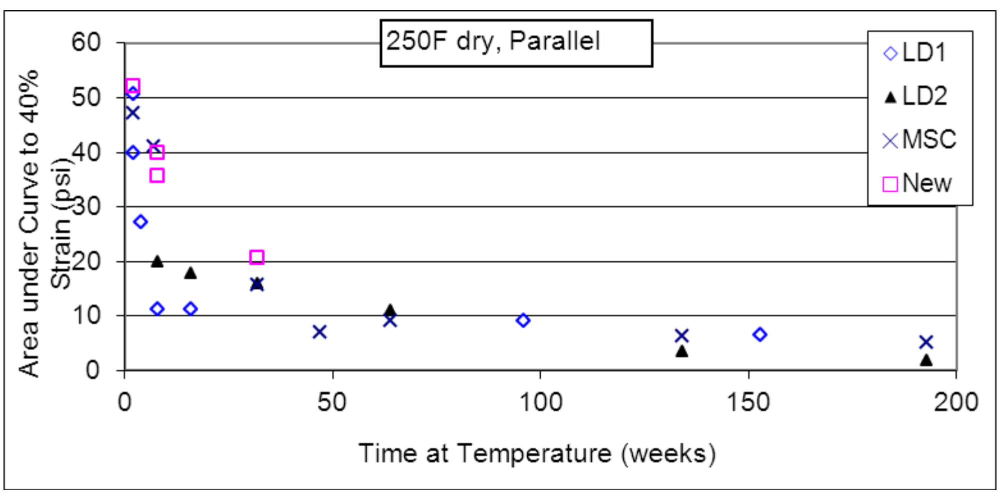


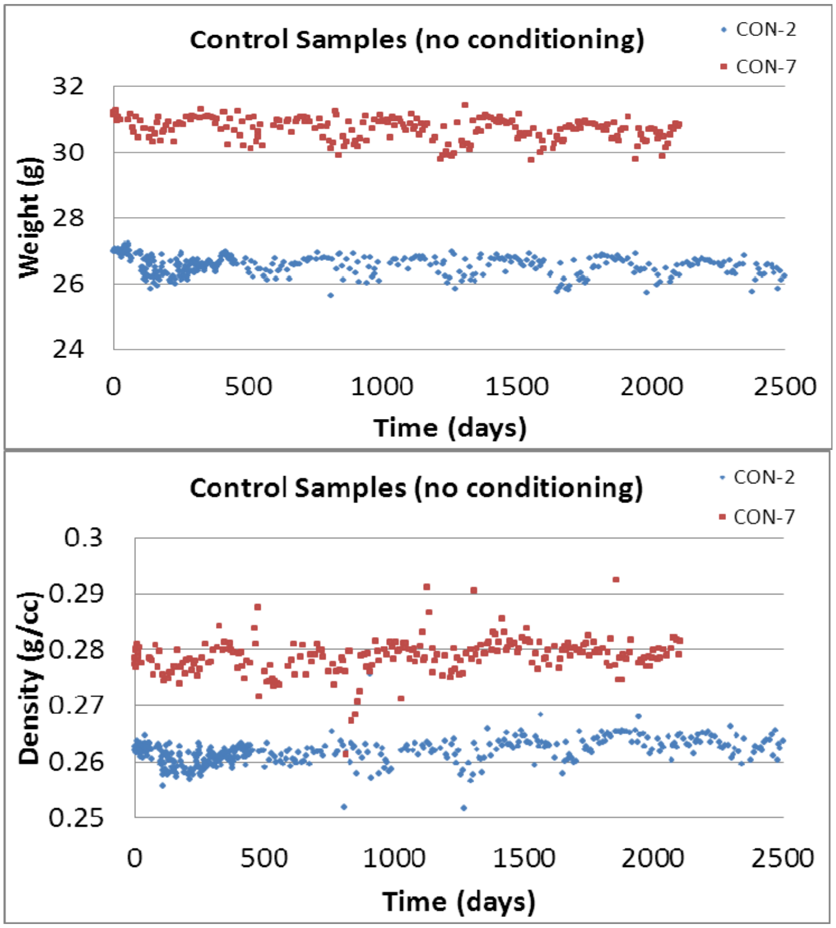
Figure 14. Compression test metric (area under the stress-strain curve up to 40% strain) for samples conditioned at 250 °F and tested in the parallel orientation.

Figure 15. Typical physical property samples after removal from the 250 °F environment. These samples were conditioned for 225 weeks.

(a)

(b)

Figure 16. Typical thermal conductivity samples (a) and specific heat capacity samples (b) after conditioning at 250 °F for 272 weeks and 268 weeks, respectively. Each is shown with an undegraded sample (on left), for comparison.



(a) Control sample weight data

Rate of weight change:

CON-2 -2.87 E-4 %/day
CON-7 -5.63 E-4 %/day

(a) Control sample density data

Rate of density change:

CON-2 +4.62 E-4 %/day
CON-7 +5.03 E-4 %/day

Figure 17. Weight and density data for physical property control samples.

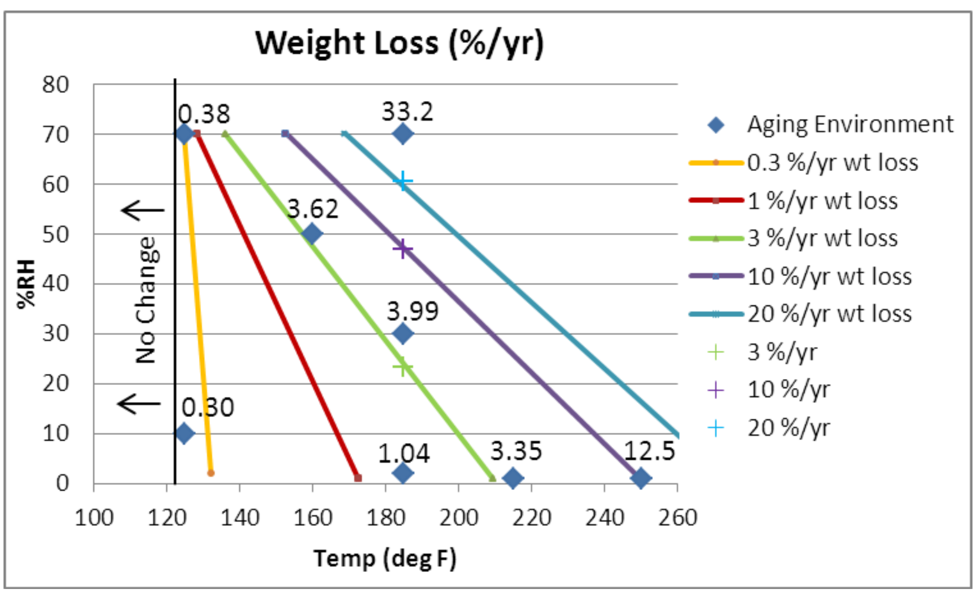


Figure 18. Fiberboard weight loss model. Lines represent contours of equal rate of weight loss. Numerical values are the average degradation rates of aged samples.

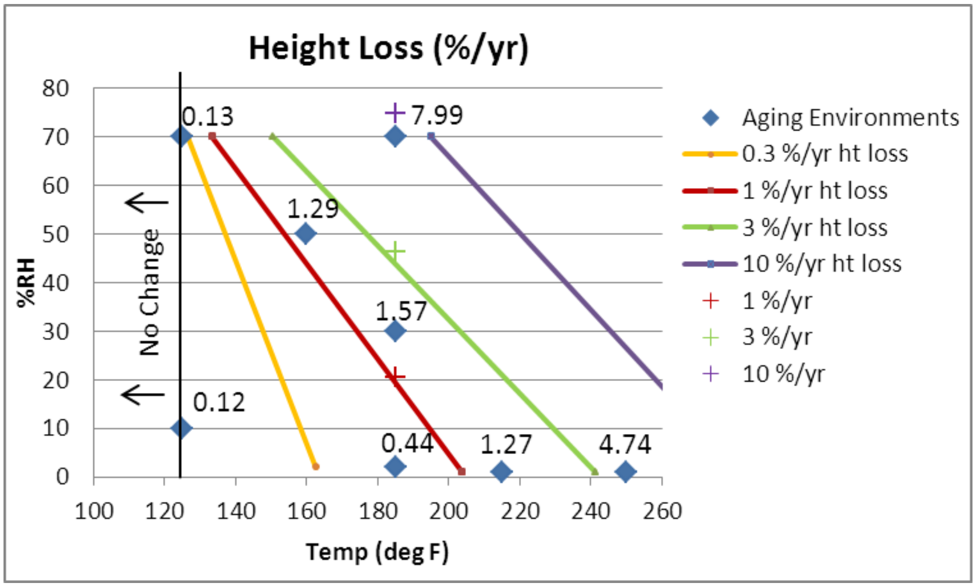


Figure 19. Fiberboard height loss model. Lines represent contours of equal rate of height decrease. Numerical values are the average degradation rates of aged samples.

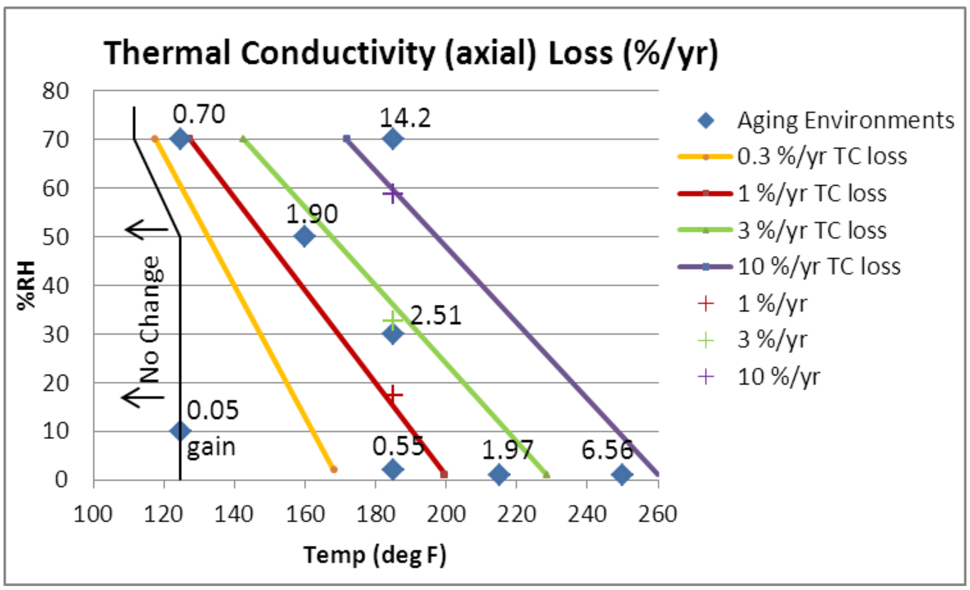


Figure 20. Fiberboard thermal conductivity, axial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the axial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in the 125 °F dry environment. This rate of change was not included in the modeling.

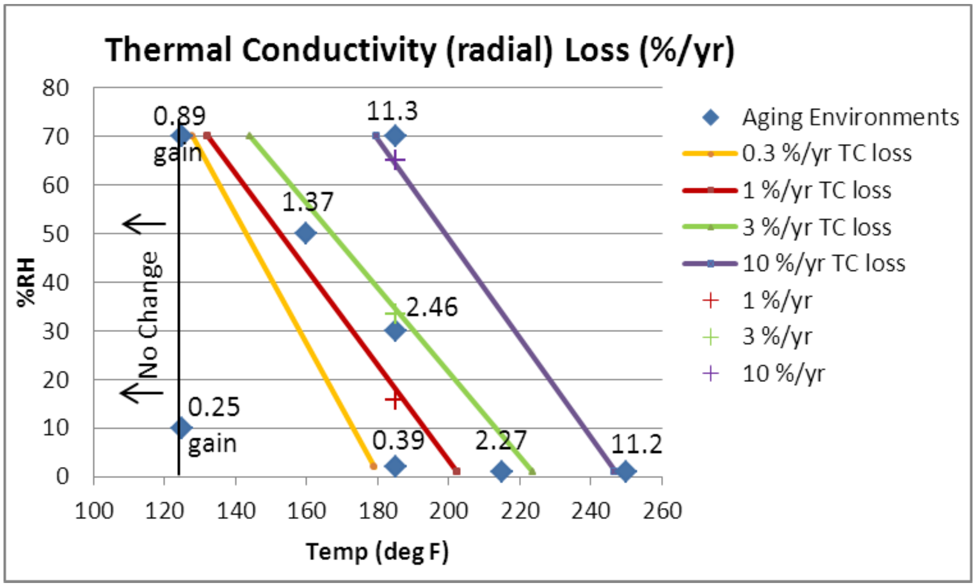


Figure 21. Fiberboard thermal conductivity, radial orientation model. Lines represent contours of equal rate of thermal conductivity decrease in the radial orientation. Numerical values are the average degradation rates of aged samples. The rate of thermal conductivity change was positive in both 125 °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.

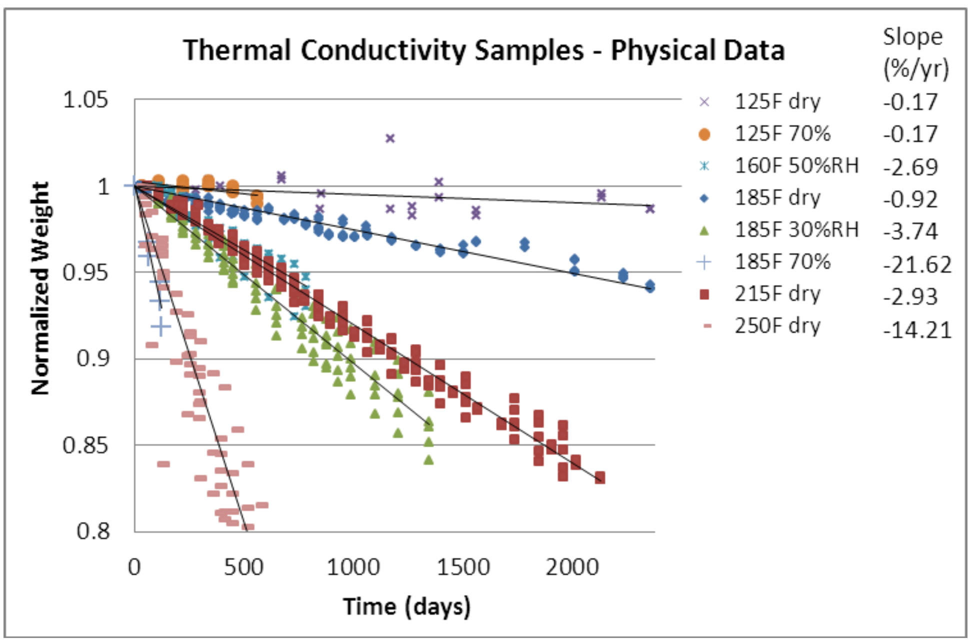


Figure 22. Physical data (weight change) trends from thermal conductivity samples

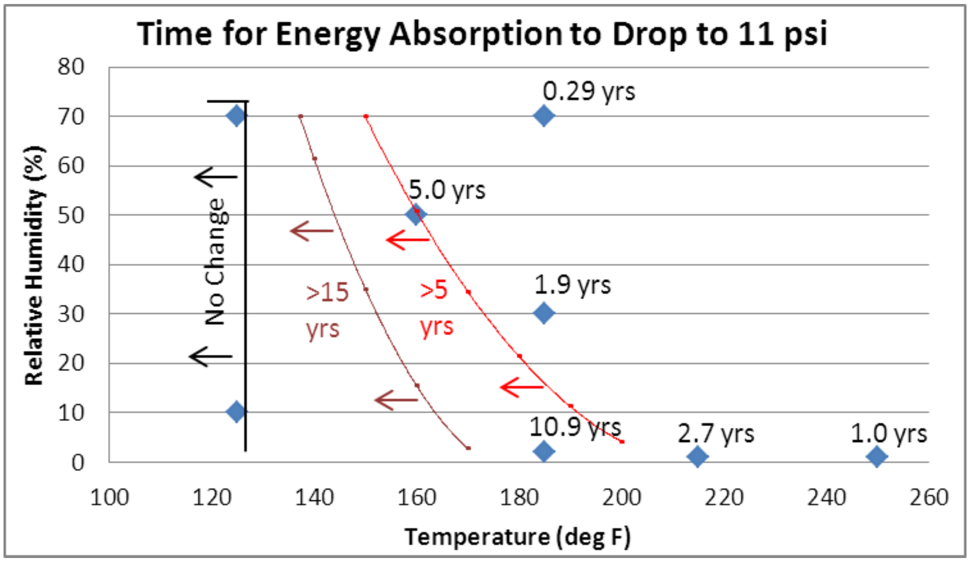


Figure 23. Model for energy absorption, based on compression test area under the stress-strain curve up to 40% strain. This graph shows contour lines describing environments for which energy absorption is predicted to drop to 11 psi over periods of 5 years and 15 years.

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