COMPACTION OF FIBERBOARD IN A 9975 SHIPPING PACKAGE

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ABSTRACT
Compaction of lower layers in the fiberboard overpack has been observed in 9975 packages that contain elevated moisture. Lab testing has resulted in a better understanding of (1) the relationship between the fiberboard moisture level and compaction of the lower fiberboard assembly, and (2) the behavior of the fiberboard during transport. In laboratory tests, higher moisture content has been shown to correspond to higher total compaction of fiberboard material, greater rate of compaction, and continued compaction over a longer period of time. In addition, laboratory tests have shown that the application of a dynamic load results in higher fiberboard compaction. The test conditions and sample geometric/loading configurations were chosen to simulate the regulatory requirements for 9975 package input dynamic loading. Dynamic testing was conducted over a period of several months to acquire immediate and cumulative changes in geometric data for various moisture levels. Currently, one sample set has undergone a complete dynamic test regimen, while testing of another set is still in-progress. The dynamic input, data acquisition, test effects on sample dynamic parameters, and interim results from this test program will be summarized and compared to regulatory specifications for dynamic loading. This will provide a basis from which to evaluate the impact of moisture and fiberboard compaction on the safety basis for transportation (Safety Analysis Report for Packaging) and storage (facility Documented Safety Analysis) at the Savannah River Site (SRS).

INTRODUCTION
The Savannah River Site (SRS) stores packages containing plutonium (Pu) materials in the K-Area Materials Storage (KAMS) facility. The Pu materials are packaged per the DOE 3013 standard [1] and stored within 9975 packages in KAMS. The 9975 is a certified radioactive material shipping package designed and sponsored by the Savannah River National Laboratory (SRNL).

The Facility Documented Safety Analysis (DSA) [2] credits the 9975 package to perform several safety functions, including criticality control, impact resistance, containment, and fire resistance to ensure the plutonium materials remain in a safe configuration during normal and accident conditions. In the storage facility, the 9975 package is assumed to perform its safety function for at least 12 years from initial packaging. Knight-Celotex® cane- or softwood-based fiberboard is used as overpack material in the 9975 (Figure 1) and supports the fire resistance, criticality control, and impact resistance functions.

The DSA recognizes the degradation potential for the materials of package construction over time in the KAMS storage environment, and requires an assessment of materials performance to validate the assumptions of the analysis and ultimately predict service life and the need for repackaging. One of the parameters used to monitor the fiberboard condition is the axial gap between the drum flange and the top of the fiberboard assembly. Experience with fiberboard compaction includes the identification of several packages in which this gap has increased and exceeded the response threshold of 1 inch (2.5 cm). This observation was generally accompanied by elevated moisture levels in the bottom fiberboard layers and compaction of those layers. Elevated moisture might accumulate within the fiberboard due to the introduction of moisture to the package, or by the concentration of existing moisture into local regions through migration under thermal gradient.

The impact of elevated moisture on fiberboard properties and the response of the package to changing moisture conditions has been described [3]. Over time, elevated moisture levels will accelerate the degradation rates of the fiberboard properties [4, 5].

The bottom of the 9975 outer drum is dished, and the fiberboard overpack is fabricated with a flat bottom. Therefore, as the load on the fiberboard increases, the bottom layer will increasingly compress from the outer edge inward as it conforms to the drum bottom. The lead shield, containment vessels, and payload sit on an aluminum bearing plate embedded within the lower fiberboard assembly. The shield, containment vessels, and a loaded 3013 container place a load of approximately 263 pounds (119 kg) on the 11.2 inch (28 cm) diameter bearing plate.

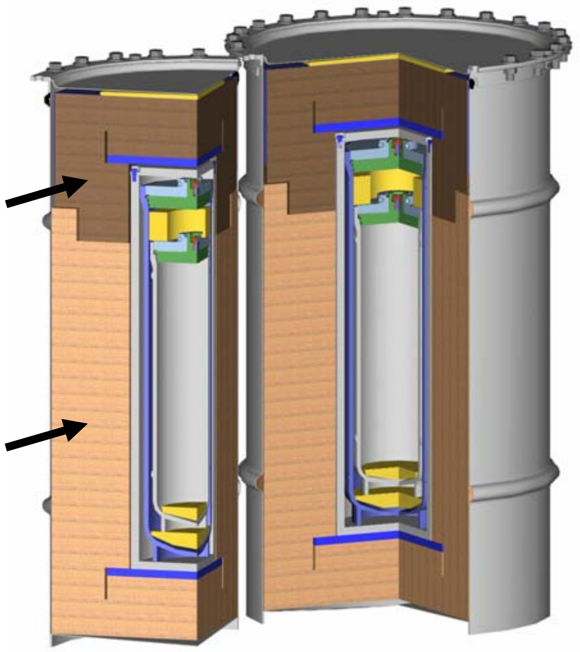

Figure 1. Cross section of the 9975 shipping package showing the configuration of the fiberboard overpack. The upper and lower fiberboard assemblies are indicated (arrows).

Typically, a compressed ring approximately 1½ - 2 inches (4 - 5 cm) wide will form around the bottom fiberboard surface. As the bottom layers compress further (due to increased loading or reduced fiberboard strength), this ring will widen until the entire fiberboard bottom surface is in contact with the drum bottom. This has been observed in packages with elevated moisture content, and is illustrated in Figure 2. With the limited contact area, the local stress in the bottom fiberboard layers is typically no greater than 3.4 psi (23 kPa). As the compressed region widens, the local peak stress decreases to 2.7 psi (18 kPa), which is the stress immediately under the bearing plate.

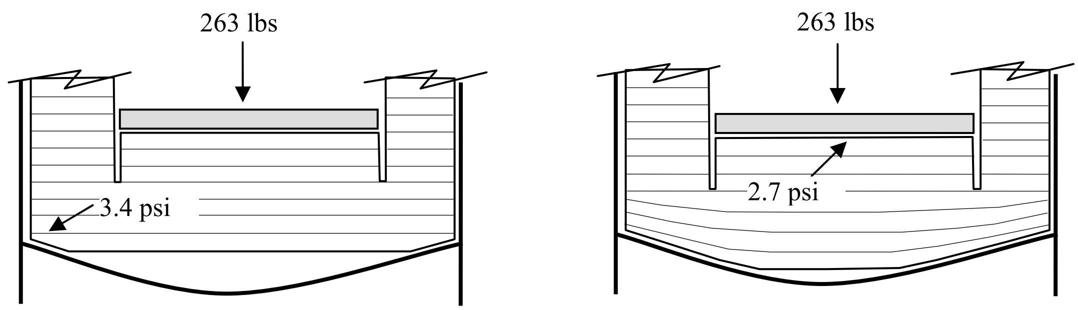

Figure 2. Varying degree of contact between the lower fiberboard assembly and drum bottom. As the contact area increases, the peak fiberboard stress will decrease to that immediately under the bearing plate. NOTE: Degree of curvature exaggerated for visual effect.

TEST METHODOLOGY

Previous laboratory tests were performed to compare the response of fiberboard to transient loadings on different time scales. Short-term tests measured the fiberboard response under load within a single, very long load cycle. Intermediate time scale tests using standard compression test data subjected the samples to a single half-cycle loading event, These results were presented in a paper at the Institute for Nuclear Materials Management (INMM) conference in 2010 [6]. Recent dynamic tests have subjected the samples to a dynamic load of varying frequency and amplitude, such as might occur during handling and transport. While the other methods offer a simpler look at the basic response of the fiberboard under dynamic load, the dynamic tests presented in this paper better simulate the conditions a package might experience in service.

Dynamic Testing: Fiberboard samples have been placed under load similar to that seen in service by the lower layers in a 9975 package, and compaction values are being tracked over time. Some samples are subjected to periodic dynamic loading that simulates potential transport conditions. The remaining samples experience a static load only. Sample height and moisture content are recorded periodically.

Samples are approximately 3.8 x 3.8 x 2 inches (9.9 x 9.6 x 5.2 cm), and were removed from the same fiberboard assembly used for short-term and intermediate scale tests. Two sets of samples were prepared for testing. The first set consists of three samples that contain moisture levels of approximately 10, 20 and 30 %WME (wood moisture equivalent)[1]. The second set consists of three samples that contain moisture levels of approximately 6, 25, and 35 %WME. Each sample is enclosed within a box to help maintain a constant moisture level throughout testing. The target stress level for nominal moisture samples (6 - 15 %WME) is approximately 3.4 psi. For higher moisture content ($\geq$ 20 %WME), the target stress level is approximately 2.7 psi. These stress levels are achieved by placing a weight on each sample. The dynamic samples are secured to a cart, and the dynamic loadings result as the cart is moved over a rough surface (metal plates mounted to an expanded metal sheet) according to a set pattern (see Figure 3). The degree of sample compression is measured after each transport cycle simulation. The dynamic load, transmitted to the samples by rolling the cart over the rough surface, is recorded using accelerometers. One accelerometer (PCB model #353B33, Sensitivity=0.104 Volt/g) is screw mounted to the top of the sample enclosure, and a second accelerometer (Kistler model #8630B5, Sensitivity=0.984 Volt/g) is mounted with wax adhesive to the floor of the cart proximate to a corner.

[1]%WME represents the electrical resistivity measured by a wood moisture meter. For cane fiberboard, it relates to moisture content by: wt% moisture $\cong$ 0.67 * %WME + 2.6, over a range up to ~40 %WME.

Figure 3. Test setup of the dynamic load test for samples
(a) Sample boxes on cart (b) Arrangement within sample boxes

RESULTS OF DYNAMIC TESTING

The samples are subjected to a dynamic transport simulation cycle immediately after they are placed under nominal load, and then once per week for a period of approximately 6 months (relatively little change was observed after 19 weeks). Following dynamic testing of the first set, a second set of dynamic samples began testing and has currently accumulated 8 weeks exposure. Sample heights are measured before and after each cycle of dynamic excitation. The relative change in height for each of these samples is shown in Figure 4.

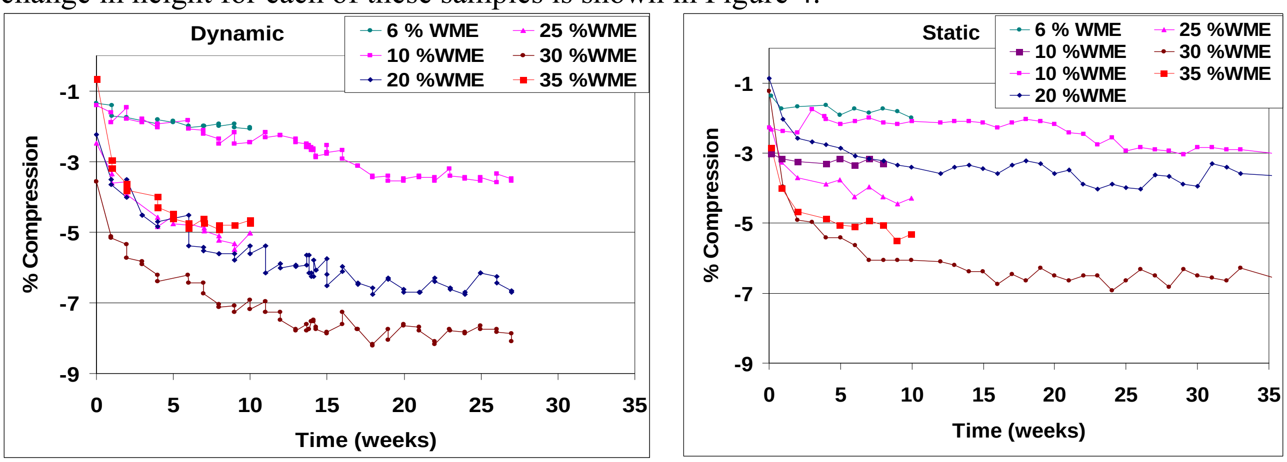

Figure 4 Relative change in height under load for test samples. The 6 and 10 %WME samples were loaded to 3.4 psi, while the other samples were loaded to 2.7 psi.

During the transport simulation cycle, acceleration measurements were recorded in 2 second intervals for conversion to spectral data in a frequency range of 0-200 Hertz. The dynamic data were captured using a Fast Fourier Transform (FFT) analyzer, in a continuous capture mode, to collect all data while the cart was rolled over the rough surface. The FFT analyzer was configured with measurement parameters that included Peak Continuous capture mode (i.e., the peak value measured at each frequency is retained and updated for each increment of the overall measurement), and Hanning Window data smoothing to improve measurement accuracy by minimizing FFT leakage resulting from waveform time-to-frequency domain transformation.

Typical cart dynamic acceleration measurements are shown in Figures 5A through 5D**.** The measurements in Figures 5A-5B were collected at the beginning of the test program for the first set of samples. The measurements in Figures 5C-5D were collected in the middle of the test program for the second set of samples. “Inst Time” in Figures 5A and 5C is a 2 second interval of the recorded acceleration response for the accelerometer locations. The “Power Spectrum” plots in the figures show the acceleration maximum measured for each frequency in the 0-200 Hertz range.

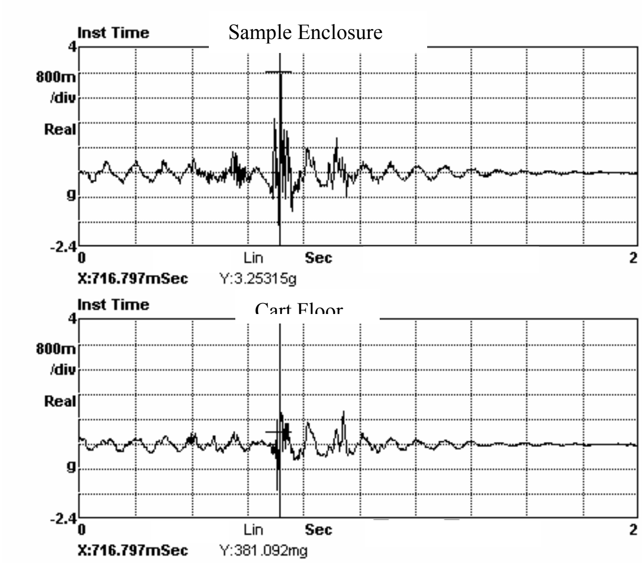

Figure 5A Two second interval of acceleration response recorded 6/16/2010.

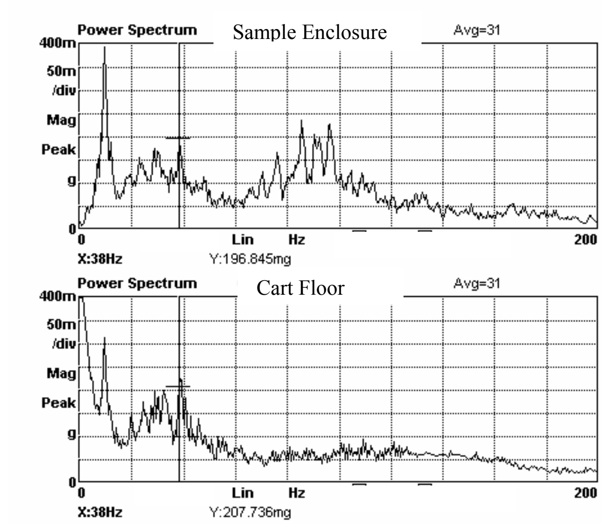

Figure 5B Spectral Acceleration maxima measured for 29 two second intervals. Recorded 6/16/2010

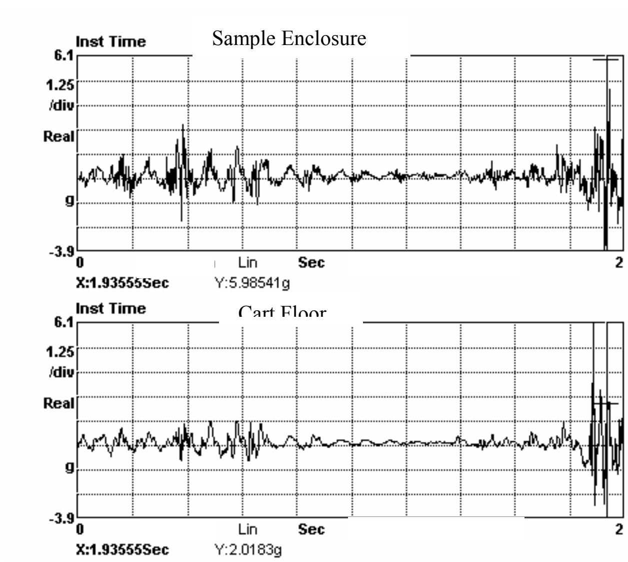

Figure 5C Two second interval of acceleration response recorded 4/13/2011.

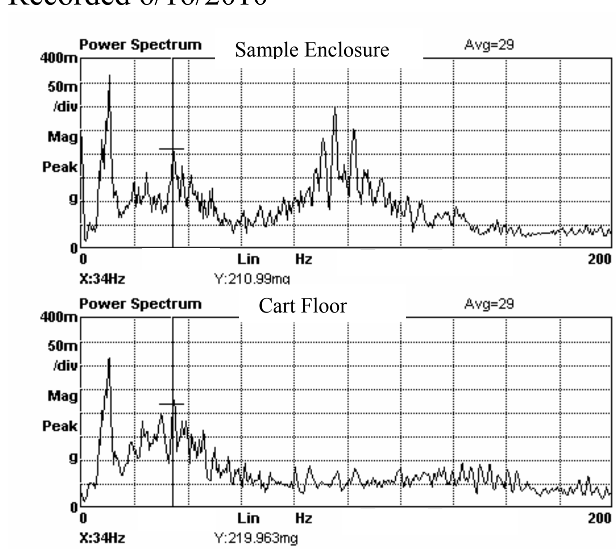

Figure 5D Spectral Acceleration maxima measured for 31 two second intervals. Recorded 4/13/2011

The "Avg=#" in each spectrum plot indicates the number of two second intervals collected to obtain the displayed data. Comparison of Figure 5A with 5C is not performed, because of the transient nature of the time data. However, comparison of the spectral data in Figures 5B and 5D should, and does, show close correlation based on elimination of most transient aspects of the data by conversion to the frequency domain and averaging. Examination of the power spectra, recorded at the two different times in the test program, shows minimal variation over the 9 month duration of testing. Spectra from both dates have approximately the same spectral shape, and a similar broadband input magnitude of ~0.1-0.2g at the cart floor and on the top of the plastic enclosure. Figure 5E contains an overlay of the background acceleration power spectrum measurements from the 6/16/2010 and 4/13/2011 test dates. For each background measurement, the cart was stationary, and the only input to the cart was due to vibration transmission from the building floor into the cart's wheels. Based on the ~0.003g peak value, it is obvious that the background acceleration level is insignificant when compared to the Figure 5B 0.1-0.2g magnitude.

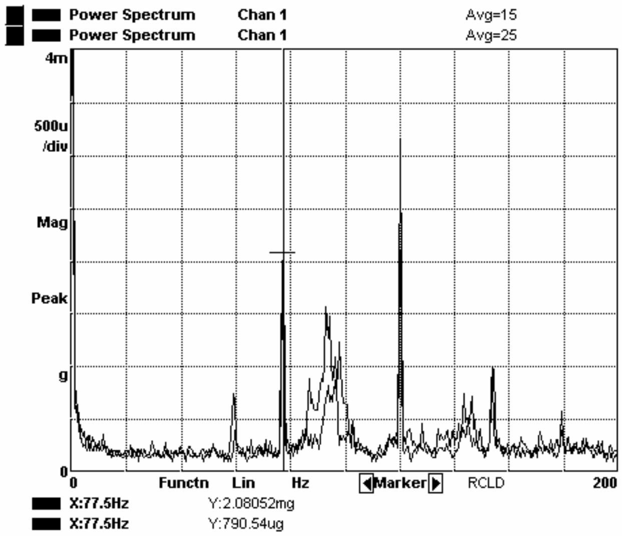

Figure 5E Floor Input Acceleration data for tests on 6/16/2010 and 4/13/2011

DISCUSSION

The degree of compression observed to date in the second set of samples is not entirely consistent with that for the first set. Between the two sets of samples, the initial compression rates for samples at 20 - 35 %WME moisture content does not present a consistent trend. Testing of the second set is continuing to identify if this trend persists.

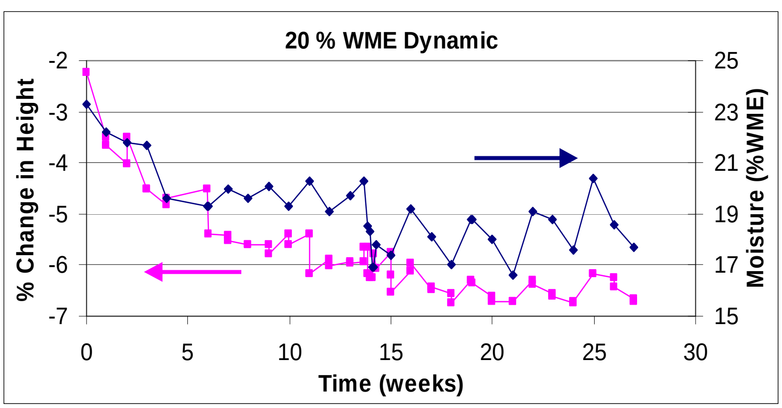

Figure 6. Typical correlation between moisture content and compression, shown for 20 %WME dynamic sample

In general, higher fiberboard moisture content corresponds to higher total compaction, a greater rate of compaction, and continued compaction over a longer period of time. These trends have been noted previously [6]. Superimposed on these trends, as moisture levels fluctuate, the sample height tends to fluctuate in unison, as illustrated in Figure 6. This correlation with moisture fluctuation was stronger for moisture levels from 6 %WME to 25 % WME.

The safety analysis for the 9975 package includes discussion of the vibration from road transportation loadings [7]. The vibration levels are bounded by a high amplitude low frequency envelope of 1 – 1.5g at 2 – 7 Hz, and a power spectral density value of 0.001 g/Hz^2 in the frequency range from 10-40 Hz. The low frequency high acceleration input would not result in significant packaging response due to the higher resonant frequencies indicated in packaging qualification calculations. However, input over the 10-40Hz range would result in significant package response, as this is where the fundamental frequency of the system occurs, and as such defines the input envelope and a conservative bound to typical vibrations experienced on a smooth road. Similar loadings might be postulated to result from handling packages within a facility.

The measured displacement data for the first sample set (Sample IDs 50C, 40E, 40F), and the data obtained to-date for the second sample set (Sample IDs D-50-6, D-40-25, D-40-35) are included in Table 1. Measurements for the first sample set are complete, and data are still being recorded for the second sample set.

Table 1: Measured Response Data

Sample ID	Nominal Moisture Content %WME	[A] Initial Sample Height w/o weight (in)	[B] Initial Height with weight (in)	[W] Weight Added (Lb)	[D] Final Height with Weight (in)	[E] Final Height w/o Weight (in)
50C	10	2.116	2.095	50.6	2.041	2.07
40E	20	2.192	2.166	40.7	2.045	2.069
40F	30	2.300	2.262	40.5	2.114	2.139
D-50-6	6	2.208	2.191	50.6	2.165	*
D-40-25	25	2.292	2.270	40.7	2.178	*
D-40-35	35	2.278	2.252	40.5	2.145	*

*Test In-Progress

In the context of this study, important sample dynamic parameters include stiffness, damping, natural frequency, and Transport Acceleration. Using the data in Table 1, it is possible to calculate stiffness, natural frequency, and the "Transport Acceleration" input requirement for each individual sample. Results for the sample dynamic parameters are obtained using the Table 1 data, and the same dynamic analysis methodology implemented for 9975 package qualification. The dynamic system model used for the 9975 closely matches the loaded sample configuration used for these tests where a rigid mass is provided vertical support by fiberboard.

The fundamental resonant frequency of the package system, where stiffness of the container inside the 9975 is considered sufficiently high to decouple rigid body response of the content/fiberboard system from the flexible response of the container, was calculated as ~22 Hz in the 9975 evaluation, and the Transport Acceleration, corresponding to this frequency and a damping value of 0.1, which is less than published dry fiberboard damping values [8] was determined to be 0.42g. In comparison to the dynamic testing acceleration input shown in Figures 5B and 5D, the 0.1-0.2g input is 25-50% of the Transport Acceleration requirement with an assumed fiberboard damping value of 0.1. The cumulative duration of dynamic excitation for sample set 1 was approximately 1.5 hours over 6 months. There is not an exposure duration requirement for transport design vibration available that can be compared to the duration of dynamic testing, but the cumulative number of vibration cycles experienced by the test samples is likely to be much smaller than would be experienced during a cross country package transport. However, the 1.5 hours of sample dynamic input did include continuous shock input, unlike what would be expected to occur during package transport. The shock input is indicated by the high amplitude short duration acceleration values in Figures 5A and 5C.

In regard to fiberboard damping, the exact value of damping has not been determined. Intuitively, the addition of moisture to the fiberboard should increase the overall response damping of the system. Since a value of 0.1 was used in evaluating the package closure vibration loads, it is also used here for all samples regardless of moisture content. It should be noted that increasing damping level in calculations for the Transport Acceleration input would result in closer agreement with the applied dynamic test input. Impulse/Response testing is planned as part of future sample testing to determine the damping level associated with each sample.

The sample dynamic parameter results listed in Table 2 were obtained using the following equations:

$f=(386.4K/W)^{1/2}/2\pi$, [Ref 7, pages Appendix 2.2, pages 87-90]
K=Sample Stiffness (lb/in)
W=Compression Weight (lb)
f=fundamental resonant frequency (Hz)

$G_{out}=(\pi PfQ/2)^{1/2}$, [Ref 7, Appendix 2.4 pages 54-56]
P=0.001g2/Hz, transportation power spectral density for $10 \leq f \leq 40$ Hz
G_{out}=Transportation acceleration level (g)
Q=Amplification factor=$1/(2\zeta)$
ζ =Damping ratio, 0.1

Examination of the Table 2 data results in several noteworthy observations. First, variations in stiffness for the samples do not result in significant variations in natural frequency, with a range of 16-24 Hz calculated, and in good agreement with the package documented value of 22 Hz from [1]. Looking at column [F], all samples experienced permanent compression with values increasing proportional to the moisture level. For the 30 %WME sample, the initial compression caused by weight addition was not recovered when the weight was removed, as indicated by comparison of data in columns [C] and [G]. This is indicative of an overall change in sample stiffness during the dynamic test period. The other samples from set 1 fully recovered initial compression despite experiencing some permanent compression. Columns [H], [I] and [J] all show changes in total sample compression, sample compression after the weight was added, and permanent deformation that occurred during the dynamic test sequence respectively. The data for each of these quantities show a trend of increasing value with an increase in moisture level.

Table 2: Calculated Dynamic Response Data

Sample ID	Nominal Moisture Content %WME	[C]=A-B Initial Sample Compression (in)	[F]=A-E Permanent Compression (in)	[G]=E-D Sample Elastic Rebound (in)	[H]=A-D Total Compression with Weight (in)	[I]=B-D] Sample Deformation Post Weight Addition (in)	[J]=B-E Permanent Deformation after initial compression (in)	[K]=W/C Stiffness (lb/in)	Fundamental Resonant Frequency (Hz)	Transport Acceleration (g)
50C	10	0.021	0.046	0.029	0.075	0.054	0.025	2410	21.59	0.41
40E	20	0.026	0.123	0.024	0.147	0.121	0.097	1565	19.40	0.39
40F	30	0.038	0.161	0.025	0.186	0.148	0.123	1066	16.05	0.36
D-50-6	6	0.017	*	*	0.043	*	*	2976	23.99	0.43
D-40-25	25	0.022	*	*	0.114	*	*	1850	21.09	0.41
D-40-35	35	0.026	*	*	0.133	*	*	1558	19.40	0.39

* Test in Progress

The effects of the dimensional changes on package dynamics can be postulated based on the Table 2 results. Since the overall height of the fiberboard samples decreased, the fiberboard experienced “sag” due to either slow creep under the constant static load, or slow creep with possible additional sag contribution from the dynamic excitation. It is likely that the overall shock absorption capability of the reduced fiberboard column also decreased. However, the initial shock absorption capability of the fiberboard was excessive in regard to demand, and the reduction due to sagging of the fiberboard is likely small. For transportation accident impacts, the fiberboard and drum are not credited since the SARP includes an analysis of the 9975 shielding body with internal containment vessels directly impacting an unyielding surface in the accident sequence.

For samples 40E and 50C, the initial deformation due to weight addition is approximately equal to the sample rebound. This result indicates that the sample stiffness was unchanged at the end of the 6 month test period. In contrast, sample 40F did not recover a substantial amount of the initial compression. This indicates that the overall stiffness of 40F has increased to approximately that of 40E, based on nearly identical rebound values in column [G]. Since the variation in stiffness and natural frequency for all of the samples only results in a difference of ~0.05g for the Transport Acceleration, the change in fiberboard stiffness would have a minimal affect on the dynamic behavior of the 9975 package/container system. However, given a substantial increase in the fiberboard stiffness, due to greater sagging, it is possible that natural frequency increases coupled with a reduction in damping could result in higher loads experienced by package contents. Once again, the margin between capacity and demand related to vibration loading is great, and a limited amount of sagging should not produce unacceptable response. Based on the test data presented, a 5% reduction in sample 40F height was measured, and limiting package post loading deformation to a similar value would likely provide a conservative bound for maintaining acceptable package dynamic response.

Examination of Figures 5A through 5D shows higher acceleration values in both “Inst Time” and “Power Spectrum” plots for the accelerometer mounted on the sample enclosure. This result is expected as the hard plastic enclosure has additional flexibility which amplifies the base input. Since multiple sample enclosures are placed on the cart for dynamic loading, the dynamic acceleration imparted to each sample from the cart floor would be slightly different, but bounded by the “Sample Enclosure” and “Cart Floor” data.

The power spectrum for “Cart Floor” in Figure 5D is considered typical for sample dynamic loading. The spectrum indicates a fairly uniform acceleration input of 0.1-0.2g in the 5-200 Hertz frequency range. Excitation in the 0-5 Hertz range is low, as expected, due to the hardness of the cart wheels, and steel expanded metal surface. The hard surfaces of contact result in a broad frequency range of input, as opposed to a smaller range of low frequency input if the duration of impact were increased by using softer material for the cart wheels. Since the mass mounted on the top of each sample is rigid, the dynamic force experienced by a sample would be equivalent to the input acceleration multiplied by the weight of the compressing object, applied as a sinusoidal load over a duration equal to time spent rolling the cart over the rough surface. Additionally, the peak static equivalent dynamic shock load can be approximated by multiplication of the compressive weight by the peak acceleration value shown in either Figure 5A (>3g) or 5C (~6g). This is a very short duration acceleration, and as such, mechanical response or stress assessment would need to take into account time dependent properties for shock effect evaluation.

CONCLUSIONS

Moisture levels and dynamic loading contribute to the compaction of the fiberboard. For a given moisture level, dynamic loadings on the fiberboard will lead to greater compaction than static loading. Beyond a certain degree of compaction, continued dynamic loading causes little additional compaction. Rather, subsequent change in fiberboard height is driven more by variation in moisture content.

The exposure of the samples to dynamic excitation indicates a general trend of greater compaction for higher moisture levels. There appears to be a threshold moisture level where fiberboard initial compression becomes unrecoverable. Below this threshold, the fiberboard would show no change in dynamic response, but may have slightly reduced shock absorption capabilities. Negative transportation effects due to fiberboard "sag" may be avoided by in-service inspection of the fiberboard height reduction with time. Above the threshold moisture value, the fiberboard stiffness increases, but based on an increase in the fundamental resonant frequency, the net effect may result in either slightly higher or even significantly lower transportation dynamic loading depending on the final stiffness. The shock absorption capability of the higher moisture exposure would result in reduced shock absorption capability based on higher fiberboard stiffness, and the related reduced fiberboard height. While higher moisture would likely result in greater damping, the fiberboard damping level as a function of moisture level is unknown, but would greatly influence the dynamic response of the package. Additional tests to determine damping level are warranted to fully characterize dynamic response of the fiberboard and packaging.

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