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**OVER-THE-ROAD TESTS OF NUCLEAR MATERIALS
PACKAGE RESPONSE TO NORMAL ENVIRONMENTS**

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Abstract

In support of the development of American National Standards Institute standards for the transport of radioactive materials, Sandia has a program to characterize the normal transport environment. This program includes both analytical modeling of package and trailer responses, and over-the-road tests to measure those responses. This paper presents the results of a series of over-the-road tests performed using Chem-Nuclear equipment in the Barnwell, SC, area.

The test events included a variety of road types such as rough concrete, shock events such as railroad grade crossings, and driver responses such as sharp turns. The response of the package and trailer to these events was measured with accelerometers at various locations to determine the inertial loads. Either load cells or strain gages were used to measure tiedown response. These accelerations and loads were measured on systems with flexible and "rigid" tiedowns.

The results indicated that while significant accelerations occur on the trailer bed, these do not translate into equivalent loads in either the package or the tiedown system. This indicates that trailer-bed response should not be used in determining the load factor for fatigue calculations of the package components or in determining design loads for tiedowns.

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Introduction

Sandia National Laboratories has an ongoing program to characterize the normal environments encountered during the transport of radioactive materials. This effort consists of obtaining experimental data from both road simulator and over-the-road tests and of analyzing the data to obtain numerical models to simulate those environments (1-3).

Following discussions with the Nuclear Regulatory Agency, further test activities were added to the completed tests (1-3). These included: (1) over-the-road testing with a system incorporating a rigid tiedown system (CNS 3-55), (2) hard braking, and (3) hard turning. The results of these rigid tiedown system tests agreed with these previous test results, in that all tiedown loads were well below design limits established in draft ANSI standards and by the Department of Transportation. Package response during any given test is specific to that package and trailer. Based on the full range of over-the-road tests, road simulator tests, and analyses, the current tests provide additional data to support the response envelopes previously presented (3).

These data and models are currently being used in defining the design basis for resistance to shock and vibration and in defining the requirements for tiedowns for truck transported radioactive materials. This work is in conjunction with the American National Standards Institute development of national standards.

This report provides the data from a series of over-the-road tests performed with Chem-Nuclear Systems, Inc equipment near Barnwell, South Carolina. The data include responses of the packaging to driving over various road types as well as measurements of the response of the packaging and trailer to hard braking and turning events. The data include the responses of both flexible and rigid tiedown systems. The results indicate that the forces in tiedowns for these tests were less than 0.05 g based on package weight.

Events

The trailer and packagings were subjected to nine separate events to determine both the acceleration and tiedown loads experienced during normal transport. These are summarized in Table 1. Five types of roads were used: (1) smooth asphalt primary (Figure 1); (2) rough asphalt primary (Figure 2); (3) rough concrete primary (Figure 3); (4) rough asphalt secondary (Figure 4); and (5) spalled asphalt secondary (Figure 5). The roads provided a vibrational environment for the packaging. To subject the packaging to a shock environment, a railroad crossing (Figure 6) and bridge approach (Figure 7) were selected. Finally, to determine the package's response to maneuvering, a hard turn and a stop were executed.

The speed driven for each event was the lesser of either the posted legal speed limit or the fastest speed consistent with safe operation of the tractor.

For each event, approximately 15 seconds of data were recorded. This provides 15,000 samples per data channel. This is adequate time, as can be seen in the data in the Appendices, to capture shock events, such as the rail crossing plus damping back to the random vibration state. For the random vibration events, such as smooth asphalt roads, it provides a representative sampling. This is demonstrated in the frequency content of the packaging where the lowest frequency response is between 1 and 2 Hz, so that a 15 second record captures 15 to 30 response cycles.

Packagings

Two packagings were tested: the CNS 14-170 and the CNS 3-55, selected on the basis of weight and tiedown type.

The CNS 14-170 is a lead and steel Type A package used to ship dewatered or solidified waste material, and has an empty package weight of 33,800 lbs. with a payload weight of 14,000 lbs. The package is transported vertically and has a flexible tiedown system.

Table 1: Events

<u>Event</u>	<u>Primary Load Type</u>	<u>Description</u>
1	Vibration	Smooth Asphalt Primary
2	Shock	Railroad Grade Crossing
3	Vibration	Rough Asphalt Primary
4	Shock	Bridge Approach
5	Vibration	Rough Concrete Primary
6	Rigid Body	Turn
7	Rigid Body	Stop
8	Vibration	Rough Asphalt Secondary
9	Vibration	Spalled Asphalt Secondary

The CNS 3-55 is a steel-encased lead-shielded Type B package. The empty package weight is 56,912 lbs. with a payload capacity of 9,220 lbs. The package is transported horizontally in the cradle representative of "rigid" tiedown systems (Figure 8).

Figure 1. Smooth Asphalt Primary Road

Figure 2. Rough Asphalt Primary Road

Figure 3. Rough Concrete Primary Road

Figure 4. Rough Asphalt Secondary Road

Figure 5. Spalled Asphalt Secondary Road

Figure 6. Railroad Crossing

Figure 7. Bridge Approach

Instrumentation

The primary role of the instrumentation was to obtain the acceleration at various points on the trailer and package, and to either directly measure forces in the flexible tiedown, or to measure strains in the cradle which can be used to determine forces acting on the tiedown. The locations and measurements obtained from each instrument are given in Table 2. A total of nine instruments were used in each test.

A triaxial accelerometer was placed on the package's center top to measure the package response along each axis. The stiffness of the package made this measurement representative of the entire package. At the same longitudinal location, an accelerometer measured the trailer's vertical acceleration. The maximum accelerations on a trailer are obtained at its front and rear. Longitudinal and vertical accelerometers were placed on the trailer bed over the rear axle, and a vertical accelerometer placed on the trailer over the kingpin. The combination of vertical accelerometers at these three trailer locations allowed the bounce, pitch, and bending modes to be detected. The longitudinal and transverse accelerometers were useful in detecting the effects of braking and turning.

Figure 8. CNS 3-55 Cradle

Table 2: Instrumentation Locations

<u>Location</u>	<u>Test</u>	<u>Location</u>	<u>Measurement</u>
1	1,2	Package Top	Transverse Acceleration
2	1,2	Package Top	Vertical Acceleration
3	1,2	Package Top	Longitudinal Acceleration
4	1,2	Trailer Center	Vertical Acceleration
5	1,2	Trailer Rear	Vertical Acceleration
6	1,2	Trailer Rear	Longitudinal Acceleration
7	1,2	Trailer Front	Vertical Acceleration
13	1	Front Tiedown	Separation Force
14	1	Rear Tiedown	Separation Force
13	2	Front Tiedown Strap	Vertical Strain
14	2	Rear Tiedown Strap	Vertical Strain

The response of the tiedown systems was determined from load cells in the links between attachment points on the CNS 14-170 and with strain gages mounted on the cradle straps for the CNS 3-55. The load cell was zeroed after preloading so that only transport-induced loads are measured. The strain gages were arranged in a bridge to remove the effects of bending and hence only measure the strain in the direction of the strap.

The uncertainty that can be expected in the data is ± 15 percent (4) based on uncertainty analyses of data acquisition systems, data reduction techniques, and transducers at Sandia. This uncertainty exceeds manufacturer's published uncertainty values for each type of transducer, since it includes the spectrum of activities required to obtain, analyze, and present data.

Test Results

This section describes the results for the over-the-road tests. Because of the volume of information acquired from tests of this type, the actual time histories and resultant power spectral densities (PSD) are located in the appendices. The results for Test 1 are located in Appendix A, and the results for Test 2 are located in Appendix B. The plot of measured time history and the derived PSD for each transducer are grouped by event in the appendices. Appendix A also contains a description of the data reduction technique.

Shock events, such as the railroad grade crossing and bridge approach, are not stationary events, and hence PSD calculations are not appropriate. Rigid body events, such as the turn and hard stop, were performed to determine the response magnitude only, independent of frequency response.

It is from these data that the results are summarized. The time histories provide the mean-to-peak response at the different locations. From these time histories, the auto spectral density (PSD) is generated. The PSD transforms the time history data into the frequency domain to

relate how the response energy varies as a function of frequency. From this data, it is determined which modes of vibration are contributing to the overall response, and the root-mean square response (RMS) can also be calculated.

Table 3 summarizes the peak acceleration results for Test 1. The RMS responses are presented in Table 4. The tiedown responses are given in Table 5. The results of Test 2 are presented in Tables 6, 7, and 8.

Table 3: Peak Accelerations for Shock and Vibration Events (g),
CNS 14-170

Accelerometer ¹	Event ²						
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>8</u>	<u>9</u>
1	0.17	0.16	0.21	0.28	0.12	0.13	0.22
2	0.23	0.62	0.32	0.45	0.20	0.35	0.58
3	0.17	0.9	0.38	0.63	0.22	0.64	0.88
4	0.21	2.3	0.37	0.85	0.07	0.07	0.08
5	0.46	5.3	1.4	4.6	0.95	1.68	3.1
6	0.14	2.8	0.37	1.65	0.22	0.43	0.85
7	0.73	4.5	1.7	3.4	1.3	2.7	4.5

1. Accelerometer locations and direction are: 1 - Package Top, Transverse; 2 - Package Top, Vertical; 3 - Package Top, Longitudinal; 4 - Trailer Middle, Vertical; 5 - Trailer Rear, Vertical; 6 - Trailer Rear, Longitudinal; 7 - Trailer Front, Vertical.
2. Events are: 1 - Smooth Asphalt; 2 - Railroad Crossing; 3 - Rough Asphalt; 4 - Bridge Approach; 5 - Rough Concrete; 8 - Secondary Asphalt; 9 - Spalled Asphalt.

The time history shown in Figure 9a is the measured vertical acceleration of the rear trailer bed in response to the spalled asphalt event for Test 1. This figure shows a fairly severe vibrational environment, with two large transient events occurring 3 and 9 seconds into the run. There is also a quieter section from 6 to 7 seconds. The random nature of the data is evident from the time histories.

Figure 9b shows the same response in the frequency domain, in PSD form. The response is shown as g^2/Hz on a log-log plot. The larger response at 1.5 Hz is due to the first bounce mode of the tractor/trailer

combination. This bounce mode of the vehicle is caused by the structure bouncing in unison on the suspension system of the trailer. The next feature seen in Figure 9b is the response at 4 Hz. This is the frequency of the vehicle's first pitching mode. This is caused by the kingpin/rear tractor suspension deflecting down while the trailer rear suspension and tractor front suspension deflect up. The high-frequency modes, from 10 to 20 Hz, are combinations of the trailer bending with the tractor pitching and bending. The first bending mode occurs at approximately 11 Hz.

Table 4: RMS Accelerations (g) for Vibration Events, CNS 14-170

Accelerometer ¹	Event ²				
	<u>1</u>	<u>3</u>	<u>5</u>	<u>8</u>	<u>9</u>
1	0.042	0.043	0.025	0.027	0.054
2	0.041	0.096	0.050	0.066	0.125
3	0.041	0.057	0.055	0.143	0.227
4	0.040	0.093	0.01	0.011	0.011
5	0.135	0.211	0.233	0.401	0.718
6	0.030	0.042	0.059	0.088	0.180
7	0.254	0.294	0.403	0.571	1.03

1. Accelerometer locations and direction are: 1 - Package Top, Transverse; 2 - Package Top, Vertical; 3 - Package Top, Longitudinal; 4 - Trailer Middle, Vertical; 5 - Trailer Rear, Vertical; 6 - Trailer Rear, Longitudinal; 7 - Trailer Front, Vertical.
2. Events are: 1 - Smooth Asphalt, 3 - Rough Asphalt, 5 - Rough Concrete, 8 - Secondary Asphalt, 9 - Spalled Asphalt.

Table 5: Peak Tiedown Loads (lbs), CNS 14-170

Load Cell ¹	Event ²								
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
13	430	700	580	400	220	800	630	350	460
14	220	650	360	300	150	550	480	280	650

1. Load cell locations are: 13 - Front Tiedown, 14 - Rear Tiedown.
2. Events are: 1 - Smooth Asphalt, 2 - Railroad Crossing, 3 - Rough Asphalt, 4 - Bridge Approach, 5 - Rough Concrete, 6 - Turn, 7 - Stop, 8 - Secondary Asphalt, 9 - Spalled Asphalt.

Table 6: Peak Accelerations (g) for Shock and Vibration Events, CNS 3-55

	Accelerometer ¹							Event ²	
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>8</u>	<u>9</u>		
1	0.1	0.14	0.13	0.11	--	0.34	--		
2	0.12	0.47	0.25	0.23	0.12	0.37	0.2		
3	0.12	0.50	0.15	0.45	--	0.38	0.28		
4	0.09	0.8	0.25	0.32	0.17	0.35	0.22		
5	0.55	5.9	1.4	2.4	1.0	2.7	1.95		
6	0.13	3.0	0.21	0.47	0.3	0.81	0.4		
7	0.85	6.5	1.1	3.4	1.2	3.4	2.65		

1. Accelerometer locations and direction are: 1 - Package Top, Transverse; 2 - Package Top, Vertical; 3 - Package Top, Longitudinal; 4 - Trailer Middle, Vertical; 5 - Trailer Rear, Vertical, 6 - Trailer Rear, Longitudinal; 7 - Trailer Front, Vertical.
2. Events are: 1 - Smooth Asphalt, 2 - Railroad Crossing, 3 - Rough Asphalt, 4 - Bridge Approach, 5 - Rough Concrete, 8 - Secondary Asphalt, 9 - Spalled Asphalt.

The calculation of RMS response also uses the PSD format. The mean squared response is the area under the PSD response curve. The RMS is the square root of this value. The RMS relates the probability of a certain level of response occurring, and is equal to the standard deviation since the mean is zero. For example, three times the RMS will envelope 99.9 percent of all expected responses.

The transform magnitude plots for the railroad grade crossing event are also shown in the appendices. These plots are discrete Fourier transforms of the measured response and are provided to show the frequency content of the transient record. Shock spectra are not presented because the structure can not be assumed to resemble a single degree-of-freedom system. For the other shock-producing events, only the time history is presented.

The complete time histories and PSD responses are located in the appendices. The description of the individual events for Test 1 follows and reference should be made to the figures located in Appendix A, Figures A1 through A124. Refer to Table 2 for instrumentation locations.

Table 7: RMS Accelerations (g) for Vibration Events, CNS 3-55

Accelerometer ¹	Event ²				
	<u>1</u>	<u>3</u>	<u>5</u>	<u>8</u>	<u>9</u>
1	0.02	0.032	--	0.042	--
2	0.027	0.072	0.024	0.075	0.043
3	0.023	0.035	--	0.097	0.075
4	0.027	0.069	0.028	0.078	0.048
5	0.28	0.23	0.24	0.65	0.53
6	0.028	0.042	0.058	0.11	0.096
7	0.102	0.22	0.32	0.77	0.63

1. Accelerometer locations and direction are: 1 - Package Top, Transverse; 2 - Package Top, Vertical; 3 - Package Top, Longitudinal; 4 - Trailer Middle, Vertical; 5 - Trailer Rear, Vertical, 6 - Trailer Rear, Longitudinal; 7 - Trailer Front, Vertical.
2. Events are: 1 - Smooth Asphalt, 3 - Rough Asphalt, 5 - Rough Concrete, 8 - Secondary Asphalt, 9 - Spalled Asphalt.

Table 8: Peak Tiedown Loads (lbs), CNS 3-55

Strain Gage ¹	Event ²								
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>
13	1900	--	2040	--	1130	960	--	2060	1680
14	2530	--	2350	2040	1560	1440	--	3120	2200

1. Strain Gage locations are: 13 - Cradle Front, 14 - Cradle Rear.
2. Events are: 1 - Smooth Asphalt, 2 - Railroad Crossing, 3 - Rough Asphalt, 4 - Bridge Approach, 5 - Rough Concrete, 6 - Turn, 7- Stop, 8 - Secondary Asphalt, 9 - Spalled Asphalt.

Figure 9a. Representative Time History

Figure 9b. Representative PSD

Test 1 Results

Event 1 was the smooth asphalt road. The responses are shown in Figures A1 through A18. The road was driven at 55 mph and included a bridge crossing. The package acceleration and tiedown load responses were very small with an average RMS acceleration of 0.042 g in all three directions, and a peak acceleration of 0.23 g. Locations on the trailer bed experienced a greater response level, with the trailer kingpin being the greatest at 0.2 g RMS, and a peak response of 0.73 g. The bridge crossing can be seen in the time histories, and is responsible for the peak response in most records. The force in the tiedowns was measured to be 220 lbs. peak and 70 lbs. RMS for the rear and 430 lbs. peak and 141 lbs. RMS for the front tiedown. This corresponds to a maximum load in the tiedowns of 0.009 g with respect to the packaging weight.

Event 2 was the railroad grade crossing. The time histories for this event are shown in Figures A19 through A27. The rail crossing was traveled at a speed of 30 mph and produced a severe shock to the vehicle. Table III shows the largest peak responses measured for this structure. The package top shows peak accelerations of 0.16 g transverse, 0.62 g vertical and 0.9 g longitudinal. The rear of the trailer shows a 5.3 g peak acceleration vertically, and 2.8 g acceleration longitudinally, while the front of the trailer experienced a 4.5 g peak vertical acceleration. The peak force in the tiedown was 700 lbs. for the front, and 650 lbs. for the rear. This corresponds to a maximum tiedown load of 0.015 g.

From the frequency analysis of the railroad crossing shock data, shown in Figures A28 through A36, it is possible to see the modes which contribute to the shock response. The package vertical response is due primarily to the bounce mode of the structure at 1.5 Hz, shown in Figure A29, while the longitudinal response is due to the first pitch mode at 4 Hz, and to the bending modes above 10 Hz. The accelerometer at the trailer center was apparently close to a vibration node as it shows response due primarily to the bounce mode, and very little response due to the pitch or bending modes of the trailer. This is a graphic demonstration of the spatial dependence of response on the trailer bed. The vertical response at the rear and the front of the trailer, shown in Figures A32 and A34, shows strong contributions from the first several modes. This is predictable at these locations because they are the only points having large deflections due to the bounce, pitch, and bending of the trailer. From Figures A35 and A36, it can be seen that the force response in the tiedown is primarily due to the bounce mode, with some additional influence from the first bending mode of the trailer.

Event 3 was the rough asphalt primary road surface. Figures A37 through A54 show the results for this test. This test track was driven at a speed of 45 mph. The package peak acceleration was 0.38 g longitudinally, 0.057 g RMS, 0.32 g vertically, and 0.096 g RMS. Package vertical accelerations were primarily due to the first bounce mode, while the longitudinal acceleration was composed of bending modes, with a lesser input from the first pitch mode. Trailer vertical accelerations of 1.4 g peak at the rear and 1.7 g at the front were measured. The RMS levels at these locations were 0.211 g and 0.294 g, respectively. Maximum forces

measured in the tiedowns were 580 lbs. in the front, 156 lbs. RMS, and 360 lbs. in the rear, 93 lbs. RMS. This corresponds to a maximum tiedown load of 0.012 g.

Review of the time history shows a large transient between two and four seconds in the test in Figure A41. The high package longitudinal response is due to the trailer's pitching response. A single low dip across the road surface was the cause of this shock, and since no unusual transverse response was detected, the dip was symmetrical to the direction of travel. This is demonstrated by the time delay in the vertical response of the trailer front and rear. Because of this transient superimposed on the vibration data, the RMS response is much less than the peak for all vertical responses. The package longitudinal peak acceleration is higher than the vertical response, even though the longitudinal RMS level is much less than the vertical.

Event 4 was the bridge crossing. Figures A55 through A63 show the time histories for this event. The bridge was crossed at a speed of 54 mph. The most notable responses were measured in the longitudinal direction, where the package peak acceleration was 0.63 g, which was greater than the package vertical acceleration of 0.45 g. The rear trailer location had the greatest measured response of 4.6 g, while the trailer front measured 3.4 g. For every location the measured response was less than the railroad grade crossing event. The tiedown forces were approximately half the rail crossing, with 400 lbs. peak in the front tiedown, 300 lbs. peak in the rear. This corresponds to a maximum tiedown load of 0.008 g.

Event 5 was the rough concrete pavement. The concrete was overlain with an old layer of asphalt in which the surface was broken up along the joints of the concrete sections. Peak response levels were approximately two thirds of those measured for the rough asphalt event, and the tiedown forces were approximately half. The RMS responses were comparable with the rough asphalt, though for the trailer rear the rough concrete levels were higher. The mid-trailer response was caused mainly by the pitching of the structure, while the response to the rough asphalt was primarily due to the first bounce mode. This correlates to the generally higher frequency input of the rough concrete. For similar reasons, the response of the kingpin was made up primarily of high frequency bending modes, while the rough asphalt kingpin response was composed of the bounce mode and bending response.

The tiedown PSD functions also showed a greater percentage of energy due to the bending modes above 10 Hz. The tiedown forces were measured to be 220 lbs. peak and 55 lbs. RMS for the front tiedown, and 150 lbs. peak and 36 lbs. RMS for the rear tiedown, for a maximum tiedown load of 0.004 g. The tiedown RMS response was one third the level measured in the rough asphalt event.

Event 6 was the hard turn driven at a speed of 26 mph. Time histories for the package accelerometer in the transverse direction and the tiedown front and rear force time histories are shown in Figures A82 through A84, respectively. This event was completed to show the actual tiedown forces

which result from a severe turn. A side acceleration of 0.42 g was measured at the package top, and peak tiedown restraint forces of 800 lbs. forward and 500 lbs. rear were seen in the event. This maximum tiedown force of 0.017 g was the largest measured during Test 1.

Event 7, a hard stop, was used to complete the maneuvering data. The truck had an initial speed of 54 mph. This stopping event was equivalent to an emergency stop as all wheels were locked and the truck stopped in 3.4 seconds. The package top longitudinal accelerometer and rear longitudinal accelerometer time histories, shown in Figure A85 and A86, respectively, measured a 0.6 g deceleration for the stop. Package tiedown force time histories show a peak force of 630 lbs. or 0.013 g in the front tiedown, and 480 lbs. in the rear, as shown in Figures A87 and A88, respectively.

Event 8 was the secondary asphalt event, driven at a speed of 20 mph. The time histories and PSD for this event are shown in Figures A89 through A106. As expected, the response levels are all above those measured for the rough asphalt test. The PSD functions show much greater response due to the bending of the trailer than during the rough asphalt event. The middle accelerometer response was twice the rough asphalt. The PSD shows that pitching of the trailer was responsible for this increase. Both trailer rear and front responses showed a significant increase in the bending mode participation.

The tiedown response also showed a significant participation by the higher frequency bending modes. Again, the trailer response does not translate directly into tiedown forces. The measured tiedown forces for this event were significantly less than for the rough asphalt event, even though the trailer response was significantly higher than for the rough asphalt. The tiedown forces were approximately 60 percent of the rough asphalt restraint forces even though the trailer responses were up to 60 percent higher. Peak tiedown forces were 350 lbs. or 0.007 g for the front, and 280 lbs. for the rear location. The RMS levels for the trailer were approximately twice the rough asphalt results.

Event 9 was the spalled secondary asphalt road surface driven at a speed of 20 mph. Results for this event are shown in Figures A107 through A124. This was a very severe operation of the truck. This event produced peak accelerations in the package equal to the railroad grade crossing and produced the most severe RMS accelerations. The tiedown RMS levels were found to be 137 lbs. for the front and 150 lbs. for the rear, and the peak forces were measured to be 460 lbs. for the front and 650 lbs., or 0.014 g, for the rear. These peak forces were of the same magnitude as the railroad grade crossing, and the RMS levels were similar to the rough asphalt for the front tiedown. The rear tiedown RMS level is the highest measured at this location for all events, and the PSD function shows response due to the bounce and bending modes. All PSD functions show strong response due to the bending of the trailer.

Test 2 Results

The results for the heavier, Type B package will be described here. The figures showing the respective test results are located in Appendix B. The events were completed in the same order used in Test 1. For the

tiedown strain gage data, the conversion factor to produce pounds from strain is 30×10^6 psi X 8 square inches. As was stated earlier, the configuration of the strain gages provided net axial force in the tiedown straps.

Event 1 was the smooth asphalt surface driven at a speed of 55 mph. Figures B1 through B18 show the measured data for this event. Very low response was seen in the package as a maximum of 0.12 g was measured, 0.027 g RMS. Peak response on the trailer bed was 0.85 g, at the trailer kingpin location. The largest RMS level of 0.102 g was measured at this same location. Peak force in the tiedowns was 2530 lbs. at the rear station, 1008 lbs. RMS, while 1900 lbs. peak was measured in the front tiedown, 840 lbs. RMS. These correspond to a maximum tiedown load of 0.038 g.

Vertical response in the package was primarily due to the bounce mode. For the longitudinal response, the pitch and bending modes were dominant. On the trailer bed the vertical response was equally distributed among the three mode types. The tiedown frequency analysis shows a significant input due to the pitch and bending modes of the trailer, along with the primary bounce mode input. This was caused by the increased length of the package on the trailer which, by geometry, puts the tiedown in a location of greater deformation of the system. The bounce mode was dominant in the results of the front tiedown, whose location is closer to the vibratory node for the bending modes thereby reducing the total input from this mode. The RMS levels in the tiedowns were the highest found for either test.

Event 2, the railroad grade crossing, provided the maximum responses for both tests. The crossing was traveled at a speed of 38 mph. Plots of this event's time history data are shown in Figures B19 through B25. While the package maximum response was 0.5 g longitudinally and 0.47 g vertically, the response on the trailer was 6.5 g vertically at the kingpin, and 5.9 g vertically at the trailer rear. As expected, the longitudinal response and trailer extreme responses contained pitch and bending mode participation. The middle vertical location was dominated primarily by the bounce mode. The strain gage data was faulty for this event, so no tiedown loads can be reported. The frequency analysis of the shock data, Figures B26 through B32, show a very strong participation of the bending modes to the vertical responses of the trailer.

Event 3 was the rough asphalt primary surface driven at 45 mph, and the response data is shown in Figures B33 through B50. Peak response of the package was 0.25 g vertically, with the other two directions being approximately 0.15 g. The most significant accelerations were found on the trailer extremes in the vertical direction, with 1.4 g peak at the rear and 1.05 g peak at the front.

Tiedown forces were among the highest measured for this system. Responses at the rear were a peak of 2350 lbs. or 0.035 g and 878 lbs. RMS, and a front peak force of 2040 lbs. and 749 lbs. RMS. The tiedown PSD show dominance of the bounce mode with a very small participation of the bending mode. Responses of the trailer show a very strong contribution due to the bending modes of the trailer.

Event 4 was the bridge crossing at 55 mph. Time histories for this event are shown in Figures B51 through B59. Levels recorded for this event were less than the railroad grade crossing. The maximum acceleration on the package was 0.45 g in the longitudinal direction. Peak trailer bed vertical accelerations were 3.4 g in the front and 2.4 g in the rear. The front tiedown showed no appreciable increase due to the event; background noise caused by the strap inertial effects are all that is seen in the record. The rear tiedown showed a peak 2040 lbs. force or 0.031 g.

Event 5 was a rough concrete surface test driven at 47 mph. Response plots are found in Figures B60 through B73. The speed was slower than Test 1 because the heavier truck could not go faster up the slight grade. Results for this test were generally less than those of the rough asphalt with some notable exceptions. The RMS levels for the trailer extremes were all higher than the rough asphalt. From the PSD plots we can see a significant input due to the higher frequency modes induced by the concrete surface. The tiedown responses were much lower than they were for the rough asphalt.

Event 6 was the turning event, executed at 28 mph. Figure B74 shows the package transverse time history and Figures B75 and B76 show the front and rear tiedown response, respectively. The package showed an overall 0.27 g response. This is less than for Test 1 because of a heavier load and the wet road surface. The tiedown forces measured 960 lbs. in the front and 1440 lbs. or 0.022 g in the rear.

Event 7 was the stopping event which started from a speed of 47 mph. Figure B77 and B78 show the longitudinal acceleration of the package top and trailer rear. Both accelerometers recorded 0.4 g deceleration for the event. Again, the wet road conditions resulted in a lower deceleration than Test 1. No appreciable tiedown forces were recorded at either location, and Figures B79 and B80 show the time histories for the tiedowns.

Event 8 was the secondary asphalt event driven at a speed of 40 mph. Figures B81 through B98 show the results for this test. This event produced the highest vibration of the package in all three directions. The package averaged 0.36 g peak acceleration for all three directions, with 0.075 g RMS vertically and 0.097 g RMS longitudinally. The trailer response was recorded at 2.7 g peak for the rear vertical and 3.4 g peak at the front. The trailer longitudinal response was 0.81 g peak, the highest measured for a vibration event. The RMS levels on the rear of the trailer were the highest measured with 0.65 g RMS vertically and 0.113 g RMS longitudinally. A 0.769 g RMS response was measured at the trailer front.

The tiedown response was also the highest recorded for all the events. The peak force measured was 2060 lbs. in the front tiedown and 3120 lbs. or 0.047 g in the rear. The RMS force was found to be 605 lbs. in the front and 881 lbs. in the rear. The high frequency bending modes were responsible for a large part of the response for most of the records, including the tiedown force response.

Event 9 was the spalled asphalt surface driven at 40 mph. Figures B99 through B114 show the results for this event. Peak responses in the 0.25 g range were measured for the package while RMS levels of 0.043 g vertically

and 0.075 g longitudinally were calculated. Trailer vertical response was measured to be 1.95 g peak at the rear, 0.526 g RMS, and 2.65 g peak above the kingpin, 0.628 g RMS. Forces in the tiedowns were measured to be 1680 lbs. peak in the forward location, 523 lbs. RMS, and 2200 lbs. peak or 0.033 g, 765 lbs. RMS, in the rear tiedown. As with the spalled asphalt surface, the higher frequency modes dominated the response spectrums.

Discussion of Results

The most severe acceleration from Test 1 was measured at the trailer rear in the vertical direction, 5.3 g, during the railroad grade crossing. The next most severe acceleration of 4.5 g was measured at the front of the trailer during the railroad grade crossing and during the spalled asphalt event. The greatest acceleration measured for Test 2 was 6.5 g, which was again measured during the railroad grade crossing, but at the trailer front. This was also the greatest acceleration measured for either test. The trailer rear vertical location for the same event was the next most severe at 5.9 g.

Tiedown maximum forces of 800 lbs. were measured for Test 1 during the turning event, with the railroad grade crossing being next most severe at 700 lbs. For Test 2, the maximum tiedown force, 3120 lbs., was measured during the secondary asphalt event.

For the vibration events of Test 1, the most severe peak acceleration was measured during the spalled asphalt event, at the trailer front. The secondary asphalt event provided the next most severe results. For Test 2, the secondary asphalt event provided the worst vibration environment, with the spalled asphalt being next most severe.

For Test 1, the rough asphalt event produced 50-100 percent greater response than did the smooth asphalt event, both in peak values and in RMS values. Similar results are seen for the RMS values for Test 2, but the peak response differences are less exaggerated. Tiedown differences for these surfaces are less pronounced for the RMS values for Test 1 and are reversed for Test 2. Upon inspection of the tiedown PSD curves for Test 2 events 1 and 3, it is evident that the higher frequency responses of the smooth asphalt are greater than those from the rough asphalt test and contribution from these sources push the net response of the tiedown up for event 1. While the amplitude of vibration from the rough input is greater, the package does not respond differentially from the trailer for the bounce mode, whereas the higher frequency bending and pitch modes cause some separation of the package from its cradle.

The length and mass of the package control the type and magnitude of vibration response. Because of the greater length of the package used in Test 2, as compared to the relatively short package used in Test 1, the spalled asphalt event did not produce accelerations equivalent to the railroad grade crossing event, as was found in Test 1. Also, because of the height of the package used in Test 1, the package longitudinal accelerations were generally one-half to two times the response from the lower profile package.

Trailer responses for the spalled asphalt event from Test 1 were approximately twice the responses from Test 2. This was caused by the package stiffening the trailer bending responses; the triple axle rear suspension also contributed to the differing responses. The additional mass and stiffer rear suspension used during Test 2 are responsible for the increased accelerations during the railroad grade crossing, as the same displacement time history is imposed on both systems.

The high center of gravity of the package in Test 1 pushes its longitudinal responses equal to or higher than the vertical response. This further illustrates the point that each package system responds in a way based on package configuration, as well as road type. Tiedown forces for a system cannot be extrapolated from response data from a given location on the trailer bed. A direct example of this is seen in the results of Test 2. The rough asphalt trailer responses were approximately half those from similar locations during the secondary asphalt event, but the tiedown force RMS levels were either equal to or greater than the secondary asphalt events responses, and the peak levels were comparable.

Conclusions

It is apparent from the test results that the amplitude of the accelerometer responses are dependent on both the type of event to which the system is being subjected and the location of the accelerometer in the package or trailer. The normalized vertical accelerations measured during the CNS 3-55 test at four locations for the shock and vibration events are given in Table 9. The data are normalized to the rail crossing acceleration at each location.

The railroad crossing produced the largest peak accelerations on the trailer. These result from translating the stepwise displacement function of the road surface into the various response modes of the trailer and package.

Table 10 normalizes the same responses as Table 9, but with respect to the trailer front vertical response for each event. Even for a distributed load such as the CNS 3-55, the front and rear of the trailer experience accelerations at least four times greater than the accelerations at the midplane of the trailer and package. This response is apparent from the tractor/trailer/package mode shapes. For the first pitch and bending modes, the midplane acts as a node while the front and rear of the trailer experience relatively large displacements (2, 3).

Finally, the tiedowns in these tests experience the small loads given in Tables 5 and 8. These forces were less than 0.05 g based on package weight. This phenomenon is due to the small relative displacements between the package and trailer. These small relative displacements indicate that the package and trailer are acting in unison to the driving force from the suspension system. This force is small when compared with the accelerations measured at other locations on the trailer, as the small percentages in column 2 of Table 10 show. This illustrates the difficulty in extrapolating data from the trailer bed, and attempting to relate this to cask acceleration.

Table 9: Event Dependence of Normalized Vertical Accelerometer Response Normalized with Respect to the Rail Crossing Response

	<u>Trailer Rear</u>	<u>Package Top</u>	<u>Trailer Middle</u>	<u>Trailer Front</u>
Smooth Asphalt	0.093	0.26	0.11	0.13
Rail Crossing	1.0	1.0	1.0	1.0
Rough Asphalt	0.24	0.53	0.31	0.16
Bridge Approach	0.41	0.49	0.40	0.52
Rough Concrete	0.17	0.26	0.21	0.18
Secondary Asphalt	0.46	0.79	0.44	0.52
Spalled Asphalt	0.33	0.43	0.28	0.41

Table 10: Spatial Dependence of Normalized Vertical Accelerometer Response Normalized with Respect to the Trailer Bed Front Response

	<u>Trailer Rear</u>	<u>Package Top</u>	<u>Trailer Middle</u>	<u>Trailer Front</u>
Smooth Asphalt	.65	.14	.11	1.0
Rail Crossing	.91	.072	.12	1.0
Rough Asphalt	1.33	.24	.24	1.0
Bridge Approach	.71	.068	.094	1.0
Rough Concrete	.83	.10	.14	1.0
Secondary Asphalt	.79	.11	.10	1.0
Spalled Asphalt	.74	.075	.083	1.0

References

1. Glass, R. E. and Gwinn, K. W., "Trupact-I Over the Road Test," SAND87-0513, Sandia National Laboratories, Albuquerque, NM, 1987.
2. Glass, R. E. and Gwinn, K. W., "Shock and Vibrations Environments: Test and Analysis," Institute of Nuclear Materials Management 27th Annual Meeting, June 1986.
3. Glass, R. E. and Gwinn, K. W., "Design Basis for Resistance to Shock and Vibration," 9th International Symposium on the Packaging and Transportation of Radioactive Materials, June 1989.
4. Gonzales, A., "Instrumentation Uses to Determine Structural Responses Under Various Test Conditions," SAND87-2645, Sandia National Laboratories, Albuquerque, NM, 1989.

Appendix A

DATA REDUCTION TECHNIQUE

The test data was reduced by the procedure described here. The original test data was recorded as an analog signal from the transducers. A 100 Hz analog filter was first applied to insure that the recorded data was band limited. This prevents aliasing errors during the digitization process. Since the amplitude of signals greater than 50 Hz are orders of magnitude less than those under 50 Hz, no significant information is lost in the filtering process.

The analog signal was then digitized. The sample rate was determined by the block size times the effective frequency resolution.

Voltage drift inherent in amplifiers and recording circuits causes the voltage to drift in the original signal, and must be removed before the calculations. The mean for each plot is calculated and subtracted out of each record before the PSD and RMS calculations are completed, but the time histories are shown as digitized from the original information. At this point, a fast fourier transform is implemented to transform the data to the frequency domain. Autospectral density plots, PSD, are calculated. Discrete fourier transforms of the shock data are calculated to produce the transform magnitude plots for these events. A complete description of the data analysis steps are contained in Vibration Data System for SNLA Area III Reference Manual, SAND84-0350.

Appendix B

DATA

Figure A1. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Smooth Asphalt

Figure A2. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Smooth Asphalt

Figure A3. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Smooth Asphalt

Figure A4. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Smooth Asphalt

Figure A5. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Smooth Asphalt

Figure A6. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Smooth Asphalt

Figure A7. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Smooth Asphalt

Figure A8. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Smooth Asphalt

Figure A9. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Smooth Asphalt

Figure A10. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Smooth Asphalt

Figure A11. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Smooth Asphalt

Figure A12. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Smooth Asphalt

Figure A13. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc #7; Smooth Asphalt

Figure A14. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Smooth Asphalt

Figure A15. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Smooth Asphalt

Figure A16. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Smooth Asphalt

Figure A17. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Smooth Asphalt

Figure A18. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Smooth Asphalt

Figure A19 Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1: Rail Road Xing

Figure A20 Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2: Rail Road Xing

Figure A21 Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3: Rail Road Xing

Figure A22 Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4: Rail Road Xing

Figure A23. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5, Rail Road Xing

Figure A24. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6, Rail Road Xing

Figure A25. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7, Rail Road Xing

Figure A26. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13, Rail Road Xing

Figure A27. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rail Road Xing

Figure A28. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rail Road Xing

Figure A29. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rail Road Xing

Figure A30. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rail Road Xing

Figure A31. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rail Road Xing

Figure A32. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Rail Road Xing

Figure A33. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Rail Road Xing

Figure A34. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Rail Road Xing

Figure A35. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Rail Road Xing

Figure A36. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rail Road Xing

Figure A37. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough Asphalt

Figure A38. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough Asphalt

Figure A39. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Asphalt

Figure A40. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Asphalt

Figure A41. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough Asphalt

Figure A42. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough Asphalt

Figure A43. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough Asphalt

Figure A44. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough Asphalt

Figure A45. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Rough Asphalt

Figure A46. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Rough Asphalt

Figure A47. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Rough Asphalt

Figure A48. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Rough Asphalt

Figure A49. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Rough Asphalt

Figure A50. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Rough Asphalt

Figure A51. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Rough Asphalt

Figure A52. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Rough Asphalt

Figure A53. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough Asphalt

Figure A54. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough Asphalt

Figure A55. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1, Bridge Approach

Figure A57. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3, Bridge Approach

Figure A56. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2, Bridge Approach

Figure A58. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4, Bridge Approach

Figure A59. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5, Bridge Approach

Figure A60. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6, Bridge Approach

Figure A61. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7, Bridge Approach

Figure A62. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13, Bridge Approach

Figure A63 Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Bridge Approach

Figure A64. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough Concrete

Figure A65. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough Concrete

Figure A66. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Concrete

Figure A67. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Concrete

Figure A68. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough Concrete

Figure A69. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough Concrete

Figure A70. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough Concrete

Figure A71. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough Concrete

Figure A72. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Rough Concrete

Figure A73. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Rough Concrete

Figure A74. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc #6; Rough Concrete

Figure A75. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Rough Concrete

Figure A76. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc #7; Rough Concrete

Figure A77. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Rough Concrete

Figure A78. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Rough Concrete

Figure A79. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Rough Concrete

Figure A80. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough Concrete

Figure A81. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough Concrete

Figure A82. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Hard Right Turn

Figure A83. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Hard Right Turn

Figure A84. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Hard Right Turn

Figure A85. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Hard Stop #8

Figure A86. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Hard Stop #8

Figure A87. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Hard Stop #8

Figure A88. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Hard Stop #8

Figure A89. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough
Secondary

Figure A90. Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1; Rough
Secondary

Figure A91. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Secondary

Figure A92. Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2; Rough Secondary

Figure A93. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough
Secondary

Figure A94. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3; Rough
Secondary

Figure A95. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough
Secondary

Figure A96. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4; Rough
Secondary

Figure A97. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5, Rough
Secondary

Figure A98. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5, Rough
Secondary

Figure A99. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6, Rough
Secondary

Figure A100. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6, Rough
Secondary

Figure A101 Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7, Rough
Secondary

Figure A102 Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7, Rough
Secondary

Figure A103 Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13, Rough
Secondary

Figure A104 Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13, Rough
Secondary

Figure A105. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough
Secondary

Figure A106. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Rough
Secondary

Figure A107 Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1, Spalled
Asphalt

Figure A108 Road Test-CNS 14-170-1 Cask (Test 1)
Top Transverse Loc. #1, Spalled
Asphalt

Figure A109 Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2, Spalled
Asphalt

Figure A110 Road Test-CNS 14-170-1 Cask (Test 1)
Top Vertical Loc. #2, Spalled
Asphalt

Figure A111 Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3, Spalled
Asphalt

Figure A112. Road Test-CNS 14-170-1 Cask (Test 1)
Top Longitudinal Loc. #3, Spalled
Asphalt

Figure A113. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4, Spalled
Asphalt

Figure A114. Road Test-CNS 14-170-1 Cask (Test 1)
Mid Vertical Loc. #4, Spalled
Asphalt

Figure A115. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5; Spalled
Asphalt

Figure A116. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Vertical Loc. #5, Spalled
Asphalt

Figure A117. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Spalled
Asphalt

Figure A118. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Longitudinal Loc. #6; Spalled
Asphalt

Figure A119 Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Spalled
Asphalt

Figure A120. Road Test-CNS 14-170-1 Cask (Test 1)
Front Vertical Loc. #7; Spalled
Asphalt

Figure A121. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Spalled
Asphalt

Figure A122. Road Test-CNS 14-170-1 Cask (Test 1)
Front Load Cell Loc. #13; Spalled
Asphalt

Figure A123. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Spalled
Asphalt

Figure A124. Road Test-CNS 14-170-1 Cask (Test 1)
Rear Load Cell Loc. #14; Spalled
Asphalt

Figure B1. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Smooth Asphalt

Figure B2. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Smooth Asphalt

Figure B3. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Smooth Asphalt

Figure B4. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Smooth Asphalt

Figure B5. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Smooth Asphalt

Figure B6. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Smooth Asphalt

Figure B7. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Smooth Asphalt

Figure B8. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Smooth Asphalt

Figure B9. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Smooth Asphalt

Figure B10. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Smooth Asphalt

Figure B11. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Smooth Asphalt

Figure B12. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Smooth Asphalt

Figure B13. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Smooth Asphalt

Figure B14. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Smooth Asphalt

Figure B15. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Smooth Asphalt

Figure B16. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Smooth Asphalt

Figure B17. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Smooth Asphalt

Figure B18. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Smooth Asphalt

Figure B19 Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1, R R Crossing

Figure B20 Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2, R R Crossing

Figure B21 Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3, R R Crossing

Figure B22 Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4, R R Crossing

Figure B23. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5: R R Crossing

Figure B24. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6: R R Crossing

Figure B25. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7: R R Crossing

Figure B26. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1: R R Crossing

Figure B27. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; R R Crossing

Figure B28. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; R R Crossing

Figure B29. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; R R Crossing

Figure B30. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; R R Crossing

Figure B31. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; R R Crossing

Figure B32. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; R R Crossing

Figure B33. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Rough Asphalt

Figure B34. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Rough Asphalt

Figure B35. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Asphalt

Figure B36. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Asphalt

Figure B37. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Rough Asphalt

Figure B38. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Rough Asphalt

Figure B39. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Asphalt

Figure B40. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Asphalt

Figure B41. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Asphalt

Figure B42. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Asphalt

Figure B43. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Asphalt

Figure B44. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Asphalt

Figure B45. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Asphalt

Figure B46. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Asphalt

Figure B47. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Asphalt

Figure B48. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Asphalt

Figure B49. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Rough Asphalt

Figure B50. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Rough Asphalt

Figure B51. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1: Bridge Approach

Figure B52. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2: Bridge Approach

Figure B53. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3: Bridge Approach

Figure B54. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4: Bridge Approach

Figure B55. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Bridge Approach

Figure B57. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Bridge Approach

Figure B56. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Bridge Approach

Figure B58. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Bridge Approach

Figure B59. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Bridge Approach

Figure B60. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Concrete

Figure B61. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Concrete

Figure B62. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Concrete

Figure B63. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Concrete

Figure B64. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Concrete

Figure B65. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Concrete

Figure B66. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Concrete

Figure B67. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Concrete

Figure B68. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Concrete

Figure B69. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Concrete

Figure B70. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Concrete

Figure B71. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Concrete

Figure B72. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14, Rough Concrete

Figure B73. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14, Rough Concrete

Figure B74. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Hard R Turn

Figure B75. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Hard R Turn

Figure B76. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Hard R Turn

Figure B77. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Hard Stop

Figure B78. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Hard Stop

Figure B79. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Hard Stop

Figure B80. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Hard Stop

Figure B81. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Rough Secondary

Figure B82. Road Test-CNS 3-55 Cask (Test 2)
Top Transverse Loc. #1; Rough Secondary

Figure B83. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Secondary

Figure B84. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Rough Secondary

Figure B85. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Rough Secondary

Figure B86. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Rough Secondary

Figure B87. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Secondary

Figure B88. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Rough Secondary

Figure B89. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Secondary

Figure B90. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Rough Secondary

Figure B91. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Secondary

Figure B92. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Rough Secondary

Figure B93. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Secondary

Figure B94. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Rough Secondary

Figure B95. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Secondary

Figure B96. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Rough Secondary

Figure B97. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Rough Secondary

Figure B98. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Rough Secondary

Figure B99. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Spalled Asphalt

Figure B100. Road Test-CNS 3-55 Cask (Test 2)
Top Vertical Loc. #2; Spalled Asphalt

Figure B101. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Spalled Asphalt

Figure B102. Road Test-CNS 3-55 Cask (Test 2)
Top Longitudinal Loc. #3; Spalled Asphalt

Figure B103. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Spalled Asphalt

Figure B104. Road Test-CNS 3-55 Cask (Test 2)
Mid Vertical Loc. #4; Spalled Asphalt

Figure B105. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Spalled Asphalt

Figure B106. Road Test-CNS 3-55 Cask (Test 2)
Rear Vertical Loc. #5; Spalled Asphalt

Figure B107. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Spalled Asphalt

Figure B108. Road Test-CNS 3-55 Cask (Test 2)
Rear Longitudinal Loc. #6; Spalled Asphalt

Figure B109. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Spalled Asphalt

Figure B110. Road Test-CNS 3-55 Cask (Test 2)
Front Vertical Loc. #7; Spalled Asphalt

Figure B111. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Spalled Asphalt

Figure B112. Road Test-CNS 3-55 Cask (Test 2)
Front Strain Gage Loc. #13; Spalled Asphalt

Figure B113. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Spalled Asphalt

Figure B114. Road Test-CNS 3-55 Cask (Test 2)
Rear Strain Gage Loc. #14; Spalled Asphalt

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