USED FUEL DISPOSITION CAMPAIGN

Transportation Shock and Vibration Literature Review

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
Steven J. Maheras (PNNL)
Erik A. Lahti (PNNL)
Steven B. Ross (PNNL)

June 6, 2013
FCRD-UFD-2013-000169
PNNL-22514

EXECUTIVE SUMMARY

This report fulfills the M4 milestone M4FT-13OR08220112, “Report Documenting Experimental Activities.”

The purpose of this report is to document the results of a literature review conducted of studies related to the vibration and shock associated with the normal conditions of transport for rail shipments of used nuclear fuel from commercial light-water reactors. As discussed in Adkins (2013), the objective of this report is to determine if adequate data exist to realistically evaluate the impacts of the shock and vibration associated with the normal conditions of transport on commercial light-water reactor used nuclear fuel shipped in current-generation high-capacity rail transportation casks.

The literature review concentrated on papers and reports related to the transport of used nuclear fuel, radioactive waste, or other radioactive material, in part because of the weight associated with commercial light-water reactor used nuclear fuel rail transportation casks, which is about 300,000 lb., and because the weight of the transportation cask on a railcar directly affects the magnitude of vibrations and shock imparted to the used nuclear fuel contained in the transportation cask. In addition, the railcars that will be used by the U.S. Department of Energy to ship transportation casks containing used nuclear fuel from commercial light-water reactors are required to meet American Association of Railroads (AAR) Standard S-2043 (AAR 2008). Therefore, searches were also conducted for studies where the railcar met AAR Standard S-2043. Because the focus of the modeling described in Adkins (2013) is at the fuel assembly and fuel rod levels, studies where accelerations were measured on fuel assemblies or fuel rods were also especially relevant.

During the literature review conducted of studies related to the vibration and shock associated with the normal conditions of transport for rail shipments of used nuclear fuel, over 200 documents were collected from a wide variety of sources, including studies performed by Sandia National Laboratories, the Hanford Engineering and Development Laboratory, Ontario Hydro, Battelle Columbus Laboratories, and the Savannah River Site, as well as studies performed by other investigators. The results of the literature review follow.

- There were few recent studies of the shock and vibration associated with the normal conditions of transport. Most of the studies that were related to the shipment of used nuclear fuel, radioactive waste, or radioactive material were published in the 1960s, 1970s, and 1980s. Relatively few studies were published after the mid-1990s.
- No studies were found that evaluated a rail transportation cask or other cargo that was similar in weight to the weight of a commercial light-water reactor used nuclear fuel rail transportation cask, about 300,000 lb. The largest transportation casks evaluated were in a study by Prulhiere and Israel (1980), where the TN 12 transportation cask, weighing 220,000 lb., was evaluated; and in a study by Pujet and Malesys (1989), where the NTL 11 transportation cask, weighing 176,000 lb., was evaluated.
- No studies using railcars that met AAR Standard S-2043 were found.

- One study (Prulhiere and Israel 1980) was found where a fuel assembly was instrumented inside a used nuclear fuel transportation cask. However, Prulhiere and Israel (1980) provided data in summary form and more detailed data from this study were not available.

Based on the results of the literature review, the data currently used to characterize the shock and vibration associated with the normal conditions of transport by rail appear to overestimate the shock and vibration that would be encountered during shipment of a transportation cask on an AAR Standard S-2043-compliant railcar. In addition, the cask weights used to derive the current data are not representative of current generation cask weights. For these reasons, it is recommended that additional shock and vibration data be obtained to realistically model the effects of the normal conditions of transport on rail shipments of commercial light-water reactor used nuclear fuel at the fuel assembly and fuel rod level. Options for implementing this recommendation are discussed in Adkins (2013).

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FIGURES

TABLES

ACRONYMS

AAR	American Association of Railroads
CANDU	Canadian deuterium-uranium reactor
CARDS	Cask-Rail Car Dynamic Simulator
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
MT	metric ton (Tonne)
NRC	U.S. Nuclear Regulatory Commission
SAR	safety analysis report

USED FUEL DISPOSITION CAMPAIGN

Transportation Shock and Vibration Literature Review

1. INTRODUCTION

The purpose of this report is to document the results of a literature review conducted of studies related to the vibration and shock associated with the normal conditions of transport for rail shipments of used nuclear fuel from commercial light-water reactors. As discussed in Adkins (2013), the objective of this report is to determine if adequate data exist to realistically evaluate the impacts of the shock and vibration associated with the normal conditions of transport on commercial light-water reactor used nuclear fuel shipped in current-generation high-capacity rail transportation casks. In addition, the focus of the modeling discussed in Adkins (2013) will be at the fuel assembly and fuel rod levels.

For rail transportation casks that are currently licensed to transport used nuclear fuel from commercial light-water reactors, weights range from 187,200 lb. for the HI-STAR HB (NRC 2010) to 312,000 lb. for the MAGNATRAN (Leduc 2012). However, the HI-STAR HB is used for the storage and transportation of used nuclear fuel from Humboldt Bay, which used shorter fuel than a typical light-water reactor. A representative weight for a high-capacity rail transportation cask that would be used to transport used nuclear fuel from commercial light-water reactors is about 300,000 lb.

As a first step in the literature review, U.S. Nuclear Regulatory Commission (NRC) guidance on evaluating the vibration and shock normally incident to transport was evaluated. In Section 2.5.5.5 of NUREG-1617, *Standard Review Plan for Transportation Packages for Spent Nuclear Fuel* (NRC 2000), two references for vibration evaluation of transport packages are cited:

- NUREG/CR-2146, *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Final Summary Report* (Fields 1983a)
- NUREG/CR-0128, *Shock and Vibration Environments for a Large Shipping Container During Truck Transport (Part II)* (Magnuson 1978).

In addition, transportation cask safety analysis reports (SARs) were reviewed to determine the industry approach for evaluating vibration and shock because of the normal conditions of transport during transportation cask licensing. The transportation cask SARs reviewed were those that are licensed to transport used nuclear fuel from shutdown sites, such as the MP187, NAC-STC, NAC-UMS UTC, TS125, and the HI STAR 100 and HI-STAR HB. In these SARs, the applicants typically assumed that a 2 g vertical acceleration was bounding based on the guidance provided in ANSI N14.23 (ANSI 1980). In addition, for the MP197 transportation cask, which is not licensed for transporting used nuclear fuel from the shutdown sites, the applicant used the shock and vibration data from NUREG-766510 (Magnuson and Wilson 1977).

The literature review consisted of searches conducted of various sources and databases and extracting papers and reports that were relevant to the shock and vibration associated with the normal conditions of transport. The following sources and databases were used:

- the Pacific Northwest National Laboratory Technical Library
- the Sandia National Laboratories Technical Library
- the U.S. Department of Energy (DOE) Office of Science and Technical Information Science Research Connection
- Defense Technical Information Center, which included the Shock and Vibration Bulletin
- Defense Threat Reduction Information Analysis Center Scientific and Technical Information Archival and Retrieval System
- International Nuclear Information System, which is maintained by the International Atomic Energy Agency
- Yucca Mountain Records Information System, which is being maintained by the DOE Office of Legacy Management
- Transport Research International Documentation, which is an integrated database that combines the records from the Transportation Research Board, Transportation Research Information Services Database and the Organisation for Economic Co-Operation and Development Joint Transport Research Centre’s International Transport Research Documentation Database
- the journals *Packaging, Transport, Storage and Security of Radioactive Material,* and the *International Journal of Radioactive Materials Transport*
- *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, supplied by Oak Ridge National Laboratory
- Compendex, Inspec, and the National Technical Information Service
- the DOE/U.S. Department of Defense (DOD) Environmental Data Bank, which is maintained by Sandia National Laboratories
- other nuclear related journals such as *Nuclear Technology*
- packaging-related journals such as *Packaging Technology and Science*.

Searches of these sources and databases concentrated on papers and reports related to the transport of used nuclear fuel, radioactive waste, or other radioactive material, in part because of the weight associated with commercial light-water reactor used nuclear fuel rail transportation casks, which is about 300,000 lb., and because the weight of the transportation cask on a railcar directly affects the magnitude of vibrations and shock imparted to the used nuclear fuel cargo contained in the transportation cask. In addition, the railcars that will be used by DOE to ship transportation casks containing used nuclear fuel from commercial light-water reactors are required to meet American Association of Railroads (AAR) Standard S-2043 (AAR 2008). Therefore, searches were also conducted for studies where the railcar met AAR Standard S-2043. In the context of acceleration, this standard requires that peak vertical car body acceleration of 1.0 g, a peak lateral car body acceleration of 0.75 g, or a peak longitudinal car body acceleration of 1.5 g trigger a train-stop alarm. Because the focus of the modeling described in Adkins (2013) is at the fuel assembly and fuel rod levels, studies where accelerations were measured on fuel assemblies or fuel rods would also be especially relevant.

2. RELEVANT PREVIOUS STUDIES

There have been numerous studies conducted related to transportation shock and vibration. This section summarizes relevant previous studies related to the shock and vibration associated with the normal conditions of transport. It includes studies performed by Sandia National Laboratories, the Hanford Engineering and Development Laboratory, Ontario Hydro, Battelle Columbus Laboratories, and the Savannah River Site, as well as studies performed by other investigators. Because the purpose of the literature review is to evaluate studies related to the rail transport of commercial light-water reactor used nuclear fuel, in many cases, studies not directly related to the rail transport of commercial light-water reactor used nuclear fuel are not discussed.

2.1 Sandia National Laboratories

From the 1960s through the 1990s, Sandia National Laboratories conducted numerous studies related to the shock and vibration associated with the normal conditions of transport. One of the earliest studies related to railroad transportation shock and vibration testing identified in the literature review was by Adams (1961) at Sandia National Laboratories.

In this report, these studies are grouped based on the time period during which they were conducted: 1) Foley and Gens, who conducted studies in the 1960s and early 1970s, 2) Magnuson, who conducted studies in the mid-1970s and early 1980s, and 3) Glass and Gwinn, who conducted studies in the mid-1980s and early 1990s. The majority of these studies were summarized by Sanders et al. (1992). Also discussed in this section are other studies conducted by Sandia National Laboratories and the Sandia Environmental Data Bank, which has existed since 1959.

2.1.1 Foley and Gens

Foley and Gens conducted transportation shock and vibration studies in the 1960s and early 1970s. In one study, shock and vibration data were obtained for an unloaded truck that traveled from Fort Eustis, Virginia to Wilmington, Delaware. The truck was then loaded with a 15-ton radioactive materials transportation cask and shock and vibration data were obtained for travel from Wilmington, Delaware to Albuquerque, New Mexico. This study is summarized in the following sources:

- “Preliminary Analysis of Data Obtained in the Joint Army/AEC/Sandia Test of Truck Transport Environment” (Foley 1966a)
- *The Environment Experienced by Cargo on a Flatbed Tractor-Trailer Combination* (Foley 1966b)
- *Transportability Study Covering Highway Movement of Atomic Energy Commission 15-ton Nuclear Cask from Wilmington, Delaware to Albuquerque, New Mexico* (Bryan 1965)
- *Force-Controlled Vibration Testing* (Otts 1965a)

- *Impedance Measurement of a Flatbed Truck* (Otts 1965b)
- *Joint Army/AEC/Sandia Test of Truck Transport Environment, December 7-17, 1964 (Test No. T-10767)* (Mortley 1965)

A second study evaluated the shock and vibration transportation environment associated with shipping a Beech liquid helium Dewar flask on a Ford F600 flatbed truck (Foley 1968, Foley 1969).

In a third study, Foley and Gens evaluated the shock and vibration transportation environment for shipping a 15-ton used nuclear fuel cask that traveled by truck from Oak Ridge, Tennessee to Paducah, Kentucky, and by rail from Paducah, Kentucky to Oak Ridge, Tennessee. This study is summarized in the following reports:

- "The Rail Transport Environment" (Gens 1970)
- "Shock and Vibration Measurements During Normal Rail and Truck Transport" (Foley and Gens 1971a)
- *Environment Experienced by Cargo During Normal Rail and Truck Transport–Complete Data* (Foley and Gens 1971b)

The listed studies and others resulted in two guidance documents for package designers:

- *I. Techniques for Measuring Transportation and Handling Environments; II. Available Literature and How It May Help Package Designers* (Foley 1970)
- *Transportation Shock and Vibration Descriptions for Package Designers* (Foley 1972)

2.1.2 Magnuson

Magnuson conducted transportation shock and vibration studies in the mid-1970s and early 1980s. For example, Magnuson and Wilson (1977) reviewed previous tests on truck and rail used nuclear fuel transportation cask shipments and summarized vibration and shock results for seven different truck and tractor-trailer configurations. Included were trucks equipped with conventional spring and air-cushioned suspension systems. Cargo weights ranged from no-load to 15 tons. Table 2-1 presents the truck vibration results and Figure 2-1 shows the truck shock envelopes from Magnuson and Wilson (1977).

Table 2-2 lists the rail vibration results and Figure 2-2 shows the rail shock response envelopes from Magnuson and Wilson (1977) for a 15-ton used nuclear fuel rail transportation cask. Magnuson and Wilson (1977) also present rail coupling shock data. These data are for an ATMX railcar with a 5-ton cargo.[1] Tables 2-3 and 2-4 summarize the results from Magnuson and Wilson (1977) for truck and rail shipments. Magnuson and Wilson (1977) and Wilson (1978) also present analytical results for ATMX railcars.

Table 2-1. Truck Vibration Data

	Measurements on Cargo Floor (g) 99% Level of Zero to Peak Amplitude		
Frequency Band (Hz)	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.10	0.10	2.0
5-10	0.08	0.06	1.04
10-20	0.84	0.15	1.68
20-40	0.51	0.24	1.20
40-80	0.36	0.42	0.50
80-120	0.24	0.27	0.87
120-180	1.23	0.21	0.63
180-240	0.87	0.12	0.87
240-350	0.24	0.15	0.63
350-500	0.24	0.15	0.42
500-700	0.87	0.15	0.87
700-1000	1.50	0.87	1.17
1000-1400	0.87	1.17	1.17
1400-1900	0.39	0.24	0.87
Source: Magnuson and Wilson (1977)			

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[1] Rector (1962) evaluated rail coupling data for the ATMX Series 600 railcar, but it has not been possible to confirm that the data from Rector (1962) was the source of the data in Magnuson and Wilson (1977).

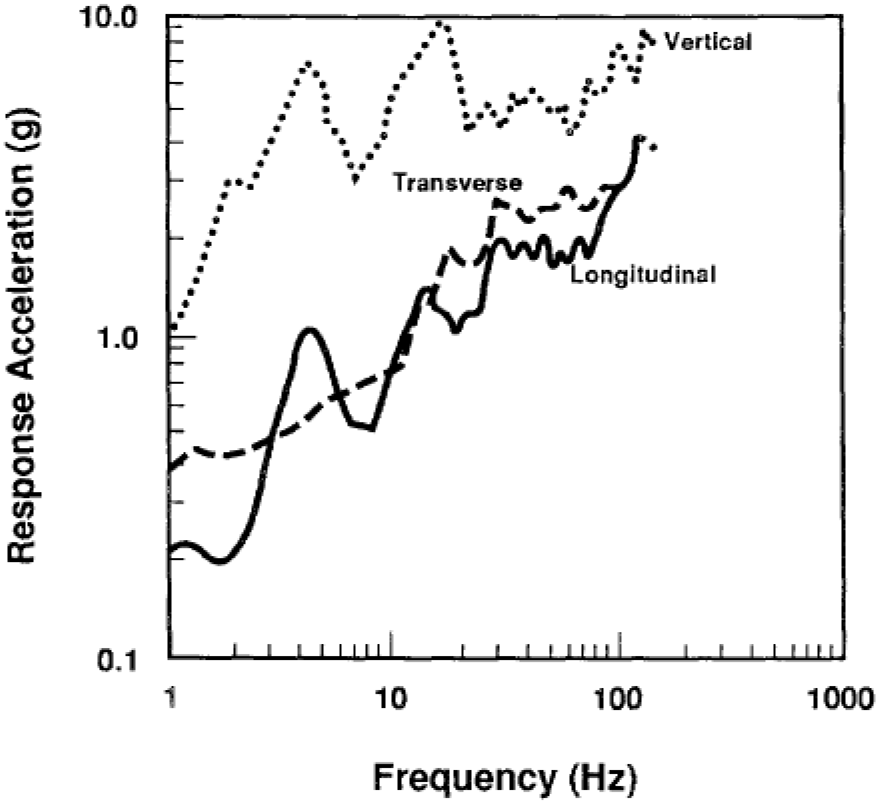

Figure 2-1. Truck Superimposed Shock Response Envelopes with 3% Damping (Magnuson and Wilson 1977)

Table 2-2. Train Vibration Data

	Measurements on Cargo Floor (g) 99% Level of Zero to Peak Amplitude		
Frequency Band (Hz)	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.14	0.14	0.37
5-10	0.072	0.072	0.14
10-20	0.072	0.072	0.10
20-30	0.10	0.10	0.27
30-45	0.19	0.14	0.37
45-60	0.10	0.10	0.27
60-87	0.10	0.19	0.19
87-125	0.10	0.19	0.19
125-175	0.10	0.10	0.19
175-250	0.10	0.14	0.14
250-350	0.10	0.10	0.14
Source: Magnuson and Wilson (1977)			

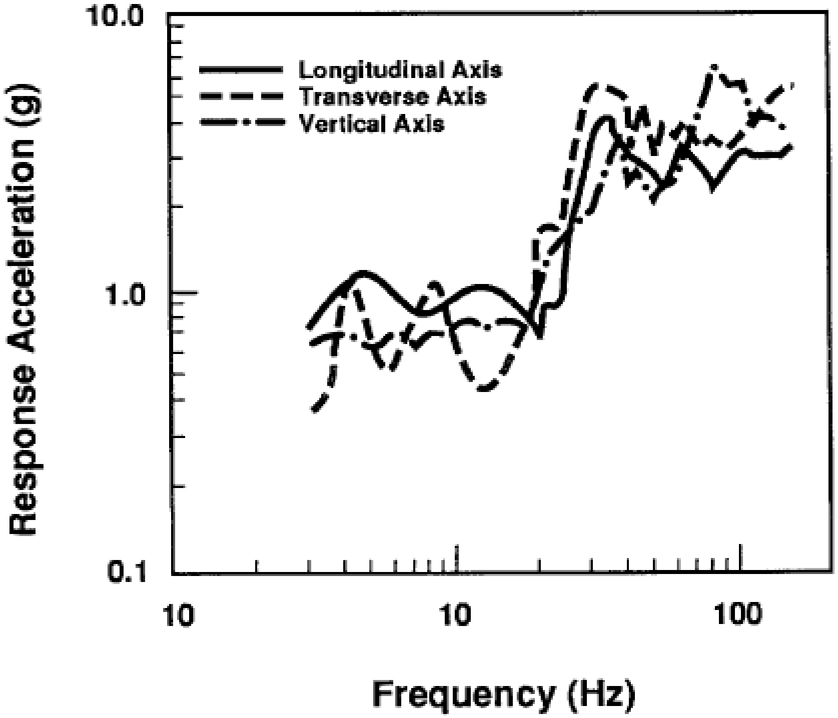

Figure 2-2. Rail Superimposed Shock Response Envelopes with 3% Damping (Magnuson and Wilson 1977)

Table 2-3. Summary of Vibration Data

Carrier	Axis	0 to Peak Maximum Acceleration (g)	Frequency Range (Hz)
Truck	Longitudinal	1.50	0-1900
	Transverse	1.17	0-1900
	Vertical	2.00	0-1900
Rail	Longitudinal	0.19	0-350
	Transverse	0.19	0-350
	Vertical	0.37	0-350
Source: Magnuson and Wilson (1977)			

Table 2-4. Summary of Shock Data

Carrier	Axis	Peak Acceleration (g)	Pulse Duration (ms)
Truck (shocks superimposed on vibration)	Longitudinal	2.8	20
	Transverse	2.3	19
	Vertical	7.0	77
Rail (shocks superimposed on vibration)	All	4.7	14
Rail coupling[a] (11.05 mph)	Longitudinal	39.0	18
	Vertical	26.0	9
Source: Magnuson and Wilson (1977) a. Based on ATMX railcar with 5-ton cargo.			

Magnuson (1977) presents shock and vibration data for shipping a 22-ton used nuclear fuel truck cask from Mercury, Nevada to Albuquerque, New Mexico. The cask was supported on each end by structures fastened to structural members of the trailer. Accelerometers were mounted in the longitudinal, transverse, and vertical directions at the structure supporting the cask. The vibration results from Magnuson (1977) are listed in Table 2-5 and the shock results are presented in Figures 2-3 through 2-5. Table 2-6 summarizes the results.

Table 2-5. Truck Vibration Data

	Measurements on Cargo Floor (g) 99% Level of Zero to Peak Amplitude		
Frequency Band (Hz)	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.14	0.14	0.27
5-10	0.19	0.19	0.19
10-20	0.27	0.27	0.27
20-40	0.10	0.27	0.27
40-80	0.14	0.14	0.52
80-120	0.07	0.10	0.52
120-180	0.07	0.10	0.52
180-240	0.05	0.10	0.52
240-350	0.05	0.10	0.52
350-500	0.05	0.05	0.14
500-700	0.04	0.04	0.07
700-1000	0.03	0.07	0.07
1000-1400	0.01	0.04	0.05
1400-1900	0.01	0.05	0.05
Source: Magnuson (1977)			

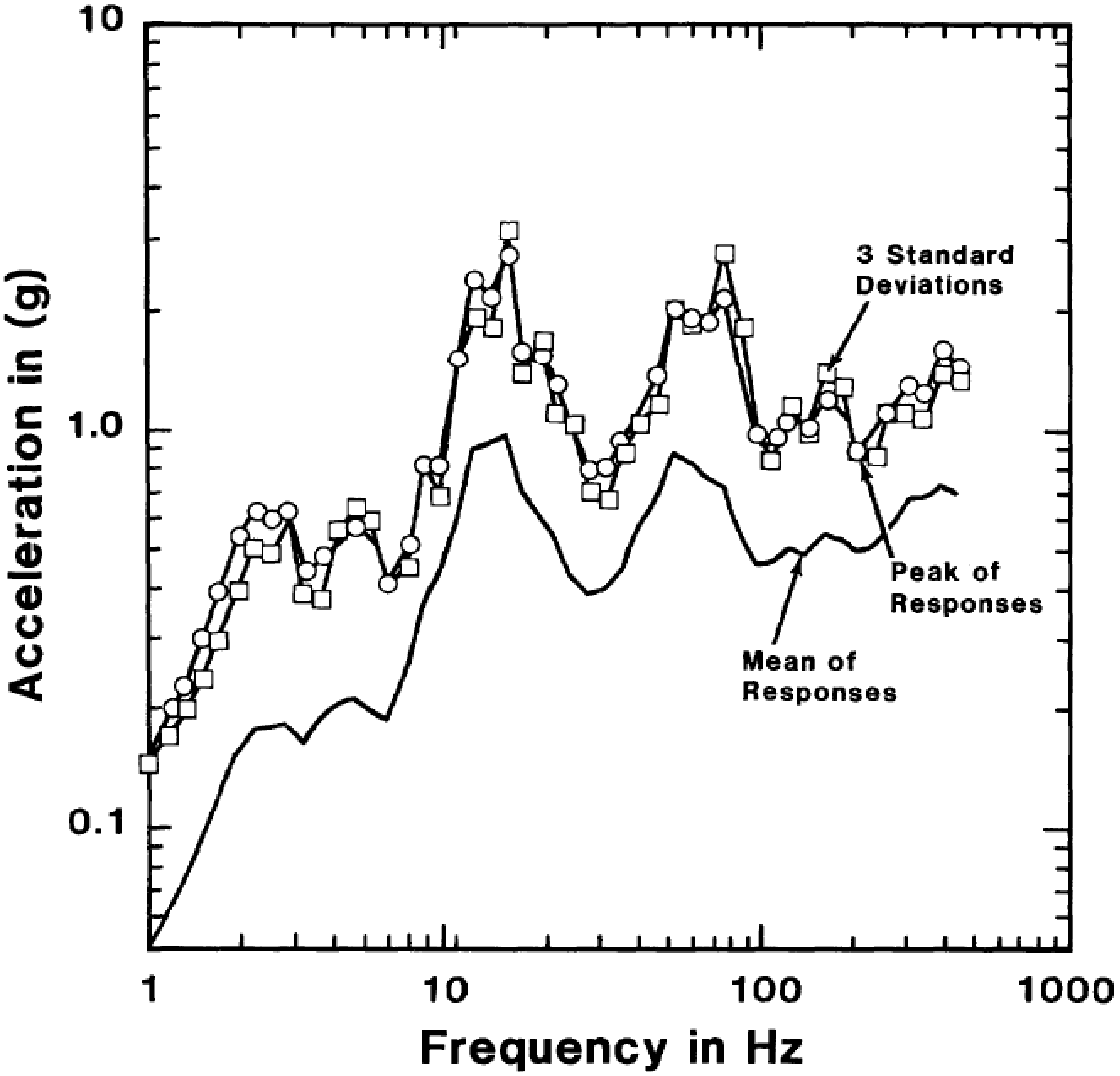

Figure 2-3. Superimposed Shock Response Spectra with 3% Damping for the Longitudinal Axis (Magnuson 1977)

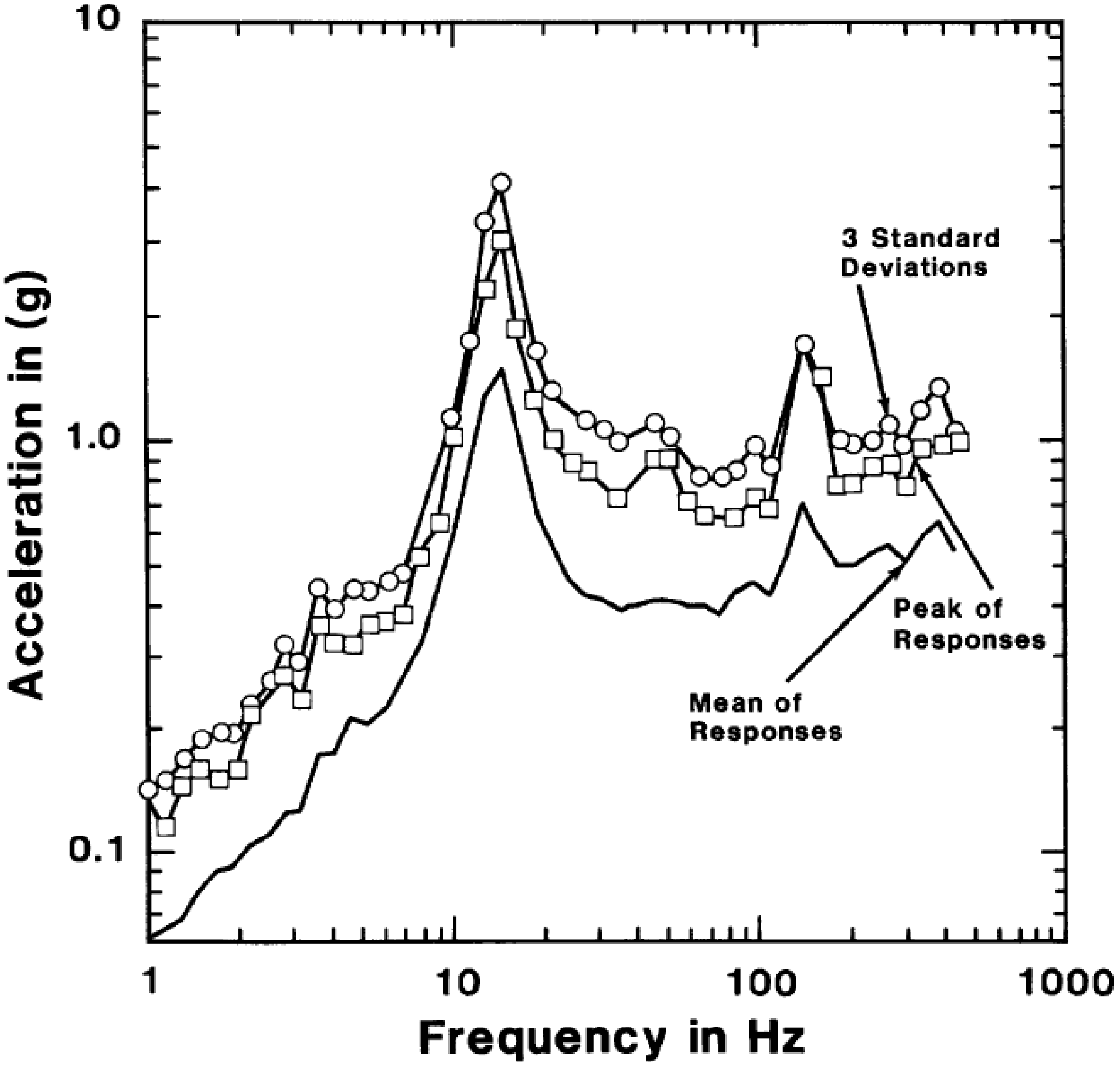

Figure 2-4. Superimposed Shock Response Spectra with 3% Damping for the Transverse Axis (Magnuson 1977)

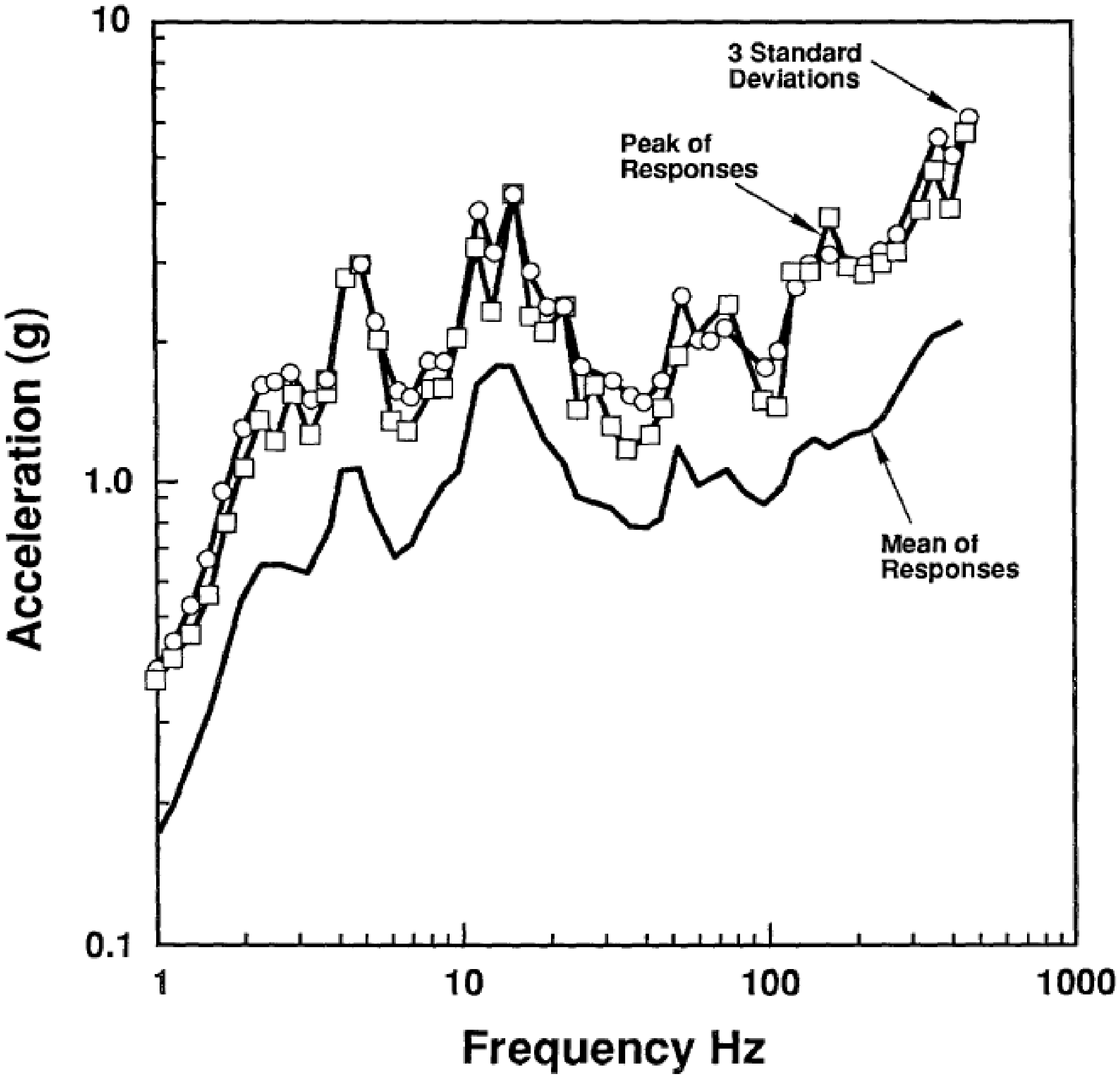

Figure 2-5. Superimposed Shock Response Spectra with 3% Damping for the Vertical Axis (Magnuson 1977)

Table 2-6. Summary of Truck Vibration and Shock Data

Vibration		
Axis	Zero to Peak Acceleration (g)	Frequency Range (Hz)
Longitudinal	0.27	0-1900
Transverse	0.27	0-1900
Vertical	0.52	0-1900
Shock		
Axis	Peak Acceleration (g)	Pulse Duration (Hz)
From Response Spectra of 3-Standard Deviations		
Longitudinal	2.5	32
Transverse	2.2	50
Vertical	2.6	67
From Response Spectra of Absolute Peak Responses		
Longitudinal	1.9	32
Transverse	1.7	50
Vertical	2.6	67
From Response Spectra of Mean Responses		
Longitudinal	0.7	32
Transverse	0.8	50
Vertical	1.0	67
Source: Magnuson (1977)		

Magnuson (1978) presents shock and vibration data for shipping a 28-ton used nuclear fuel truck cask from Mercury, Nevada to Albuquerque, New Mexico. Accelerometers were mounted the longitudinal, transverse, and vertical directions near the end of the cask on the cask tie-down structure. Magnuson (1978) interpreted the resulting accelerations as being measured at the interface between the cargo and the cargo floor. The vibration results from Magnuson (1978) are listed in Table 2-7 and the shock results are presented in Figures 2-6 through 2-8. Table 2-8 summarizes the results.

Table 2-7. Truck Vibration Data

	Input to Cargo (g) 99% Level of Zero to Peak Amplitude		
Frequency Band (Hz)	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.27	0.10	0.52
5-10	0.14	0.07	0.27
10-20	0.19	0.19	0.37
20-40	0.10	0.07	0.19
40-80	0.10	0.10	0.37
80-120	0.07	0.10	0.37
120-180	0.07	0.10	0.52
180-240	0.05	0.10	0.52
240-350	0.07	0.14	0.52
350-500	0.05	0.07	0.37
500-700	0.05	0.02	0.10
700-1000	0.05	0.02	0.10

Table 2-7. (contd)

Frequency Band (Hz)	Input to Cargo (g) 99% Level of Zero to Peak Amplitude		
	Longitudinal Axis	Transverse Axis	Vertical Axis
1000-1400	0.14	0.05	0.10
1400-1900	0.03	0.02	0.10
Source: Magnuson (1978)			

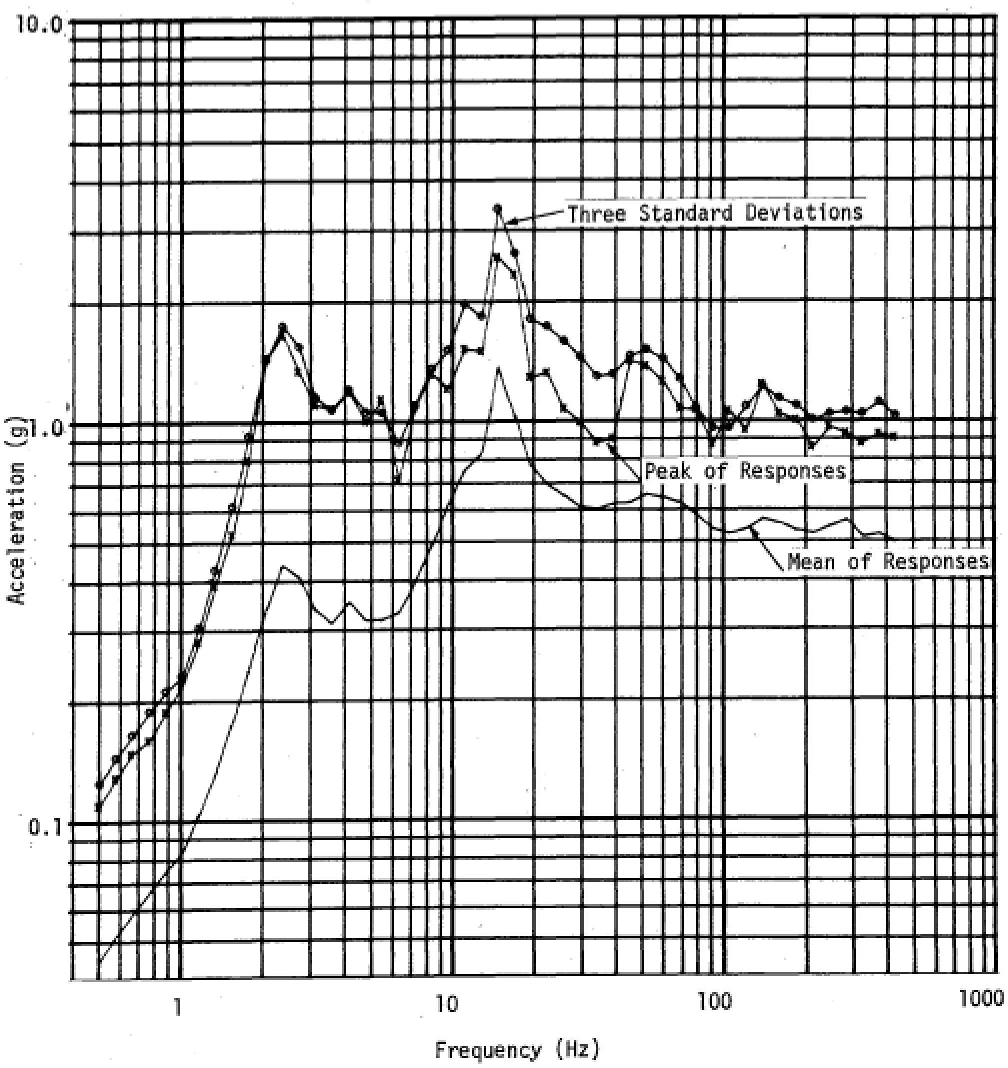

Figure 2-6. Superimposed Shock Response Spectra with 3% Damping for the Longitudinal Axis (Magnuson 1978)

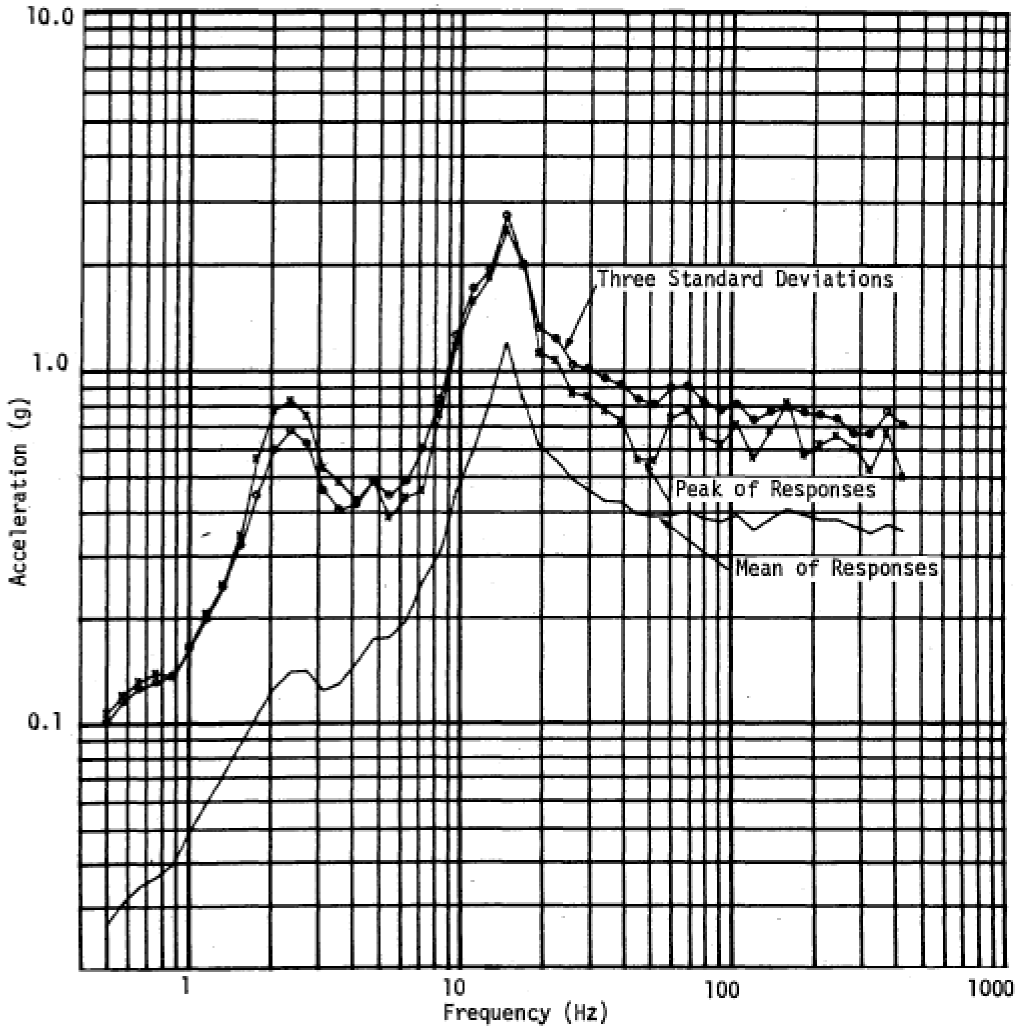

Figure 2-7. Superimposed Shock Response Spectra with 3% Damping for the Transverse Axis (Magnuson 1978)

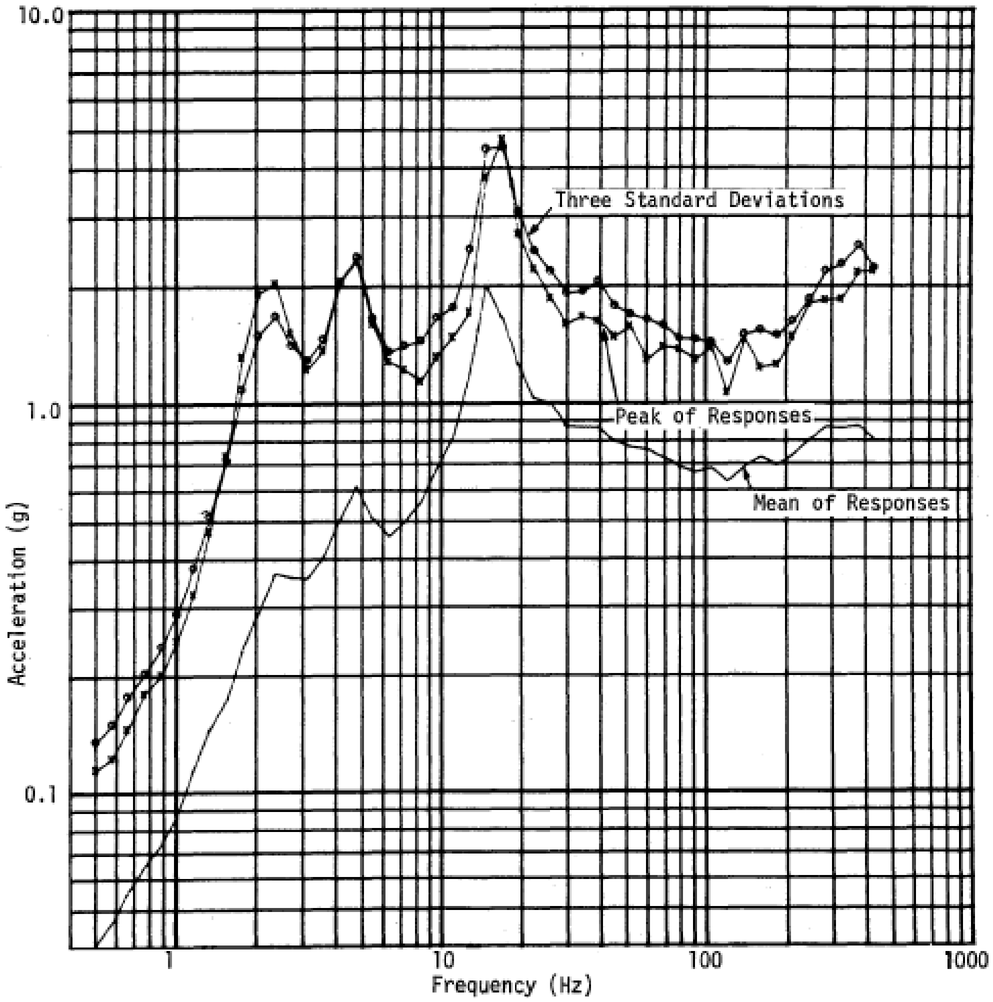

Figure 2-8. Superimposed Shock Response Spectra with 3% Damping for the Vertical Axis (Magnuson 1978)

Table 2-8. Summary of Truck Vibration and Shock Data

Vibration		
Axis	Zero to Peak Acceleration (g)	Frequency Range (Hz)
Longitudinal	0.27	0-1900
Transverse	0.19	0-1900
Vertical	0.52	0-1900
Shock		
Axis	Peak Acceleration (g)	Pulse Duration (Hz)
From Response Spectra of 3-Standard Deviations		
Longitudinal	2.2	83
Transverse	1.6	40
Vertical	2.6	67

Table 2-8. (contd)

Shock		
Axis	Peak Acceleration (g)	Pulse Duration (Hz)
From Response Spectra of Absolute Peak Responses		
Longitudinal	1.8	91
Transverse	1.3	59
Vertical	2.9	59
From Response Spectra of Mean Responses		
Longitudinal	0.8	50
Transverse	0.7	37
Vertical	1.3	37
Source: Magnuson (1978)		

Magnuson (1980) developed additional shock data from rail coupling tests conducted at the Savannah River Site for 40-ton and 70-ton transportation casks (Petry 1980). The results of the tests were used to determine the maximum peak acceleration and its pulse duration for the longitudinal, transverse, and vertical axes of the two casks, listed in Table 2-9.

Table 2-9. Rail Coupling Shock

Cargo Weight	Coupling Device	Axis	Peak Acceleration (g)	Pulse Duration (ms)
40 tons	Standard	Longitudinal	34	14
		Transverse	8	11
		Vertical	31	13
70 tons	Standard	Longitudinal	21	20
		Transverse	8	8
		Vertical (3-35 Hz)	17	50
		Vertical (35-90 Hz)	17	10
40 tons	Hydraulic end-of-car	Longitudinal	30	23
		Transverse	4.4	8
		Vertical	20	14
40 tons	Sliding center sill	Longitudinal	5.3	45
		Transverse	2.5	13
		Vertical	4.4	24
Source: Magnuson (1980)				

Magnuson (1982) presents shock and vibration data for shipping a 50-ton used nuclear fuel cask from Denver, Colorado to Albuquerque, New Mexico by rail. The used nuclear fuel transportation cask was tied to the instrumented railcar by two cables. In addition, wood blocking was used to prevent longitudinal and transverse motion of the cask relative to the railcar. Accelerometers were mounted on the rail car structure to measure the input from the railcar to the cargo. No accelerometers were placed directly on the transport cask. The vibration results from Magnuson (1982) are listed in Table 2-10 and the shock results are presented in Figure 2-9. Table 2-11 summarizes the rail vibration data.

Table 2-10. Rail Vibration Data

Frequency Band (Hz)	Input to Cargo (g) 99% Level of Zero to Peak Amplitude		
	Longitudinal Axis	Transverse Axis	Vertical Axis
0-5	0.052	0.190	0.37
5-10	0.037	0.072	0.37
10-20	0.052	0.190	0.37
20-40	0.072	0.072	0.27
40-80	0.052	0.140	0.27
80-120	0.072	0.072	0.37
120-180	0.052	0.100	0.19
180-240	0.100	0.140	0.37
240-300	0.052	0.100	0.52
300-400	0.052	0.100	0.27
400-500	0.072	0.140	0.27
500-600	0.100	0.100	0.27
600-750	0.100	0.100	0.27
Source: Magnuson (1982)			

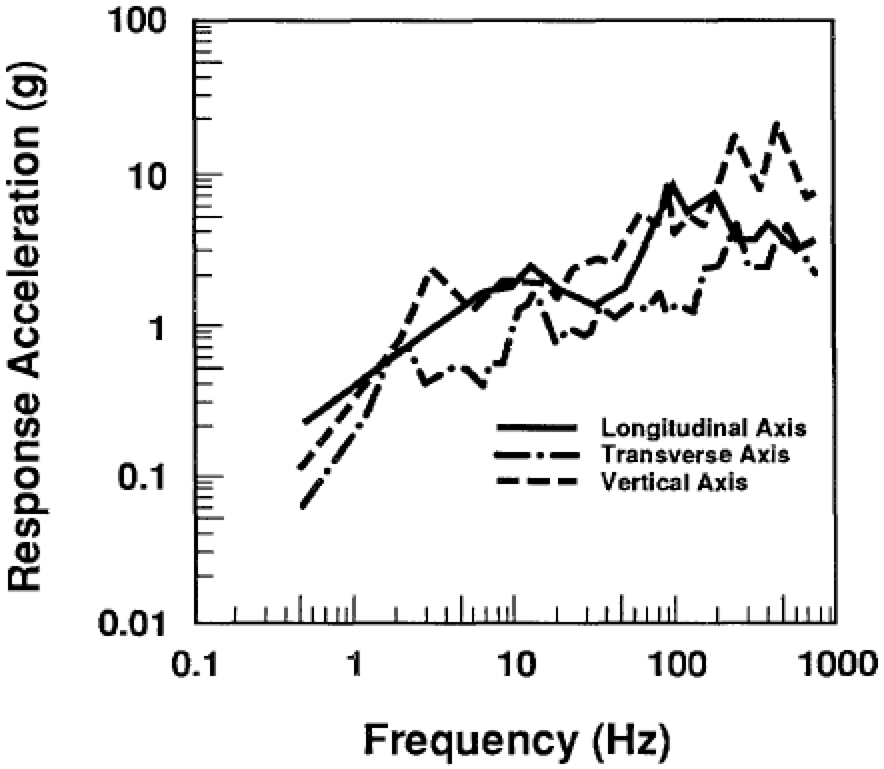

Figure 2-9. Mean Plus Three Standard Deviation Amplitude Envelopes of Shock Response Spectra with 3% Damping (Magnuson 1982)

Table 2-11. Summary of Rail Vibration Data

Axis	Zero-to-Peak Acceleration (g)	Frequency Range (Hz)
Longitudinal	0.10	0-750
Transverse	0.19	0-750
Vertical	0.52	0-750
Source: Magnuson (1982)		

2.1.3 Glass and Gwinn

Glass and Gwinn conducted transportation shock and vibration studies in the mid-1980s and early 1990s. These studies included:

- "Shock and Vibration Environments for Truck-Transported Nuclear Waste: Test and Analysis." In this study, Glass and Gwinn (1986) evaluated the shock and vibration environment during truck transport of the NuPac 7D-3.0 transportation cask weighing 26,000 lb. and carrying a load of 5400 lb., and the CNS 14-170 weighing 32,000 lb. and carrying a load of 5000 lb. Tests were conducted using a road simulator and the focus of the study was on cask tie-downs, where tie-down loads less than 0.1 g were measured, based on cask weight.
- *TRUPACT-I Over-the-Road Test*. In this study, Glass and Gwinn (1987) evaluated the shock and vibration environment during over-the-road truck transport of the TRUPACT-I transportation container. The tests consisted of six road events: a rough primary road, a railroad grade crossing, an asphalt primary road, a concrete primary road, a bridge approach, and a rough secondary road. The total weight of the TRUPACT-I transportation container and contents was 50,000 lb. The peak measured vertical acceleration was 0.835 g, encountered during the railroad grade crossing.
- "Design Basis for Resistance to Shock and Vibration." In this study, Glass and Gwinn (1989) discuss the shock and vibration environment during road simulated truck transport of the NuPac 7D-3.0 transportation cask and the CNS 14-170 transportation casks. The results of these tests were previously reported in Glass and Gwinn (1986). Glass and Gwinn (1989) also discuss over-the-road tests of the TRUPACT-I transportation container, the CNS 3-55 transportation cask, and the CNS 14-170 transportation cask. The weights of the containers were 50,000 lb. for the TRUPACT-I, 57,000 lb. for the CNS 3-55, and 47,000 lb. for the CNS 14-170. The TRUPACT-I testing was previously discussed in Glass and Gwinn (1987). For the CNS 3-55 and CNS 14-170 transportation casks, the tests consisted of nine road events: smooth asphalt, a railroad crossing, rough asphalt, bridge approach, rough concrete, secondary asphalt, and spalled asphalt. Tables 2-12 through 2-17 summarize the results of the CNS 3-55 and CNS 14-170 over-the-road testing.
- *Over-the-Road Tests of Nuclear Materials Package Response to Normal Environments*. In this study, Gwinn et al. (1991) discuss over-the-road tests of the CNS 3-55 transportation cask and the CNS 14-170 transportation cask. The weights of the containers 57,000 lb. for the CNS 3-55 and 47,000 lb. for the CNS 14-170. This testing was previously discussed in Glass and Gwinn (1989). For the CNS 3-55 and CNS 14-170 transportation casks, the tests

consisted of nine road events: smooth asphalt, a railroad crossing, rough asphalt, bridge approach, rough concrete, turn, stop, secondary asphalt, and spalled asphalt. Tables 2-12 through 2-17 summarize the results of the CNS 3-55 and CNS 14-170 over-the-road testing.

Table 2-12. Peak Accelerations for the CNS 3-55 Transportation Cask

Location	Smooth Asphalt	Railroad Crossing	Rough Asphalt	Bridge Approach	Rough Concrete	Secondary Asphalt	Spalled Asphalt
Cask Top							
Transverse (g)	0.1	0.14	0.13	0.11	--	0.34	--
Vertical (g)	0.12	0.47	0.25	0.23	0.12	0.37	0.2
Longitudinal (g)	0.12	0.50	0.15	0.45	--	0.38	0.28
Trailer-Middle							
Vertical (g)	0.09	0.8	0.25	0.32	0.17	0.35	0.22
Trailer-Rear							
Vertical (g)	0.55	5.9	1.4	2.4	1.0	2.7	1.95
Longitudinal (g)	0.13	3.0	0.21	0.47	0.3	0.81	0.4
Trailer-Front							
Vertical (g)	0.85	6.5	1.1	3.4	1.2	3.4	2.65
Source: Gwinn et al. (1991)							

Table 2-13. Root-Mean-Square Accelerations for the CNS 3-55 Transportation Cask

Location	Smooth Asphalt	Rough Asphalt	Rough Concrete	Secondary Asphalt	Spalled Asphalt
Cask Top					
Transverse (g)	0.02	0.032	--	0.042	--
Vertical (g)	0.027	0.072	0.024	0.075	0.043
Longitudinal (g)	0.023	0.035	--	0.097	0.075
Trailer-Middle					
Vertical (g)	0.027	0.069	0.028	0.078	0.048
Trailer-Rear					
Vertical (g)	0.28	0.23	0.24	0.65	0.53
Longitudinal (g)	0.028	0.042	0.058	0.11	0.096
Trailer-Front					
Vertical (g)	0.102	0.22	0.32	0.77	0.63
Source: Gwinn et al. (1991)					

Table 2-14. Peak Tie-Down Loads for the CNS 3-55 Transportation Cask

Location	Smooth Asphalt	Railroad Crossing	Rough Asphalt	Bridge Approach	Rough Concrete	Turn	Stop	Secondary Asphalt	Spalled Asphalt
Cradle Front (lb.)	1900	--	2040	--	1130	960	--	2060	1680
Cradle Rear (lb.)	2530	--	2350	2040	1560	1440	--	3120	2200
Source: Gwinn et al. (1991)									

Table 2-15. Peak Accelerations for the CNS 14-170 Transportation Cask

Location	Smooth Asphalt	Railroad Crossing	Rough Asphalt	Bridge Approach	Rough Concrete	Secondary Asphalt	Spalled Asphalt
Cask Top							
Transverse (g)	0.17	0.16	0.21	0.28	0.12	0.13	0.22
Vertical (g)	0.23	0.62	0.32	0.45	0.20	0.35	0.58
Longitudinal (g)	0.17	0.9	0.38	0.63	0.22	0.64	0.88
Trailer-Middle							
Vertical (g)	0.21	2.3	0.37	0.85	0.07	0.07	0.08
Trailer-Rear							
Vertical (g)	0.46	5.3	1.4	4.6	0.95	1.68	3.1
Longitudinal (g)	0.14	2.8	0.37	1.65	0.22	0.43	0.85
Trailer-Front							
Vertical (g)	0.73	4.5	1.7	3.4	1.3	2.7	4.5
Source: Glass and Gwinn (1989), Gwinn et al. (1991)							

Table 2-16. Root-Mean-Square Accelerations for the CNS 14-170 Transportation Cask

Location	Smooth Asphalt	Rough Asphalt	Rough Concrete	Secondary Asphalt	Spalled Asphalt
Cask Top					
Transverse (g)	0.042	0.043	0.025	0.027	0.054
Vertical (g)	0.041	0.096	0.050	0.066	0.125
Longitudinal (g)	0.041	0.057	0.055	0.143	0.227
Trailer-Middle					
Vertical (g)	0.040	0.093	0.01	0.011	0.011
Trailer-Rear					
Vertical (g)	0.135	0.211	0.233	0.401	0.718
Longitudinal (g)	0.030	0.042	0.059	0.088	0.180
Trailer-Front					
Vertical (g)	0.201	0.294	0.403	0.571	1.03
Source: Gwinn et al. (1991)					

Table 2-17. Peak Tie-Down Loads for the CNS 14-170 Transportation Cask

Location	Smooth Asphalt	Railroad Crossing	Rough Asphalt	Bridge Approach	Rough Concrete	Turn	Stop	Secondary Asphalt	Spalled Asphalt
Front Tie-Down (lb.)	430	700	580	400	220	800	630	350	460
Rear Tie-Down (lb.)	220	650	360	300	150	550	480	280	650
Source: Gwinn et al. (1991)									

2.1.4 Other Sandia Studies

In addition to the studies conducted by Foley and Gens, Magnuson, and Glass and Gwinn, several other studies conducted by Sandia National Laboratories were also identified:

- *Transportation Environments of the AL-SX (H1616)* (York 1991)
- *Vibration and Shock Test Report for the H1616-1 Container and the Savannah River Hydride Transport Vessel* (York and Joseph 1992)
- *Hydride Transport Vessel Vibration and Shock Test Report* (Tipton 1998)

These studies were evaluated but were not relevant to the shipment of used nuclear fuel by rail in high-capacity transportation casks.

2.1.5 Sandia Environmental Data Bank

Sandia National Laboratories has maintained the DOE/DOD Environmental Data Bank since 1959 as a central repository for storing weapons and equipment environment information from a variety of DOE, DOD, and industrial sources. Data are catalogued under two major headings, normal and abnormal environments. Categories of data that are included in the Environmental Data Bank include acceleration/time histories, acoustic noise, atmospheric contents, biotic, fragmentation, humidity, precipitation, pressure, radiation, shock, temperature, trajectory, vibration, and wind. Operational phases included in the Environmental Data Bank include handling, storage, transport, utilization, and a category denoted general. The transport and utilization phases are further subdivided by transport mode, e.g., truck, railroad, aircraft, and ship.

Sandia National Laboratories performed a search of the Environmental Data Bank and no additional studies involving large rail used nuclear fuel or radioactive waste transportation casks were identified.

2.2 Hanford Engineering and Development Laboratory

Over the period 1976 to 1983, the Hanford Engineering Development Laboratory conducted a study to determine the extent to which the shocks and vibrations experienced by radioactive material shipping packages during normal transport conditions are influenced by, or are sensitive to, various structural parameters of the transport system (i.e., package, package supports and vehicle). The results of this study were documented in a series of 17 reports and two papers:

1. *SAVIT – A Dynamic Model to Predict Vibratory Motion Within a Spent Fuel Shipping Cask-Rail Car System* (Fields 1978a)
2. *Dynamic Analysis to Establish Normal Shock and Vibration Environments Experienced by Radioactive Material Shipping Packages, Quarterly Project Report, October 1–December 31, 1977* (Fields 1978b)
3. *Dynamic Analysis to Establish Normal Shock and Vibration Environments Experienced by Radioactive Material Shipping Packages, Quarterly Project Report, January 1, 1978 –March 31, 1978* (Fields and Mech 1978a)
4. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, April 1–June 30, 1978* (Fields and Mech 1978b)
5. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, July–September 1978* (Fields and Mech 1979a)
6. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, October 1, 1978–December 31, 1978* (Fields and Mech 1979b)
7. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, January 1, 1979–March 31, 1979* (Fields and Mech 1979c)
8. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, April 1, 1979–June 30, 1979* (Fields and Mech 1979d)
9. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, July 1, 1979–September 30, 1979* (Fields and Mech 1980a)
10. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, October 1, 1979–December 31, 1979* (Fields and Mech 1980b)
11. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, January 1, 1980–March 31, 1980* (Fields 1981a)
12. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, April 1, 1980–June 30, 1980* (Fields 1981b)
13. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, July 1, 1980–September 30, 1980* (Fields 1981c)
14. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, October 1, 1980–December 31, 1980* (Fields 1981d)

15. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, January 1, 1981–March 31, 1981* (Fields 1981e)
16. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Quarterly Project Report, April 1, 1981–June 30, 1981* (Fields 1983b)
17. *Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages, Final Summary Report* (Fields 1983a)
18. "Dynamic Analysis to Establish Normal Shock and Vibration of Radioactive Material Shipping Packages" (Fields 1980)
19. "Simulation of the dynamic response of radioactive material shipping package – railcar systems during coupling operations" (Fields 1984).

The purpose of the study was to identify those parameters that significantly affect the normal shock and vibration environments so as to provide the basis for determining the forces transmitted to radioactive material packages. Determination of these forces provided the input data necessary for a broad range of package tie-down structural assessments.

A computer model CARDS (Cask-Rail Car Dynamic Simulator) was developed to provide the data for these assessments. A companion model Cask Rail Car Response Spectrum Generator was also developed to generate frequency response spectra using results from CARDS. These two models were used to identify parameters that significantly affect the shock and vibration environments and, in turn, the forces transmitted to the packages.

It was assumed that the greatest shock suffered by the cask-rail car in its normal transport environment will be that experienced during coupling operations in a "humping" or classification yard. An earlier study by Magnuson and Wilson (1977) showed that 99.8 percent of all train coupling operations occurred at speeds of 11.05 mph or less. Eighteen tests were conducted at the Savannah River Laboratory in 1978 during which coupling velocities as high as 11.2 mph were recorded (Petry 1980). The validity of the CARDS model as an acceptable tool for the simulation of cask-rail car systems was established by comparison of calculated results with results obtained from six of these tests.

The CARDS and Cask Rail Car Response Spectrum Generator models were used together to generate frequency response spectra, to determine the sensitivity of selected response variables to changes in parameters, and to rank the parameters according to their influence and their contribution to the sensitivity of the response variables.

2.3 Ontario Hydro

Ontario Hydro conducted a two phase shock and vibration program to evaluate the response of irradiated Canadian deuterium-uranium reactor (CANDU) fuel bundles to the transportation environment. This program was documented in a series of 13 reports:

1. *Irradiated Fuel Transportation Shock and Vibration Rail and Truck Field Tests* (Forest 1979)
2. *Dynamic Analysis of Lumped Models - General Procedure* (Elbestawi 1979)
3. *End Impact Analysis of a Railcar Carrying an Irradiated Nuclear Fuel Shipping Flask* (Elbestawi and Dokainish 1980a)
4. *Dynamic Response of a Railcar Carrying an Irradiated Nuclear Fuel Shipping Flask Subjected to Periodic and Stochastic Rail Excitation* (Elbestawi and Dokainish 1980b)
5. *Random Response of a Tractor-Semitrailer System Carrying an Irradiated Nuclear Fuel Shipping Flask* (Dokainish and Elbestawi 1980)
6. *Impact and Fatigue Strength of Irradiated CANDU Fuel Bundles* (Forest 1980)
7. "CANDU Irradiated Fuel Transportation System – Dynamics Analysis" (Loewen et al. 1980)
8. *Irradiated Fuel Transportation Shock and Vibration Study – Phase 1 Summary Report* (Forest 1982)
9. *Irradiated Fuel Shipping Module Transportation Tests* (Smrke 1983)
10. *Irradiated Fuel Shock and Vibration Environment During Off-Site Transportation* (Elbestawi and Lau 1983)
11. "Transportation of Irradiated Fuel By Tractor-Trailer: A Simulation of the Vibration Environment" (Elbestawi and Lau 1984)
12. *Irradiated Fuel Transportation Shock and Vibration Program – Phase 2 Summary* (Forest 1985)
13. "CANDU Irradiated Fuel Transportation: The Shock and Vibration Program" (Dalziel et al. 1986)

An additional study by Morandin et al. (2003) evaluated the structural integrity of CANDU used nuclear fuel bundles during normal transport conditions.

During Phase 1 it was assumed that individual bundle restraints and module stack restraints would be needed. Consequently, impact and fatigue testing of bundles in Phase 1 was conducted using an axial preload on the bundles (Dalziel et al. 1986). The results of these impact and fatigue tests proved the bundles to be highly resistant to failure. Therefore, in Phase 2, the impact and fatigue testing was repeated to establish threshold levels for axially unrestrained bundles (Dalziel et al. 1986). As discussed in Dalziel et al. (1986), shock and vibration levels and CANDU fuel bundle response was characterized by

- road transportation field measurements of normal vibration and transients
- rail transportation field measurements of normal vibration, transients, and rail car coupling impact
- modal testing of the fuel transport containers
- impact and fatigue testing on irradiated fuel and unirradiated fuel

- analytical modeling of the road and rail transportation modes.

From Dalziel et al. (1986), road field tests were done using a tractor-trailer loaded with a module placed inside a concrete mass, simulating a 32 MT cask. Accelerometers were mounted on the tractor drive axle, trailer axle, the baseplate on which the module was placed (horizontal and vertical components), and on a module tube. The tractor unit was a tandem drive with a steel spring suspension. The trailer was a single drop deck tri-axle with steel springs. The trailer mass was 9.1 MT and the combined tractor-trailer mass was 18 MT. The vehicle was driven a total of 900 km over a variety of road conditions. Table 2-18 summarizes the overall steady-state vertical accelerations for the truck tests.

A rail flat car carrying a module in a simulated 68 MT cask was instrumented with accelerometers and hauled a distance of 420 km over a variety of track conditions. The railcar was a Canadian National Series 667 flat car equipped with standard draft gear couplers. Accelerometers were mounted on the railcar rear bogie frame, the baseplate (horizontal and vertical components), and on some module tubes. Table 2-18 summarizes the overall steady-state vertical accelerations for the rail tests.

Railcar coupling impact tests were also conducted at National Research Council facilities in Uplands, Ontario. However, cask response results were of limited value because of slippage of the concrete blocks used to simulate the cask mass, but did tend to confirm g-loads from the literature and analyses.

Table 2-18. Road and Rail Normal Vertical Acceleration Levels

Mode	Location	Vertical Acceleration (g)		
		Mean	Min. (peak)	Max. (peak)
Road	Baseplate	0.10	0.06	0.18
	Central module tube	0.30	0.15	0.45
Rail	Baseplate	0.14	0.10	0.20
	Central module tube	0.20	0.16	0.30
Source: Dalziel et al. (1986)				

2.4 Battelle Columbus Laboratories

Battelle Columbus Laboratories conducted a literature review to establish the shock and vibration environment associated with truck and rail transport. Based on available data obtained in these literature reviews, the maxima of shock and vibration accelerations were established. These reviews were documented in two reports:

- *Summary Report on Study to Define the Shock and Vibration Environment during Truck Transport of Shipping Containers* (Ahlbeck 1971)
- *Summary Report on Study to Define the Shock and Vibration Environment during Rail Transport of Shipping Containers* (Ahlbeck and Doyle 1974)

For truck transport, Ahlbeck (1971) drew the following conclusions (excerpted):

1. Definition of Environment. Truck transport shock can be characterized as a recurrent, decaying sinusoidal pulse at frequencies below 20 Hz. Continuous background vibration has been shown to be random, with a Gaussian amplitude distribution. Certain events have high shock damage potential, particularly dips, bumps, chuckholes, and railroad crossings at high speed. Dips, bumps and holes appear to have greater damage potential for cargo with natural frequencies below 15 Hz, while railroad tracks have higher damage potential for cargo with higher natural frequencies. Similarly, the response severity at the cargo as a function of speed depends to a great extent on cargo natural frequency: low speeds have greater effect on low natural-frequency cargo, and vice versa. In the 10-Hz "recurrent shock" region, truck transport presents a more severe environment than rail transport, while at higher frequencies (above 100 Hz) the rail shock environment becomes more severe. For massive cargos such as the radioactive materials containers, with natural frequencies in the 3-60 Hz range, neither mode presents a distinct advantage, unless special suspensions (air or elastomeric truck suspensions) or special handling are employed.
2. Axis of Response. The vertical axis predominates as the axis with the highest potential for damage due to high-amplitude shock and vibration levels except, of course, in the event of an accident. Peak accelerations may range from 50 percent to 200 percent higher in the vertical than in either the lateral (transverse) or the longitudinal axes for typically severe transient shock events. From a comparison of limited field data, vibration levels in the two horizontal axes may be as much as an order of magnitude less than vertical vibration. The most severe location for vertical accelerations is usually over the rear axles (truck or trailer), although higher acceleration peaks and power spectral density have been recorded in some instances over the fifth wheel, and it apparently depends on the tractor suspension, trailer geometry, fifth wheel design and condition, and load configuration. The middle of the trailer is generally the least severe at most frequencies.
3. Effects of Load. The most apparent effect of load is to reduce high frequency response components (structural resonances) while accentuating the low frequency response (sprung mass). A concentrated load such as a radioactive material transportation cask produces a marked increase in low frequency (1-20 Hz) response over that of the empty vehicle. Longitudinal and lateral response levels, however, are generally lower with the loaded vehicle than the empty. Location and configuration of load were noted to have some effects on response level and spectrum shape, but trends were not clearly defined in the literature due to the load structural complexity.
4. Type of Vehicle. There is insufficient data obtained under similar enough conditions to define clearly the response differences between vehicles (truck versus tractor-semitrailer, for example). However, obvious differences

between supposedly identical vehicles were noted. Condition of the suspension system can radically change the acceleration spectrum at the cargo space; if the malfunction involves binding or friction, the high frequency components are accentuated, the low frequencies reduced. Conversely, worn shocks (low damping) will accentuate the low frequencies in the sprung and unsprung mass resonant frequency range.

5. Data Format. Data are generally reported in mixed form: shock and vibration lumped (inconveniently) together. Only by statistical analysis of acceleration data can the peak values be assigned the proper frequency/amplitude distribution "family." A great deal of data is reported simply as peak amplitude and (sometimes) dominant frequency for a given event or condition. This gives only shock response. Shock is also described in terms of shock response spectra, which may be viewed as the peak acceleration of an idealized structure (cargo) in response to the given transient event. A third method of presenting data is by means of the power spectral density plot, which provides a measure of acceleration power versus frequency in the shock/vibration environment. Akin to this is the acceleration amplitude spectral density. To combine the best features of these methods of data presentation, Sandia Corporation is now using a power spectral density envelope of the random background vibration, plus three-sigma peak values (99.7 percent of the distribution equal or less in amplitude) in particular frequency bands.
6. Tie-Down Methods. In protecting cargo by decoupling from the truck bed, the pad (or shock mounts), cargo and tie-downs act as a spring-mass-damper system. Successful isolation depends on either broadening the response spectrum (relatively high damping) or tuning the isolation system to a natural frequency removed from the important excitation frequencies of the truck bed. If the isolation system natural frequency falls close to one of these excitation frequencies, amplification will occur at that frequency.
7. Acceleration Shock and Vibration Envelopes. Based on the available data, the shock and vibration envelopes of Figure [2-10] were established for both the standard leaf-spring suspensions and the air ride suspensions. The recurring shock limits represent 99.9 percent of the expected peaks (the air ride shock limit is a conservative estimate based on very limited data); while the continuous random vibration limits represent the three-sigma (99.7 percent) envelope of the Gaussian amplitude distribution. These envelopes include both the loaded and empty (lightly loaded) vehicle, and truck and tractor-semitrailer configurations. For design purposes, the longitudinal and lateral axes may be assumed conservatively to fall within these acceleration limits.

For rail transport, Ahlbeck and Doyle (1974) drew the following conclusions (excerpted):

1. Definition of Environment. Railroad freight car vibration and shock can be characterized in two distinct categories: that occurring from over-the-road

travel, and that occurring during classification (switching) of cars. Over-the-road accelerations consist of a relatively low-level random vibration on which repetitive transients from sources such as rail joints and wheel flats are superimposed. Occasional higher-level transient shock pulses occur from traversing switch points and frogs, railroad crossings, highway grade crossings, and other structures, as well as longitudinal impacts due to run-in and run-out of coupler slack resulting from longitudinal train dynamics. Accelerations during switching result from longitudinal impacts when cars are coupled at speeds ranging from 1 to 12 miles per hour. Shock response spectra (which can be used to estimate the maximum response accelerations of the cargo) for switching events can be an order-of-magnitude higher than the spectra for over-the-road vibration and shock.

2. Dynamic Response. Acceleration levels in response to the environment result from a combination of the rail vehicle and track characteristics, and train speed. Few peak accelerations greater than 1 g occur during over-the-road operation, and continuous vibration levels are relatively low; although sustained high-amplitude vibrations can occur due to low-frequency harmonic excitation by the track geometry or due to car body or truck hunting motions. Accelerations in the low-frequency (0.5 to 10 Hz) band may be considered “recurrent shock,” while higher frequency accelerations approximate a Gaussian distribution in amplitude. High impact accelerations that occur during switching operations can be substantially attenuated by use of a freight car with energy-absorbing draft gear or cushioned underframe. Strict control of coupling speed is, of course, the most important factor in limiting switching acceleration levels. With a combination of both cushioned draft gear and reasonable handling, longitudinal shock accelerations should not exceed 4 g to the car.

3. Axis of Response. In over-the-road operation by railroads, the vertical axis predominates as the axis with the highest shock and vibration levels and greatest damage potential. Higher shock response has been noted, in the lateral axis between 1 and 3 Hz. This may be a result of car lateral or yaw modes of oscillation (hunting). At higher frequencies, the lateral and longitudinal axes are comparable in acceleration level, and generally much lower than the vertical axis. Shock spectra for switching impacts show the longitudinal axis to be most severe below about 10 Hz, while the vertical axis is most severe at higher frequencies. The lowest shock response occurs in the lateral axis. For massive cargos, such as a large nuclear material cask, which are likely to have natural frequencies in the 3 to 60 Hz range, the longitudinal response would be most severe during switching.

4. Effects of Load. Railroad freight cars commonly use friction damping in the truck suspension so that for light load and/or low excitation amplitudes the suspension is essentially locked. As a result, vibration levels for lightly-loaded freight cars are found to be higher across the entire frequency spectrum, except at specific load-dependent resonances.

5. Type of Freight Car. Dynamic response of a particular freight car depends on a number of factors, including the truck design, suspension parameters, car structure, load, truck spacing, track geometry, and speed. Certain types of cars exhibit unusual vehicle dynamic behavior such as severe rocking of 100-ton hopper cars operating at speeds of 15-20 mph on 39-foot rails or yaw modes in certain types of flat cars. The use of premium trucks and cushion draft gear on a freight car can reduce the chance of unusual dynamic behavior and provide a better shock and vibration environment.
6. Data Format. Vibration data are generally presented for the railroad environment in the form of envelopes of peak acceleration versus frequency; acceleration statistical levels (e.g., root-mean-square or three-sigma) versus frequency; distribution curves (percent exceedance versus amplitude); and discrete data points. Shock data are presented as shock response spectra (which give the maximum response acceleration of a single-degree-of-freedom system to the shock events as a function of the natural frequency and damping of that system), and as discrete acceleration/frequency points. Vibration power spectral density curves generated for specific conditions are also commonly presented.
7. Vibration and Shock Response Envelopes. Based on the available data, the vibration envelopes of Figure [2-11] are suggested as conservative for the over-the-road railroad environment. Maximum acceleration levels for all axes are enclosed by the solid line, while the dashed lines enclose the three-sigma (99.73 percent of acceleration peaks equal or less than this level) for the specific axes. In Figure [2-12], shock response envelopes are shown enclosing spectra for the given switching events and for typical over-the-road transient events.

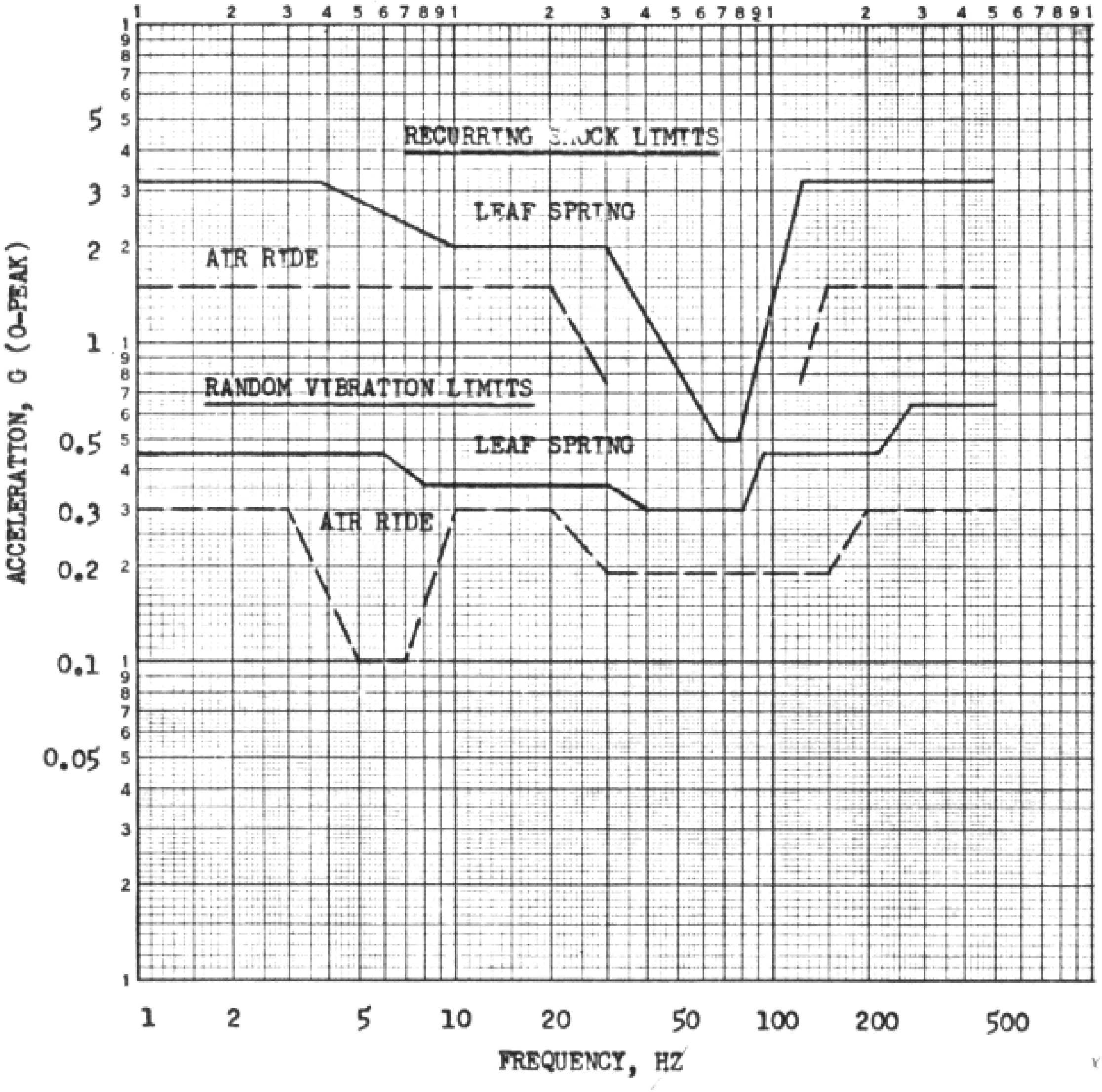

Figure 2-10. Maximum Shock and Vibration Envelopes for Vertical Axis at Cargo for the Two Basic Truck Suspension Systems (Ahlbeck 1971)

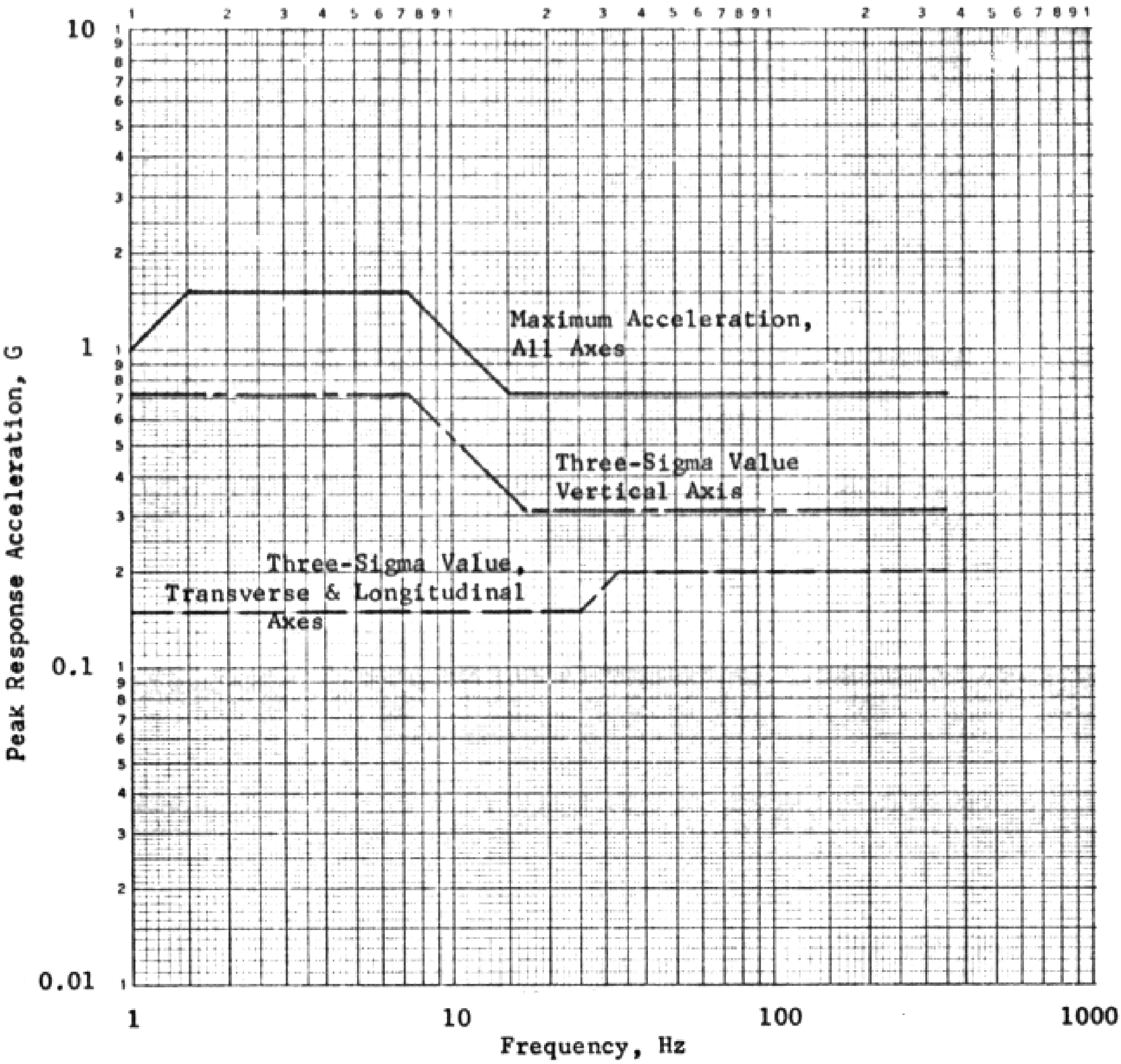

Figure 2-11. Over-the-Road Vibration Envelopes for Railroad Freight Car Environment, at Cargo (Ahlbeck and Doyle 1974)

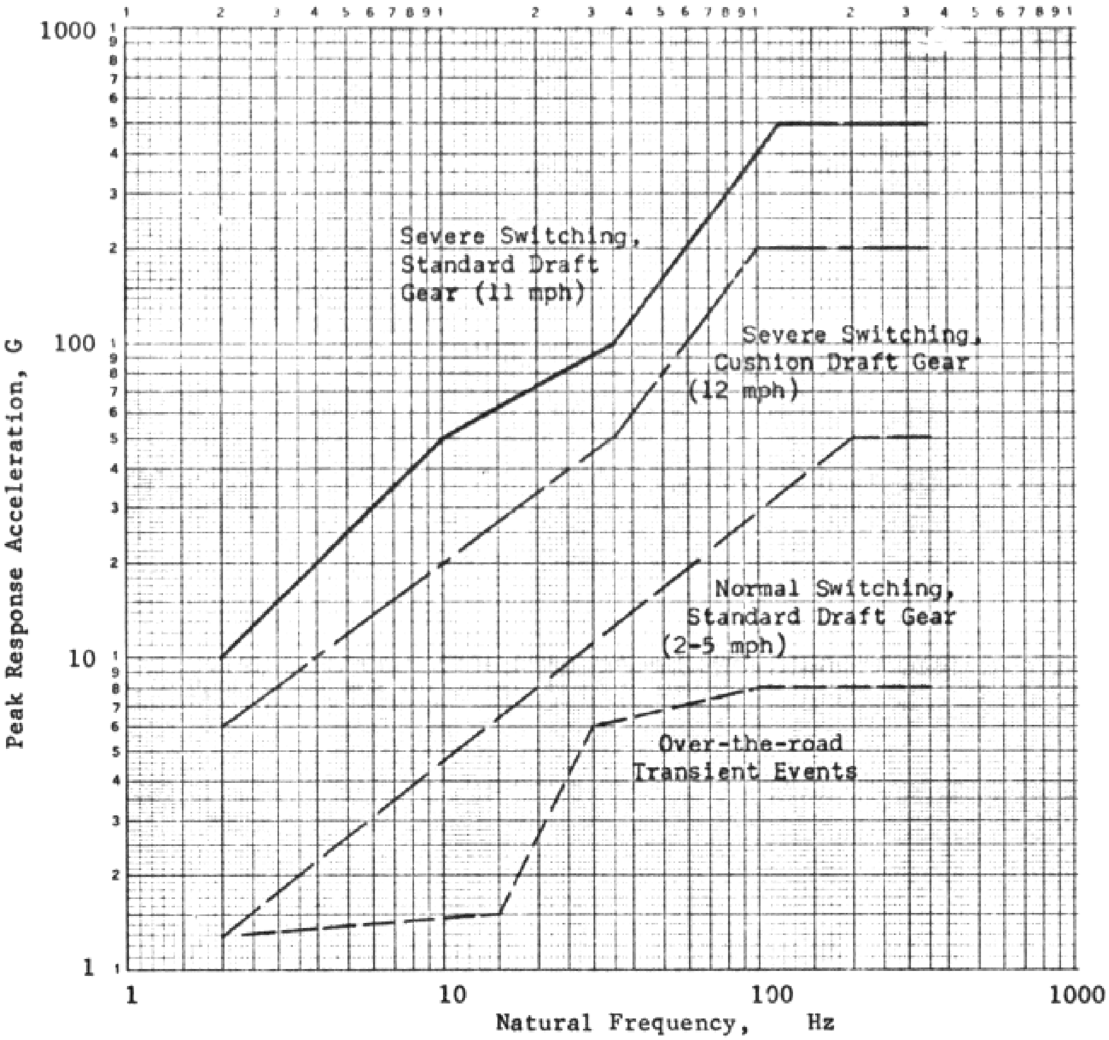

Figure 2-12. Shock Response Spectral Envelopes (All Axes) for Typical Shock Events, Railroad Freight Car Environment (Ahlbeck and Doyle 1974)

2.5 Savannah River Site

Petry (1980) discusses a rail tie-down test program that was conducted at the Savannah River Site in July and August 1978. The major objectives of the test program were to 1) provide test data as a basis to develop a tie-down standard for rail cask shipments of radioactive materials and 2) collect dynamic data to support analytical models of the railcar cask tie-down system. For each test, a 40- or 70-ton cask was secured on a railcar. The railcar was pushed to speeds up to 11 mph and allowed to couple to parked railcars simulating ordinary rail yard operations. The test car carrying the cask was heavily instrumented to measure the accelerations and forces generated at strategically selected locations. Eighteen test runs were made with different combinations of railcars, couplers, casks, speeds, and tie-down configurations. The results from six of these tests were used as validation cases for the CARDS computer code developed at the Hanford Engineering Development Laboratory (Fields 1983a). In addition, the results of the tests were used to determine the maximum peak acceleration and its pulse duration for the longitudinal, transverse, and vertical axes of the two casks (Magnuson 1980), listed in Table 2-19. These data are the same as are presented in Table 2-9.

Table 2-19. Coupling Shock

Cargo Weight	Coupling Device	Axis	Peak Acceleration (g)	Pulse Duration (ms)
40 tons	Standard	Longitudinal	34	14
		Transverse	8	11
		Vertical	31	13
70 tons	Standard	Longitudinal	21	20
		Transverse	8	8
		Vertical (3-35 Hz)	17	50
		Vertical (35-90 Hz)	17	10
40 tons	Hydraulic end-of-car	Longitudinal	30	23
		Transverse	4.4	8
		Vertical	20	14
40 tons	Sliding center sill	Longitudinal	5.3	45
		Transverse	2.5	13
		Vertical	4.4	24
Source: Magnuson (1980)				

2.6 Other Studies

This section summarizes additional shock and vibration studies performed by investigators not affiliated with Sandia National Laboratories, the Hanford Engineering and Development Laboratory, Ontario Hydro, Battelle Columbus Laboratories, or the Savannah River Site.

2.6.1 Ostrem

Ostrem conducted several literature reviews of existing information and data describing the shock and vibration environment associated with common carrier transportation modes, including truck, rail, ship, and air. These reviews were summarized in Ostrem and Rumerman (1965, 1967), Ostrem (1968, 1972), Ostrem and Libovicz (1971), and Ostrem and Godshall (1979). In the latest review, Ostrem and Godshall (1979) summarized the available data and information describing the common carrier transportation environment, including trucks, railcars, aircraft, ships, and forklift trucks. In this review, Ostrem and Godshall (1979) discussed the major shipping hazards of shock, vibration, impact, temperature, and humidity associated with the handling, transportation, and warehousing operations of typical distribution cycles. Ostrem and Godshall (1979) discussed railcar vibration, shock, and railcar coupling, but the rail studies discussed by Ostrem and Godshall (1979) typically characterized the transportation environment associated with boxcars, trailers on flat cars, or containers on flat cars and these studies did not involve cargo weights in the range of used nuclear fuel rail transportation casks. However, Ostrem and Godshall (1979) discussed studies performed by Sandia National Laboratories (Foley [1966b], Foley and Gens [1971a], Foley [1972], Foley et al. 1972], Gens [1970], and Gens [1975]).

2.6.2 Nuclear Engine for Rocket Vehicle Application

Nuclear Engine for Rocket Vehicle Application was a joint program of the U.S. Atomic Energy Commission and the National Aeronautics and Space Administration managed by the Space Nuclear Propulsion Office until both the program and the office ended at the end of 1972. As part of the Nuclear Engine for Rocket Vehicle Application program, a simulated NRX-A reactor was shipped from Large, Pennsylvania, to Las Vegas, Nevada by rail (Scialdone and Appleman 1963). The train consisted of seven cars: a locomotive, Pullman car, baggage car, a flat car carrying the reactor, caboose, piggy-back car, and caboose. The maximum vertical acceleration measured for the round trip between Large, Pennsylvania was 0.78 g and the maximum transverse acceleration was 0.50 g.

Smith (1967) also evaluated the shock and vibration loads imposed on a dummy reactor during rail transportation to and from Test Cell C, Test Cell A, R-MAD and E-MAD at the Nevada Test Site. The test was performed using the T-7 test car, dummy reactor, spacer car, manned control car, and the L-3 Railroad Transport System. During coupling, longitudinal accelerations of 0.2 g were measured. During track tests, no accelerations greater than 0.5 g were measured in any direction.

2.6.3 Luebke

Luebke (1970) investigated the vibration environment for 70-ton boxcars. This study evaluated the effects of load, speed, track irregularities, flat wheels, friction damping, variable rate springs, spring travel, and truck design on the vibration environment. This study did not involve cargo weights in the range of used nuclear fuel rail transportation casks.

2.6.4 Kachadourian

In Kachadourian (1982, 1983), additional tests were conducted on a 70-ton boxcar in order to provide data to validate the FRATE computer code. As with the study by Luebke (1970), these studies did not involve cargo weights in the range of used nuclear fuel rail transportation casks.

2.6.5 Prulhiere and Israel

Prulhiere and Israel (1980) measured the vibration environment during truck and rail transport and handling of a TN 12 transportation cask. The TN 12 transportation cask weighed 100 MT (110 tons) and was shipped from the Bugey nuclear power station (France) to the Tricastin nuclear power station (France). During rail transport, Prulhiere and Israel (1980) measured accelerations on a mock pressurized water reactor assembly inside the TN 12 transportation cask, on the cask trunnions, on the skid floor, and on the rail wheels. Prulhiere and Israel (1980) was the only study found during the literature review where accelerations were measured on a fuel assembly inside a transportation cask. Table 2-20 lists the accelerations measured on the mock fuel assembly from Prulhiere and Israel (1980).

Table 2-20. Truck, Rail, and Handling Acceleration Values

Mode	Longitudinal Acceleration (g)	Transverse Acceleration (g)	Vertical Acceleration (g)
Truck	0.15	0.5	0.4
Rail	0.6	0.4	0.5
Handling	0.2	0.2	0.2
Source: Prulhiere and Israel (1980)			

2.6.6 Pujet and Malesys

Pujet and Malesys (1989) measured the vibration environment during truck transport of the NTL 8/3 transportation cask weighing 36 MT (40 tons) and during rail transport of the NTL 11 transportation cask weighing 80 MT (88 tons). The NTL 8/3 transportation cask was shipped from La Hague, France to Tihange, Belgium, a distance of 1600 km. The NTL 11 transportation cask was shipped from Valognes (near La Hague, France) to Wurgassen, Germany, a distance of 2360 km. In both cases, accelerometers were attached to a cask trunnion. Table 2-21 lists the maximum accelerations from Pujet and Malesys (1989).

Table 2-21. Truck and Rail Acceleration Values

Mode	Longitudinal Acceleration (g)	Transverse Acceleration (g)	Vertical Acceleration (g)
Truck	1.8	1.8	2.2
Rail	1.0	1.0	1.4
Source: Pujet and Malesys (1989), Cory (1991)			

2.6.7 Becker and McCoy

Becker and McCoy (1997) conducted over-the-road shock and vibration testing of the radioisotope thermoelectric generator transportation system. Road testing was conducted in the vicinity of the Mound facility in Miamisburg, Ohio and Mobilized Systems, Inc. in Batavia, Ohio. Road testing included towing the radioisotope thermoelectric generator transportation system over railroad tracks and a curb test. The tests were conducted using an unfueled radioisotope thermoelectric generator test unit weighing slightly less than 9600 lb., and did not involve cargo weights in the range of used nuclear fuel rail transportation casks.

2.6.8 Fourgeaud

Fourgeaud et al. (2011) summarized the vibration environment for truck, rail, and sea transport, citing the studies performed by Prulhiere and Israel (1980), Pujet and Malesys (1989), and Cory (1991).

2.6.9 Packaging Technology and Science

The journal *Packaging Technology and Science* has published numerous papers related to the shock and vibration associated with transportation. Examples of the papers published in *Packaging Technology and Science* related to shock and vibration data, testing, or analysis include:

- “Analysis of Vibration and Shock Occurring in Transport Systems” (Hasegawa 1989)
- “Distribution Testing—Sine or Random?” (Caldicott 1991)
- “A Comparison of Leaf-spring with Air-cushion Trailer Suspensions in the Transport Environment” (Pierce et al. 1992)
- “Comparison Between Lateral, Longitudinal, and Vertical Vibration Levels in Commercial Truck Shipments” (Singh et al. 1992)
- “Reliability and Error Estimations of Mechanical Shock Recorders and Impact Indicators” (Singh et al. 1994)
- “Test Protocol for Simulating Truck and Rail Vibration and Rail Impacts in Shipments of Automotive Engine Racks” (Singh et al. 1995)
- “Model of Accelerated Vibration Test” (Ge 2000)
- “Remote Monitoring of Vehicle Shock and Vibrations” (Rouillard 2002)
- “Modeling of the Effects of Continual Shock Loads in the Transport Process” (Xiang and Eschke 2004)
- “The Use of Intrinsic Mode Functions to Characterize Shock and Vibration in the Distribution Environment” (Rouillard and Sek 2005)
- “Measurement and Analysis of Truck Transport Vibration Levels and Damage to Packaged Tangerines during Transit” (Jarimopas et al. 2005)
- “Measurement and Analysis of US Truck Vibration for Leaf Spring and Air Ride Suspensions, and Development of Tests to Simulate these Conditions” (Singh et al. 2006)
- “A Novel Approach to Analysing and Simulating Railcar Shock and Vibrations” (Rouillard and Richmond 2007)
- “Measurements and Analysis of Truck and Rail Shipping Environment in India” (Singh et al. 2007)
- “Measurement and Analysis of Truck Transport Environment in Brazil” (Rissi et al. 2008)

- “Measurement and Analysis of Vibration Levels for Truck Transport in Spain as a Function of Payload, Suspension, and Speed” (Garcia-Romeu-Martinez et al. 2008)
- “Dynamic Analysis of Less-than-truckload Shipments and Test Method to Simulate this Environment” (Singh et al. 2008)
- “Analysis of Shock and Vibration in Truck Transport in Japan” (Lu et al. 2008)
- “Wavelet Analysis of Shock and Vibration on the Truck Bed” (Nei et al. 2008)
- “Generating Road Vibration Test Schedules from Pavement Profiles for Packaging Optimization” (Rouillard 2008)
- “Measurement and Analysis of Truck and Rail Vibration Levels in Thailand” (Chonhenchob et al. 2010)
- “Effect of Vehicle Speed on Shock and Vibration Levels in Truck Transport” (Lu et al. 2010)
- “Transport Vibration Laboratory Simulation: On the Necessity of Multiaxis Testing” (Bernad et al. 2011)
- “Statistical Characterization of Acceleration Levels of Random Vibrations during Transport” (Otari et al. 2011)
- “Monitoring and Evolution of Damage in Packaging Systems under Sustained Random Loads” (Lamb et al. 2012)
- “Measurement and Analysis of Vibration and Temperature Levels in Global Intermodal Container Shipments on Truck, Rail, and Ship” (Singh et al. 2012)
- “Vibration Testing of Intermediate Bulk Containers for Dangerous Goods” (Schurig and Klinger 2012)

These studies did not involve cargo weights in the range of used nuclear fuel rail transportation casks, or were based on specific commodities.

3. RESULTS

During the literature review conducted of studies related to the vibration and shock associated with the normal conditions of transport for rail shipments of used nuclear fuel, over 200 documents were collected from a wide variety of sources, including studies performed by Sandia National Laboratories, the Hanford Engineering and Development Laboratory, Ontario Hydro, Battelle Columbus Laboratories, and the Savannah River Site, as well as studies performed by other investigators. The results of the literature review follow.

- There were few recent studies of the shock and vibration associated with the normal conditions of transport. Most of the studies that were related to the shipment of used nuclear fuel, radioactive waste, or radioactive material were published in the 1960s, 1970s, and 1980s. Relatively few studies were published after the mid-1990s.
- No studies were found that evaluated a rail transportation cask or other cargo that was similar in weight to the weight of a commercial light-water reactor used nuclear fuel rail transportation cask, about 300,000 lb. The largest transportation casks evaluated were in a study by Prulhiere and Israel (1980), where the TN 12 transportation cask, weighing 220,000 lb., was evaluated; and in a study by Pujet and Malesys (1989), where the NTL 11 transportation cask, weighing 176,000 lb., was evaluated.
- No studies using railcars that met AAR Standard S-2043 were found.
- One study (Prulhiere and Israel 1980) was found where a fuel assembly was instrumented inside a used nuclear fuel transportation cask. However, Prulhiere and Israel (1980) provided data in summary form and more detailed data from this study were not available.

Table 3-1 summarizes the key attributes of the most relevant studies. Figures 3-1, 3-2, and 3-3 illustrate bounding acceleration shock spectra determined for truck transport, rail transport, and rail coupling by Sanders et al. (1992). Based on the results of the literature review, the data currently used to characterize the shock and vibration associated with the normal conditions of transport by rail appear to overestimate the shock and vibration that would be encountered during shipment of a transportation cask on an AAR Standard S-2043-compliant railcar. In addition, the cask weights used to derive the current data are not representative of current generation cask weights. For these reasons, it is recommended that additional shock and vibration data be obtained to realistically model the effects of the normal conditions of transport on rail shipments of commercial light-water reactor used nuclear fuel at the fuel assembly and fuel rod level. Options for implementing this recommendation are discussed in Adkins (2013).

Table 3-1. Summary of Relevant Shock and Vibration Studies

Reference	Rail/Truck	Cargo	Comments
Foley (1966a, 1966b), Bryan (1965), Otts (1965a, 1965b), Mortley (1965)	Truck	15-ton radioactive materials cask	Transport (unloaded) from Ft. Eustis, VA to Wilmington, DE. Transport (loaded) from Wilmington, DE to Albuquerque, NM. Data presented in multiple formats.
Gens (1970) Foley and Gens (1971a, 1971b)	Rail/Truck	15-ton used nuclear fuel cask	Evaluates light cargo, particularly for the rail-shock response spectrum. Dynamic environments were similar for truck and rail. Truck transport was from Oak Ridge, TN to Paducah, KY. Rail transport was from Paducah, KY to Oak Ridge, TN.
Magnuson and Wilson (1977)	Rail/Truck	No load to 15-ton cargo, 5-ton cargo for rail coupling tests	Evaluates light cargo. Provides a summary of earlier test results, including seven different truck and tractor-trailer configurations. Observed that shock decreases as cargo weight increases. Provides shock-response spectra, bounding single-pulse representation, and rail-coupling data.
Magnuson (1977)	Truck	22-ton used nuclear fuel cask	Provides shock-response spectra and single pulse representation. Two axle 35-foot trailer with air suspension. Cask transported from Mercury, NV to Albuquerque, NM. Two sets of accelerometers on the container and four sets of accelerometers on the structure supporting the container.
Magnuson (1978)	Truck	28-ton used nuclear fuel cask	Provides shock response spectra and single pulse representation. Three axle 40-foot trailer with spring suspension. Cask transported from Mercury, NV to Albuquerque, NM. Two sets of accelerometers on the container and four sets of accelerometers on the structure supporting the container.
Magnuson (1980) Petry (1980)	Rail	40-ton to 70-ton used nuclear fuel casks, rail coupling tests	Evaluates different railcar designs. Provides shock response spectra and single pulse representation. Evaluates heavy cargo. The railcars were equipped with either standard draft gear, hydraulic end-of-car draft gear, or a sliding center sill cushion underframe.
Prulhiere and Israel (1980)	Rail/Truck	TN 12 (110 tons)	Instrumented assembly inside a used nuclear fuel cask. Presents maximum acceleration values.
Magnuson (1982)	Rail	50-ton used nuclear fuel cask	Provides shock response spectra. Includes no equivalent pulse. Evaluates heavy cargo. Cask transported from Denver, CO to Albuquerque, NM.

Table 3-1. (contd)

Reference	Rail/Truck	Cargo	Comments
Dalziel et al. (1986)	Rail/Truck	32-MT truck cask and 68-MT rail cask (simulated)	Canadian Shock and Vibration Program consisted of: (a) road transportation field measurements of normal vibration and transients; (b) rail transportation field measurements of normal vibration, transients, and railcar coupling impact; (c) modal testing of the fuel transport containers; (d) impact and fatigue testing on irradiated fuel and unirradiated fuel; (e) analytical modeling of the road and rail transportation modes.
Glass and Gwinn (1986, 1989)	Truck	NuPac 7D-3.0 cask (15.7 tons) CNS 14-170 cask (18.5 tons)	Road simulator was used. Predictive analytical method was developed. Includes no shock response spectra or equivalent pulse.
Glass and Gwinn (1987, 1989)	Truck	TRUPACT-I (25 tons)	Acceleration-time signals were reduced to power spectral densities. These give the vibrational energy as a function of shock response spectra. Includes no equivalent pulse. The Type B package was evaluated.
Pujet and Malesys (1989) Cory (1991)	Rail/Truck	NTL 8/3 (36 tons) NTL 11 (80 tons)	Maximum accelerations at the trunnions presented. NTL 8/3 truck cask shipped from La Hague, France to Tihange, Belgium, 1600 km. NTL 11 rail cask shipped from Valognes, France to Wurgassen, Germany, 2360 km.
Gwinn et al. (1991)	Truck	CNS 14-170 (23.5 tons) CNS 3-55 (28.5 tons)	Peak accelerations, root-mean-square accelerations, and peak tie-down loads at various locations presented for various road events. Power spectral densities presented.
Source: Sanders et al. (1992)			

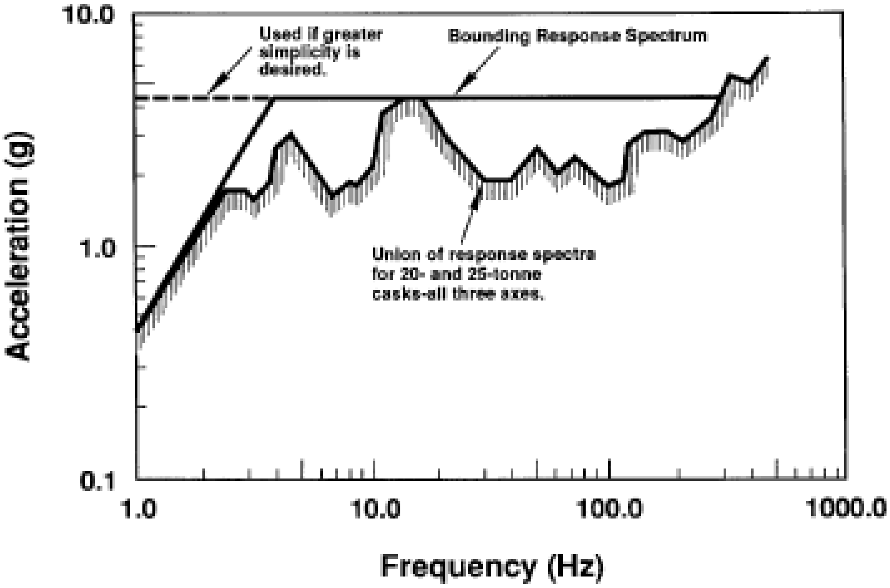

Figure 3-1. Truck Bounding Acceleration Shock Response Spectrum for 3% Damping on the Vertical, Transverse, and Longitudinal Axes (Sanders et al. 1992)

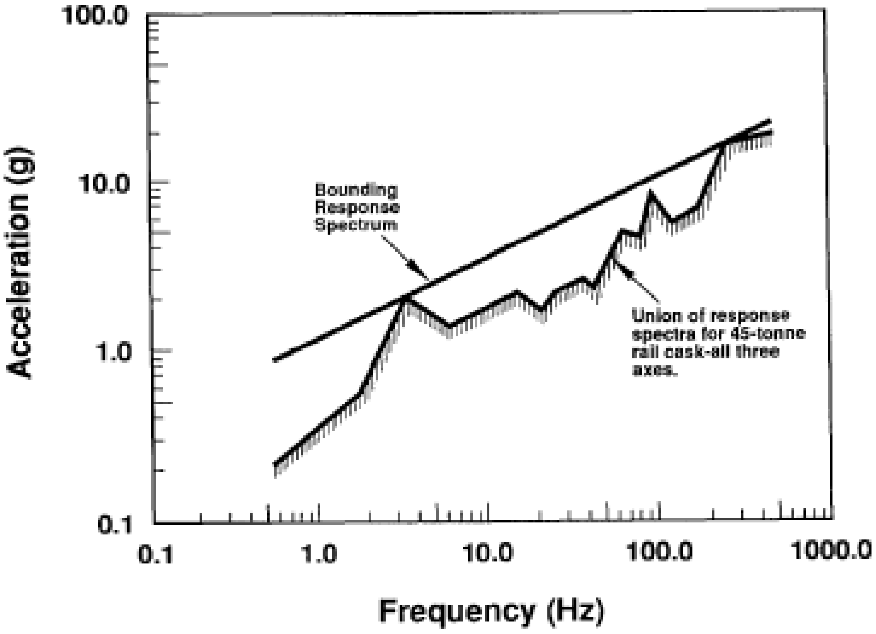

Figure 3-2. Rail Bounding Acceleration Shock Response Spectrum for 3% Damping on the Vertical, Transverse, and Longitudinal Axes (Sanders et al. 1992)

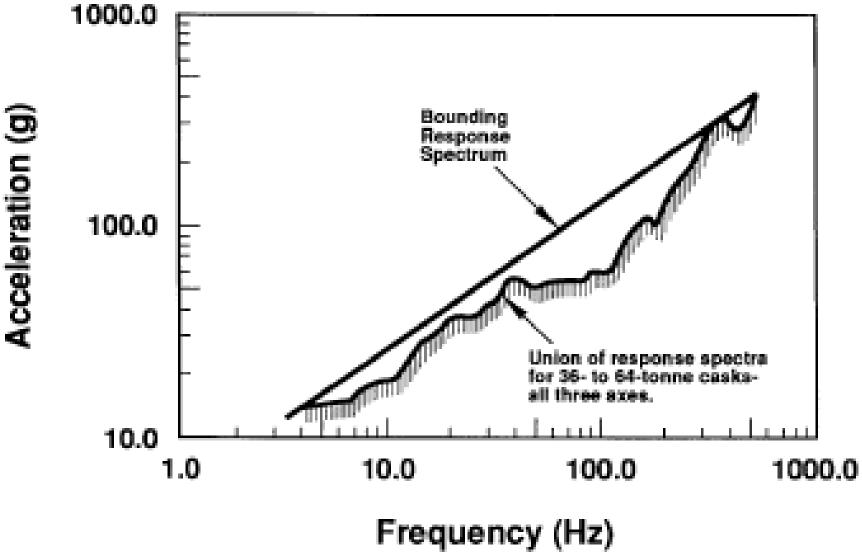

Figure 3-3. Rail Coupling Bounding Acceleration Shock Response Spectrum for 3% Damping on the Vertical, Transverse, and Longitudinal Axes (Sanders et al. 1992)

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