SHOCK AND VIBRATION MEASUREMENTS DURING NORMAL
RAIL AND TRUCK TRANSPORT*

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At the suggestion of Division of Construction, Headquarters AEC, the Union Carbide Corporation invited the Environmental Criteria Group of Sandia Laboratories to participate in a transportation test involving the transportation of a radioactive materials (RAM) cask from Paducah, Kentucky, to Oak Ridge, Tennessee, by railroad and the return to Paducah by truck. Sandia instrumented the vehicles and measured the shock and vibration inputs to the RAM cask. This paper reviews the conduct of the Sandia data experiments, describes the instrumentation, discusses the data reduction techniques used, and presents the resulting data in summary form. The summarized data provides a comparison of the intensity of the shock and vibration encountered in the rail and truck transport environments.

The main purpose of the Sandia participation was to obtain data to be used in applied research pointed towards developing descriptions of environmental inputs to cargo, and more specifically the following points:

1. To develop a more complete description of the rail transport dynamic environment than had theretofore been available.
2. To develop a description of in-transit rail transport shock as opposed to switching yard shock.
3. To provide additional information on the truck environment to supplement the results of prior work.

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4. To provide a means of comparison between environmental levels within the two modes of transport.

The rail shipment covered approximately five-hundred miles of varied terrain.

The truck shipment was approximately three-hundred miles in length. A team of Sandia engineers and technicians planned the experiment and carried it out. Data reduction and interpretation was part of the Sandia contribution. The instrumentation system was operated remotely from the cabooses of the trains involved, but directly from the cab of the truck. Piezo-electric accelerometers were employed to measure shock and vibration.

Summaries of the reduced data as well as the methods of data reduction are discussed. Summaries of the reduced data are presented in a form which permits comparison of the environments produced by rail and truck modes of transportation at the "input to cargo" interface.

When the variable dynamic characteristics of general cargo are considered in conjunction with these environment comparisons, the differences in the two modes of transport are found not to be significant from a shock and vibration standpoint.

FOREWORD

The Oak Ridge Nuclear Safety Information Center Cask Designer's Guide (ORNL-NISC-68) indicates that no description of the vibration and shock normally incident to transport of radioactive materials is described in Annex I of AECM 0529.

This paper is the record of an attempt to quantify the nature and magnitude of the normal vibration and shock environment incident to rail and truck transport. The authors hope this paper will be useful as an estimate which can be used by designers of casks and tiedown systems, and by those who are attempting to establish test criteria for general cargo systems.

INTRODUCTION

In the spring of 1968, Sandia Laboratories Criteria and Heat Transfer Division 1543 participated in a program to measure the dynamic (shock and vibration) environment of a shipment which was being transported by rail from Paducah, Kentucky to Oak Ridge, Tennessee, and returned to Paducah via truck. The cargo was a laminated uranium Fuel Element Shipping Cask and Tiedown System which had been developed by the Nuclear Division of Union Carbide Corporation at Paducah.^(1, 2) A portion of the Union Carbide cask development effort required subjecting the cask tiedown system to shipment by rail and truck. It was suggested by the Division of Reactor Development and Construction, Headquarters, AEC, that the Environmental Criteria Group, Sandia Laboratories, had, in addition to a capability for making measurements of the dynamic shipping environment, a number of other, in-house uses for the type of data that could be obtained. As a result, an invitation to join in the test was issued by Union Carbide and accepted by Sandia.

Operation of an AEC/DOD Environmental Data Bank is a primary function of the Sandia Environmental Criteria Group.⁽³⁾ Data deposited in the Bank is obtained by various means including direct measurement. The work reported in this paper is the result of such a direct-measurement activity. In addition to the primary purpose of providing a description of the dynamic environment of the trip for the Data Bank, the following complementary objectives concerning the data were satisfied during the program.

1. Measurement of the rail and truck transport environment under identical loading conditions and with identical instrumentation.
2. Measurement of the rail transport environment using more precise techniques and sophisticated instrumentation than had been utilized in previous work.
3. Further measurement of the truck transport environment to supplement other truck environment measurement work.

TEST PLANS

Activity Assignments

Discussions with Union Carbide personnel resulted in a division of assignments in the general conduct of the transportation program. Union Carbide provided the following:

1. Cargo (cask and tiedown system).
2. Railcar and truck modified as necessary to accommodate cask and tiedown system.
3. Space to work and assistance to Sandia personnel in setting up instrumentation.
4. Arrangement with the carriers for cooperation as required to carry out the joint test program.
5. Arrangements for on-board transportation of Sandia personnel during the actual testing.
6. The packaging and shipment of instrumentation to Albuquerque at the conclusion of the program.

Sandia Laboratories: (1) Provided, installed, maintained, and operated environment-measuring instrumentation, and (2) reduced, interpreted, and reported on data obtained. Each organization separately funded the costs of its activities and personnel.

Preliminary Joint Plans

A preliminary joint plan was developed during early discussions. The first portion of the shipment would be by rail. The railcar would be a flat car belonging to Union Carbide. The cargo system would be loaded and the environment measuring instrumentation mounted, checked, and calibrated at the Union Carbide plant in Paducah, Kentucky. Movement from that point to railroad switching yards would be unattended. Shock/vibration environment encountered within switching yards, including

normal switching of the car, would be recorded. Movement from Paducah to Louisville, Kentucky would be accompanied by Sandia personnel and recordings made of shock/vibration produced by notable events enroute. Movement on the railroad from Louisville to Corbin, Kentucky, and from Corbin to Knoxville, Tennessee, would be accompanied by Sandia personnel and additional environment recordings made. Movement from Knoxville to Oak Ridge, Tennessee, would be unaccompanied.

Upon arrival at Oak Ridge, the car would be routed to the Union Carbide Y-12 plant, the cargo removed from the car and reinstalled on a flat-bed trailer. Environment measuring instrumentation used on the railroad car would also be transferred to the trailer and the cargo hauled over the road back to the Union Carbide plant at Paducah. Sandia personnel would accompany this shipment and record shock/vibration produced during truck transport events.

Sandia Test Details

Guidelines

Sandia activity in conjunction with the Union Carbide shipment consisted of determination of the kinds of events which should be measured, determining the shock and vibration parameters which we needed to measure in order to make a description of the transportation environment more complete and utilization of the capabilities of our data recording equipment to its fullest extent during the actual shipment. Several guiderules were established in the planning:

- a. Measurements taken would provide a statistical sample of shock/vibration produced by various events in each mode of transport.
 1. The entire rail trip route would be investigated before making the shipment to determine the events to be sampled in transit.
 2. Truck events measured would be according to a list of events developed in prior truck tests.

- b. As many locations on the vehicle and cargo as possible would be instrumented but the key locations evaluated would be those which described the "input to cargo" interface of the vehicle/cargo systems.

Event Sampling Determinations

The preliminary survey of the proposed rail route showed six events were significant from a shock/vibration standpoint. The events checklist used in the instrumented test was as follows:

1. Run-in/run-out shock
2. Crossing bridges
3. Traversing tunnels
4. Crossing of switches
5. Crossing of other tracks
6. Switching yard activity

In a prior, more extensive truck test program, ⁽⁴⁾ seventeen events, characterized for the most part as road types were determined to be significant from a shock or vibration standpoint. The events checklist used in this test, based upon this prior work, was as follows:

1. Accidents/Incidents
2. Unpaved Road
3. Hills (climbing)
4. Hills (descending)
5. Paved Detours
6. Overpasses
7. Concrete Interstate Roads
8. Parking Lot Maneuvers
9. Asphalt Interstate Road

10. Bumps
11. Blacktop Over Concrete, Two-Lane
12. Railroad Crossings
13. Bridges
14. Concrete Two-Lane Road
15. Blacktop Two-Lane Road

Instrumentation

The rail car used was USAX38655. The loaded car is shown in Figure 1.

The cask was positioned at the center of the car and tied down by tie rods through the floor to the car frame and to plates which had been welded to the car frame. These are shown in Figure 2. The instrumentation was placed on the aft end while the forward end of the car was occupied by auxiliary equipment relating to the cargo.

The transducers were located in positions considered to give a complete picture of the dynamic environment.

The accelerometers were located on the forward tie down plate. Five accelerometers and a pressure transducer were mounted to monitor the cask and its skid. The pressure transducer is shown in Figure 3 as is the triaxial accelerometer group on the skid floor. A vertical accelerometer was mounted on each trunnion plate as may be seen in Figure 3.

Upon reaching the terminus of the rail transport demonstration test at Oak Ridge, Tennessee, the Union Carbide cask was transferred to a flatbed tractor-trailer rig for the demonstration test return trip by truck to Paducah, Kentucky.

Figure 4 shows the completely instrumented truck. The battery power supply and recording system are located ahead of the cask. The remote control lines to the truck cab were led from the recorder into the window of the truck cab. Note the location of a large C-clamp, mounted on the fifth wheel support of the trailer, near the spare tire.

This clamp mounted a triaxial accelerometer cluster at this point. This cluster was used by the instrumentation operator in the truck cab to estimate visually the accelerations being encountered in transit.

Figure 5 shows the equipment available to the instrumentation operator in the truck cab. From left to right are:

1. Monitoring device for the accelerometers near the fifth wheel.
2. Voice microphone input to tape recorder on truck.
3. Control box for recorder system on truck.
4. Hand-held tape recorder for additional commentary, and
5. Checklist of events to be sampled.

Performance of Environment Measurement Tests

Rail Tests

The rail car containing the Union Carbide cask tiedown system and Sandia instrumentation was moved to the switching yards of the first railroad to be used. Sandia engineers met the car at the switching yards, where switching shock measurements were taken.

Through the cooperation of railroad personnel, a number of events were recorded. The procedure used was for the Sandia engineer observing the events being performed to activate the recorders by radio signal just prior to impact, and to place a code number on the tape after the event, also by radio control. At the same time, another Sandia engineer made a running commentary about the event on a hand-carried tape recorder, and also recorded the event code number. This made possible the correlation of test data with event data during data reduction efforts.

After switching yard activity was completed, the instrumented car was spotted on the trip train immediately ahead of the working caboose. The Sandia test group was housed in an additional caboose immediately ahead of the test car. The test group included the Project Test Engineer and an instrumentation technician, both from Sandia, and a travelling engineer from the participating railroad. This engineer was very well acquainted with the route. His assistance was invaluable, particularly during the night, in pinpointing locations where data measurements were to be taken.

The car was attached to three different trains during the trip. The length of the trains varied from 65 to 120 cars. On one leg of the trip, the terrain was such that run-ins were essentially absent. On other legs, even though the trains were handled with great skill, run-ins were not eliminated completely. We found that many normal events encountered in rail transport tend to occur regardless of operator skill, due to such things as train condition, train length, roadbed conditions, and the topography. The route used covered approximately 500 miles.

Truck Tests

Following installation of the cask and instrumentation on the truck, the load was returned by highway to Paducah, a distance of approximately 300 miles.

One incident measured during this truck trip was an outgrowth of tornados and heavy rains in the area during the trip. Streams and rivers were running quite high and at one location, a stream had overrun its banks at a bridge crossing. The approach to the bridge was flooded to a depth of several feet, for a distance of 50-75 yards.

Upon entering this flooded roadway, a definite "floating" effect was experienced and the side pressure of the flood waters tended to force the truck off the road bed. (An overturned tractor-trailer van which had been caught in the flood crest some time earlier could be seen about 100 yards downstream.)

From a shock/vibration standpoint, the data sample obtained during this event indicated it had no shock/vibration significance. (It might have, however, had the vehicle overturned.)

With regard to bumps encountered and crossing railroad tracks, since this test was to duplicate "normal" events, bumpy areas were traversed at slow speeds, and railroad tracks were crossed slowly after coming to a full stop. Upon completion of the normal trip, however, some special high speed runs over bumps and railroad crossings were made.

Upon arrival at the Union Carbide plant at Paducah, the cask/tiedown system was examined by Union Carbide personnel, internal cask pressure was checked, and Union Carbide determined their normal transit test had been successful.

Data Reduction

Data reduction was accomplished in five steps:

1. Composite oscillograph playback
2. Bandpass oscillograph record playback
3. Calculation of shock spectra from acceleration time histories
4. VIBRAN reduction
5. VAIL combinations

The composite playback is a real-time oscillograph analog record of the data. Playback was through a 2 kc low pass filter. The playback was examined to determine whether data had been obtained, and which data sections could be considered for further detailed reduction. The second step was to take the sections where more detailed data reduction was warranted and display them on a bandpass oscillograph playback record. Examination of bandpass records permitted the choice of still shorter time segments containing the most representative acceleration amplitudes for detailed computer analysis. Certain specific events were reduced in shock response spectrum form. These were events in which a very short burst of shock-like high amplitude was found. The other events

were reduced in VIBRAN form. This VIBRAN operation resulted in a statistical presentation of acceleration amplitudes that were present within certain frequency bands (see Figure 6). Each number shown within a frequency band represents the percentage of acceleration peaks which reached the level shown on the ordinate. The program additionally computes the RMS acceleration amplitude for each frequency band, computes the overall (Broad Band) RMS acceleration amplitude and reports the total number of peak acceleration amplitudes that were counted in the sample. As a next step, the VIBRAN records for each event sampled were combined in the VAIL program. This computer program permitted the combination of all VIBRAN events in a summary form containing the same type of information as the individual VIBRAN events records.

For this paper, the VAIL program summarized the data samples obtained from each event at the "input" to cargo location on the vehicles for each of the three axes of the vehicle. This reduces all the vibration data taken in these tests to six statistical data presentations of the vibration environment experienced in the Union Carbide shipping program.

Summary of Results

General

A brief synopsis of the measurement program results was given by Clifford ⁽²⁾ in his paper at the Second International Symposium. The data herein is an amplification which provides more detailed descriptions of the environments.

Shock

Rail Test Results. -- Rail transit imposed shocks upon the cargo from various events. The most severe shocks were found during switching and coupling activities associated with shunting cars in yards and making up trains. The shocks measured during this test (on the order of 2-5 mph)

have a very high probability of occurrence (0.95); they should be considered as happening during every rail journey. Shocks measured during this test are shown in shock response spectrum envelopes in Figure 7. Shock response spectra are, in essence, predictions of the reaction of cargo systems having various natural frequencies to the input accelerations or shocks which are being considered. In Figure 7 for instance, the lowermost rail spectrum (crossing railroad tracks and switches) indicates that a cargo system with a natural frequency of 10 Hz will respond with a maximum 1 g peak acceleration to this type of event. However, if the natural frequency of a cargo system is 100 Hz, a response approaching 6 g's may be expected. The spectrum was reduced from data taken during the crossing of railroad tracks that were laid at 90° to those on which the test car was running. Speed was approximately 45 mph. The upper rail spectrum was obtained during a normal speed coupling event with the test car coupled to the engine. The car then was coupled to another car at a speed estimated at 3 mph.

While in motion, the responses of the car to shocks induced by run-in, run-out, crossing other tracks and switches show the following characteristics:

1. Regardless of the original direction of the input shock, in the lower frequencies (1-3 Hz) the response amplitude is higher in the transverse axis than in the other axes.
2. Regardless of the original direction of the input shock, in the frequencies above 30 Hz the response amplitude is higher in the vertical axis than in the other axes.

Truck Test Results. --The events which were found to produce the highest shock damage potential in the truck transport test were encounters with bumps, dips, or potholes and crossing railroad tracks at high speeds.

In general, bumps and potholes appear to produce the most severe overall conditions for cargo systems in truck transport, but the recurrent shock event, crossing railroad tracks, appears to have a higher damage potential for cargo having natural frequencies above 15 Hz than below 15 Hz. In all events measured, the vertical axis of the truck produced the highest damage potential amplitudes.

The composite truck cargo damage potential spectra for shock are shown as Figure 8.

Vibration

Rail Tests. --The vibration records obtained in the rail portion of the test tended to reinforce the results of previous work. Earlier work with less sophisticated equipment has shown few vibration amplitudes higher than 1 g. The present work had the same results. However, in the two frequency bands in which the highest amplitudes are found, the 0-5 Hz and 5-10 Hz bands, the data cannot be considered in the same manner as the data above 10 Hz. An analysis of the amplitude distribution within these low-frequency bands shows no resemblance to vibration-like distributions. It appears that a substantial number of the peaks in these bands are the result of recurring transient impulses rather than steady state vibration. If the frequency bands from 0-10 Hz are disregarded, the vibration levels are, without exception under 0.72 g in amplitude.

The data obtained were combined into summaries by program VAIL. When combined, the total number of peaks counted in each frequency band ranged from 2500 in the low frequency band to more than 75,000 in the high-frequency band. As a result, the amplitude distribution within each band may be treated statistically. Analysis of the distributions, except in the lowest two bands indicates that the distribution resembles a Gaussian one.

The 99 percent level was calculated for each frequency band. The result is displayed in Figure 9. It is noteworthy that in all bands, the amplitudes of the peaks in the vertical axis were higher than those in the other axes. In general, the transverse axis shows higher levels than the longitudinal, although in the frequency bands between 20 Hz and 60 Hz this general order is reversed.

Truck Tests. --Vibration data for the truck portion of the test was treated in the same manner. Here again, the lower (0-10 Hz) frequency bands show a high proportion of intermittent, shock-like inputs, but the rest of the data has a distribution which resembles Gaussian random.

Figure 10 is a representation of the 99 percent level of the vibration measured. The vertical axis once again predominates. In general, the longitudinal axis is second in amplitude, although in the bands between 10 and 45 Hz, the transverse axis shows higher values. In the 60 to 87 Hz band, the longitudinal and transverse axes are equal in amplitude.

Comparisons of Truck vs Rail Transport

The comparisons that we made indicate that while the dynamic environments of rail and truck transport in this test differ in precise detail, the overall environment input to cargo differs little.

Figure 11 compares two typical shock spectra envelopes. During transit, the rail shock switching spectrum indicates there is a lower shock response damage potential for cargo having natural frequencies of 3-25 Hz than that generated by the truck when it is in transit. At 25 Hz, however, the rail shock response damage potential spectrum becomes higher than the truck spectrum and maintains that position for the rest of the record. The events from which these spectra were derived are normal and may be encountered often in the course of a trip.

If one considers, that for the most part, massive cargo such as RAM containers with their tiedowns tend to have natural frequencies from 3-60 Hz, neither mode offered a distinct advantage from a shock standpoint in this test.

Figures 12 through 14 are comparisons of rail and truck vibration in each of three axes. In both modes, the vertical axis predominates. It is evident that in many frequency bands, there is little difference. It should be reiterated that the data below 10 Hz reflect, to a large degree, recurrent, shock-like impulses for these modes of transport rather than vibration. In this area, the shock spectra referred to above provide the better comparison.

In the transverse and longitudinal axes, again there is little to choose between rail and truck transport. The levels in general are quite low, rarely higher than 0.1 g.

Conclusions

The shock and vibration environment produced in rail and truck modes of transport on an identical cargo/tiedown system were measured and quantified. Comparisons of data for each mode in this test indicate no distinct difference was offered by either mode with regard to normal environment intensities encountered.

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D70-1482

Figure 1. Rail Car - Instrumented

D70-1480

Figure 2. Tiedown Plate - With Instrumentation - Rail Car

D70-1478

Figure 3. Cargo Instrumentation - Rail Car

D71-3137

Figure 4. Tractor-Trailer, Instrumented

D71-3138

Figure 5. Tractor Cab - With Instrumentation

LOC-FWD TIE PLATE AXIS-VERT												
ACCELERATION 0 TO PEAK G	PEAK DISTRIBUTION IN PERCENT											OVERALL RMS 0.15
1.400												
1.000												
0.720												
0.520												
0.370												
0.270	4.76											
0.190	1.90 15.87 0.32 0.23 0.24											
0.140	2.75 16.78 4.65 1.39 0.55											
0.100	4.65 18.59 13.41 3.01 1.03 0.21 3.24											
0.072	0.51	12.05	14.06	20.19	6.72	3.17	2.91	27.18	0.09			
0.052	0.00 0.51 3.33	12.05	13.15	17.77	13.79	9.26	5.29	36.96	0.15			
0.037	3.00 0.51 22.22	26.85	7.71	11.43	20.05	14.33	13.90	19.91	6.33			
0.027	15.00 2.02	27.78	13.53	3.85	11.63	17.50	17.97	15.27	6.17	12.13		
0.019	20.00 22.73	19.26	12.05	2.04	7.59	14.83	17.34	23.71	3.71	12.19		
0.014	20.00 25.25	11.11	5.07	1.36	5.17	9.73	12.99	15.91	1.29	14.24		
0.010	19.00 29.29	5.19	3.38	0.91	2.26	6.84	10.77	10.41	0.63	16.50		
0.000	17.00 19.19	11.11	5.71	0.91	5.17	5.91	12.35	12.79	0.90	38.36		
FREQUENCY BAND=CPS	0 5	10	20	30	45	60	87	125	175	250	350	475
	5 10	20	30	45	60	87	125	175	250	350	475	625
RMS LEVEL	0.03	0.02	0.02	0.05	0.10	0.05	0.04	0.03	0.02	0.05	0.01	
TOTAL PEAKS	100	198	270	473	441	619	863	1263	1892	2561	3272	

Figure 6. Typical VIBRAN Record

Figure 7. Shock Spectra Rail Envelope Comparison

Figure 8. Shock Response Spectra Envelopes, Truck Transport Events, High and Low Encounter Speeds, All Three Axes

Figure 9. Rail Vibration Summary - 99 Percent Level

Figure 10. Truck Vibration Summary - 99 Percent Level

Figure 11. Shock Response Spectra Comparison - Normal Transportation Events - Envelopes of Three Axes

Figure 12. Truck-Rail Vibration Summary Longitudinal Axis

Figure 13. Truck-Rail Vibration Summary Transverse Axis

Figure 14. Truck-Rail Vibration Summary Vertical Axis