An Evaluation of Current Regulations and Real Accident Conditions*

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ABSTRACT

In order to improve estimates of the effectiveness of current regulatory standards, a program was initiated by the U.S. Nuclear Regulatory Commission (NRC) to have the Lawrence Livermore National Laboratory (LLNL) evaluate regulatory standards against real world accident conditions. This paper presents the results of the evaluation performed for the hypothetical 30 foot drop onto an unyielding surface and real world impact conditions which might be experienced by a spent fuel cask being transported by a truck. The results of the evaluations performed for other pertinent accident conditions for truck and train transport will be documented at the conclusion of the program.

INTRODUCTION

Casks used for the transport of spent fuel in the United States are licensed under the regulatory standards contained in 10 CFR 71.[1] As part of the licensing process, all activities related to the design, fabrication, and use of casks are documented in a Safety Analysis Report (SAR) and conducted under a quality assurance program, both of which must be reviewed and approved by the U.S. Nuclear Regulatory Commission (NRC). All casks are designed and shown by test and/or analysis not to leak under the test conditions and containment requirements specified in 10 CFR 71. Questions have recently been raised about the suitability of the current test conditions and containment requirements to cover a wide range of real accident conditions with the related potential release of radioactive materials.

In 1984, a program was initiated by the NRC requesting the Lawrence Livermore National Laboratory (LLNL) to evaluate and document the level of protection provided by spent fuel casks designed to current regulatory standards if they were subjected to severe accident conditions during truck or rail transport. A two stage screening process was used to assess the effectiveness of current standards and to evaluate the protection provided by the casks.

The first stage involved a selection of loading parameters associated with real world accident scenarios, and a comparison with those associated with the test conditions specified in 10 CFR 71. The intent of this first stage process was to identify those real world accident scenarios for which the integrity of spent fuel cask could be readily assured. For those accident scenarios not initially screened out, the second stage screening process involved an assessment of the scenarios' probability and potential consequences in terms of the expected magnitude and characteristics of any potential radioactive source that could be released. The scenarios whose probability and radioactive source have been addressed adequately by the assessments in NUREG-0170 would be identified.[2] If any scenarios result in consequences which exceeded those estimated in NUREG-0170, the critical assumptions and uncertainties involved in the assessment would be highlighted. The potential benefits, uncertainties, and costs of performing a more precise assessment of the cask integrity when subjected to nonscreened scenarios would also be addressed.

This paper summarizes the evaluations performed in assessing the hypothetical test conditions of a cask dropping 30 feet onto an unyielding surface with the impact forces which could potentially be experienced by truck casks in real world accidents. The evaluations performed in assessing regulatory standards with respect to other potential accident conditions will be reported later in a NUREG at the conclusion of the current NRC program.

ACCIDENT LOADING PARAMETERS

While severe accidents may be characterized by fatalities, injuries, property damage, transportation equipment damage, or a combination of these consequences, we have defined the severity of an accident in terms of the magnitude and frequency of loading parameters which could be experienced by a spent fuel cask. Impact forces which could be experienced by a spent fuel cask will depend on the impact velocity and the impacted target. The targets may be either objects such as autos and trains or surfaces such as roadbeds and embankments.

For potential accidents in which the cask impacts any target, the magnitude and frequency of the impact velocity have been estimated from truck accident velocity data. This estimate conservatively disregards the fact that a reduction in impact velocity occurs due to energy absorption by the transporting vehicle. Table I summarizes the frequency of involvement of California truck/semitrailer drivers in fatal and injury highway accidents as a function of accident velocities for the years 1958 through 1967. This accident data was derived from the California Highway Patrol's (CHP) annual report on fatal and injury motor vehicle traffic accidents for the years 1958 through 1967.[3] This data represents only a sample of truck/semitrailer drivers involved in fatal and injury accidents and their estimated accident velocity. This data does not represent the total number of fatal and injury accidents involving truck/semitrailers nor does it represent the total number of truck/semitrailers involved in fatal and injury accidents. Furthermore,

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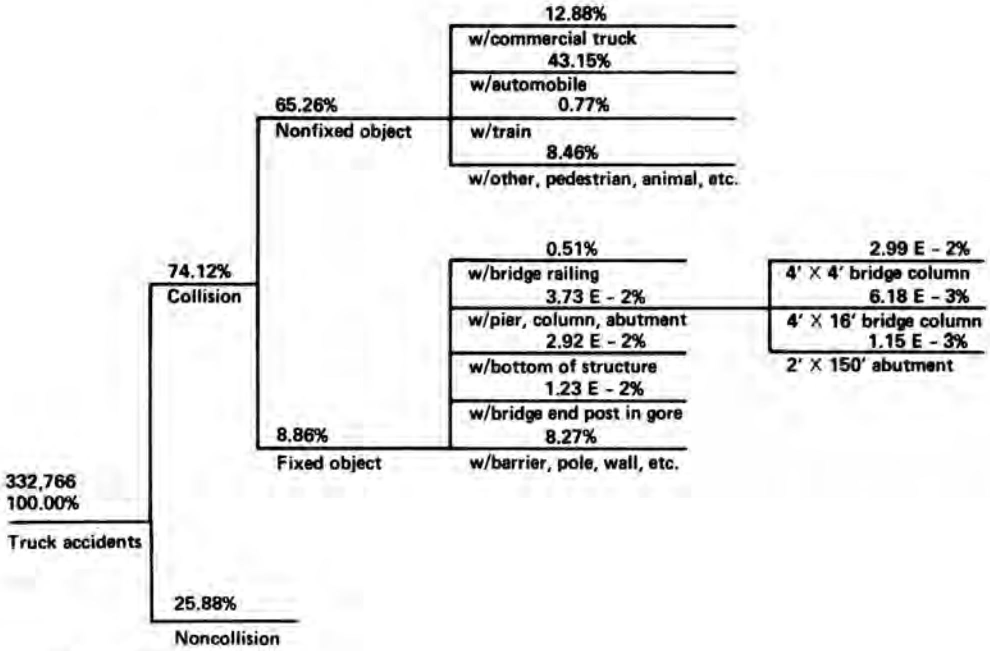


Fig. 1. Truck collision frequencies.

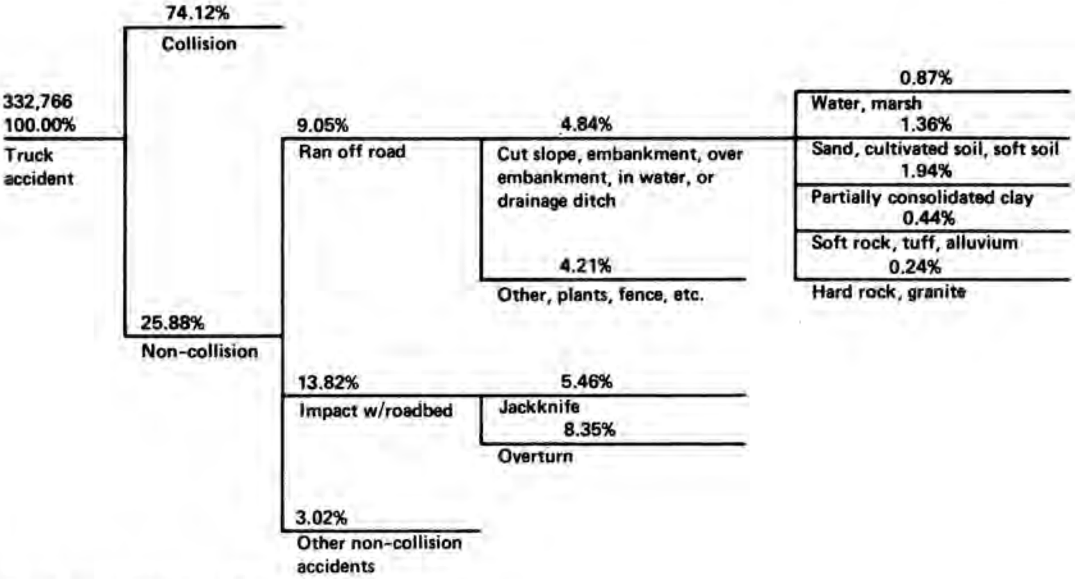


Fig. 2. Truck noncollision frequencies.

the velocities listed in Table I are the estimated velocities prior to the accident. Using the velocities listed in Table I is conservative because the impact velocity is usually reduced by the effects of braking, skidding, evasive maneuvers, etc.

For potential accidents in which the cask is struck by a train, the magnitude and frequency of the impact velocity have been estimated from railroad-highway grade crossing accident and incident velocity data. Table II summarizes the railroad-highway grade-crossing accidents and incidents involving motor vehicles as a function of train velocity for the years 1975 through 1982. This accident data was derived from the Federal Railroad Administration's (FRA) annual report on Rail-Highway Crossing Accident/Incident and Inventory for the years 1975 through 1982.[4] Accidents are defined by the FRA as any occurrence involving the operation of railroad on-track equipment (standing or moving) which results in damage to railroad equipment greater than the dollar damage threshold limit. Incidents are defined similarly by the FRA except that damages to railroad equipment must be less than the dollar damage threshold limit.

TABLE I

California 1958-67
Truck/Semitrailer Drivers
Involved in Fatal and Injury Accidents

Speed, km/h	Number	DSCRT %	CML %
Zero	1774	6.41	6.41
0 - 16	4143	14.96	21.37
17 - 32	4122	14.89	36.25
33 - 48	4248	15.34	51.59
49 - 64	4733	17.09	68.69
65 - 80	7264	26.23	94.92
81 - 96	1173	4.24	99.15
97 - 112	171	0.62	99.77
>112	63	0.23	100.00
Subtotal	27691	100.00	—
Not stated	2834	Excl	Excl
Total	30525	—	—

Table II

1975-82 Rail-Highway Grade-Crossing
Accidents/Incidents Involving Motor Vehicles
By Train Speed

Speed, km/h	Number	DSCRT %	CML %
0 - 15	27553	33.79	33.79
16 - 31	16765	20.56	54.35
32 - 47	14611	17.92	72.47
48 - 63	10788	13.23	85.50
64 - 79	7617	9.34	94.84
80 - 95	2879	3.53	98.37
96 - 111	824	1.01	99.38
112 - 127	461	0.57	99.94
128 - 143	29	0.04	99.98
>143	17	0.02	100.00
Subtotal	81544	100.00	—
Unknown	573	Excl	Excl
Total	82117	—	—

Data from several sources were collected and combined to estimate the frequency of impact of a cask with a particular target. The combined data is summarized in Figs. 1 and 2. The target frequency was primarily based on truck accident data documented in the Bureau of Motor Carriers Safety (BMCS) annual reports for the years 1973 through 1983.[5] The BMCS data is divided into collision and noncollision accidents.

The collision accident frequencies with moving objects such as trucks, autos, and trains (as compiled from the BMCS data) are summarized in Fig. 1. The BMCS accident data did not classify collisions with fixed objects, even though they ranged from stop signs to bridge columns. To classify these objects, highway accident data for objects struck along state and interstate highways were obtained from the California Department of Transportation (CALTRANS) for the years 1975 through 1983.[6] Those objects in the CALTRANS survey judged to be fixed objects were tabulated and a frequency calculated for each fixed object class. These frequencies were then applied to the fixed object collision accidents in the BMCS data to estimate the number of accidents involving each fixed object class. Since collision accidents involving piers, columns, and abutments may incur significant damage to a spent fuel cask, a survey was performed by a subcontractor to differentiate between the various sizes of piers, columns, and abutments along state and interstate highways.[7] Again, a frequency was found for each pier, column, and abutment size subclass and applied to the number of collision accidents involving piers, columns, and abutments estimated from the CALTRANS data.

The noncollision accidents including rollover, jackknifing, and running off the road are summarized in Fig. 2. The accident subcategory judged to have potential damage consequences to a spent fuel cask was the "ran off road" accident which ended up impacting a cut slope or embankment or going over the embankment because of the possibility of hitting hard rock such as granite. An estimate of relative abundance of soil and rock types in the United States was taken from Ref. 8. These relative abundances of soil and rock types were applied to the cut slope, embankment, and over embankment subcategory.

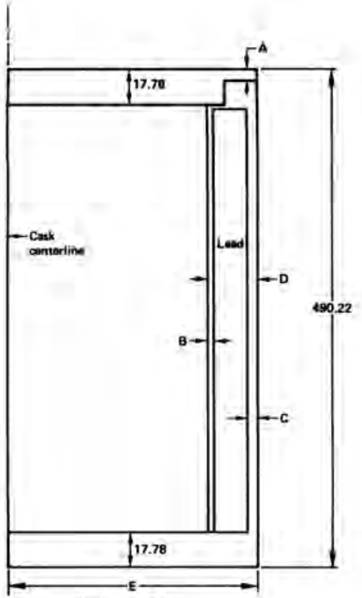
IMPACT ANALYSIS

Accident impact forces that might occur on a spent fuel cask were calculated and screened against the forces calculated from test conditions in 10 CFR 71. One of the test conditions in 10 CFR 71 requires a cask to withstand a drop of 30 feet onto an unyielding surface and to contain its contents within specified limits of radioactive release. Currently, licensed casks have been analyzed in their SARs for hypothetical impact loads which vary in the range of 30 to 260 g's or 8-160 million Newtons. The resulting impact force depends on the cask size, design, materials of construction, and type of impact limiter used.

Based on static evaluations of simplified cask designs which were similar to those licensed, two generic lead cask designs, one truck and one rail, were selected for the screening evaluations. The two designs were selected because they were representative of existing lead cask designs and the static evaluations indicated that uranium and steel casks designs would suffer significantly less damage for the same velocity impacts and targets. The pertinent materials and dimensions used in the cask analysis are shown in Fig. 3. The structural material is 304 stainless steel. The lead shielding is conservatively assumed to be unbonded and to have the material properties derived in Ref. 9. A balsa wood limiter is attached to absorb the cask energy for the regulatory drop. The cavity of the cask is inerted with helium or nitrogen in accordance with current practice.

Four limit states are defined as follows to indicate increasing levels of damage and radiation hazards for the cask.

1. The first limit state is a stress less than or equal to the yield strength for all of the structural materials in the cask. This limit assures



Dim	Truck cm	Rail cm
A	3.81	7.62
B	1.27	3.81
C	3.18	6.35
D	17.78	19.05
E	34.93	95.25

All material is 304SS except that noted otherwise

Fig. 3. Generic lead truck and rail casks.

that the 10 CFR 71 containment requirements will not be exceeded.

2. The second limit state is defined to be a stress condition slightly above the yield strength for the cask flange and/or closure bolts. This limit state assumes that the closure seal fails and gaseous radioactive contents can be released. Limited lead slump may also occur.

3. The third limit state is a stress at or near the ultimate stress state as defined by the ASME code for any of the structural components except the closure bolts. Beyond this limit, failure of the containment may occur followed by limited aerosol releases of radioactive materials. Severe lead slump may also occur.

4. The fourth limit state is defined to be a stress condition at or near the ultimate stress state as defined by the ASME code for the closure bolts. Beyond this limit, the closure may be lost and portions of fuel assemblies may be released from the cask. This state was never reached in our evaluations.

The steps used to perform the screening processes for the truck cask against 10 CFR 71 and NUREG-0170 are illustrated in Fig. 4. As previously discussed, the real world accident force loadings of importance were determined to be the accident velocities summarized in Tables I and II and the targets identified in Figs. 1 and 2. Static force evaluations were then performed to screen out low resistance objects which cannot produce significant damage to the casks, even at high impact velocities. As illustrated in Fig. 5, ultimate force-deflection characteristics were calculated for objects potentially impacted and compared to the force required to statically yield a truck cask. As an example, an automobile completely collapses in the axial direction at static forces greater than 200 thousand Newtons; whereas, the cask only starts to yield in the axial direction at forces in excess of 22 million Newtons. Since the force required to crush the automobile is significantly lower than that required to yield the cask, the automobile was screened out. Stronger and more massive objects such as trains, bridge columns, abutments, and real surfaces such as roadbeds were not screened out at this stage but were subsequently evaluated dynamically for impact with a generic cask.

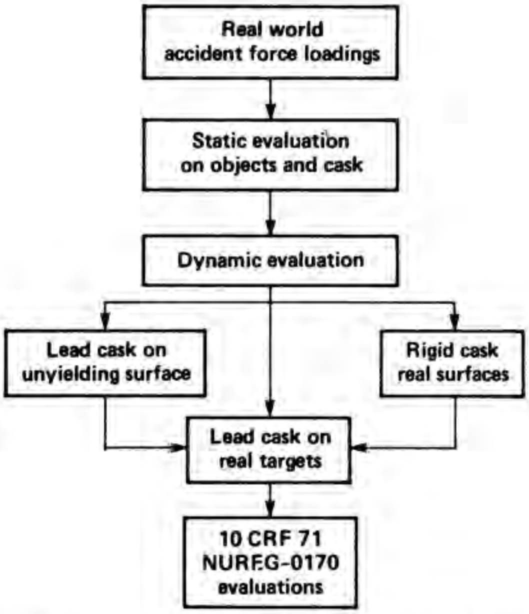


Fig. 4. Steps used to perform the two screening processes.

The cask impact calculations were performed using the DYNA 2/3D family of computer codes which were developed at LLNL. The DYNA codes use finite element analysis techniques to calculate the elastic-plastic dynamic response of impacting solids. To facilitate the evaluation of cask impacts over a range of velocities with several targets the following approach was used:

1. The generic truck cask without impact limiters was dropped onto an unyielding surface at increasing heights to obtain the structural response of the cask under increasing impact loads. The resultant interface impact force and effective plastic strain for the cask inner wall are plotted in Fig. 5 as functions of drop height for an end on drop. Lead slump which occurs is also plotted. The first three limit states for the cask are identified in Fig. 6. Cask drops greater than 36 meters resulted in impact forces greater than 380 g's and significant damage to the cask inner wall.

2. A rigid cask was dropped onto real surfaces that covered a range of soils and rocks for heights up to 140 meters. The interface impact forces are plotted in Fig. 7 for five different surfaces. The interface impact forces for the generic cask impacting an unyielding surface are also shown in Fig. 7 for comparison. The damage that might occur to a generic cask impacting a real surface was estimated to be equivalent to that calculated for the generic cask impacting an unyielding surface for the same impact force. Based on this equivalent damage technique, it may be concluded that soft soils represented by soft clay and sandy

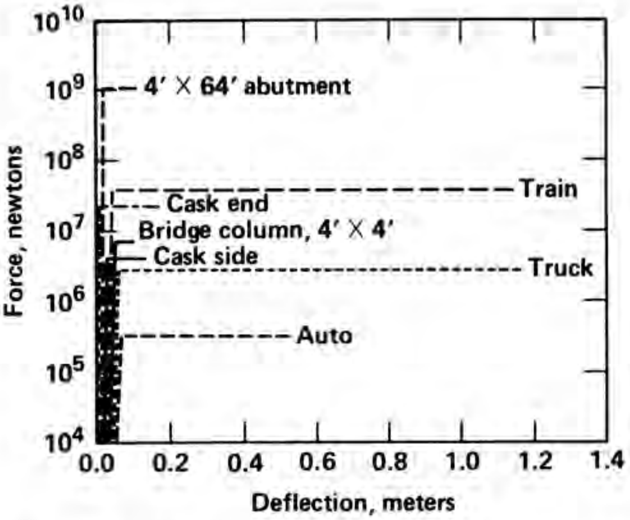


Fig. 5. Static force comparison with cask.

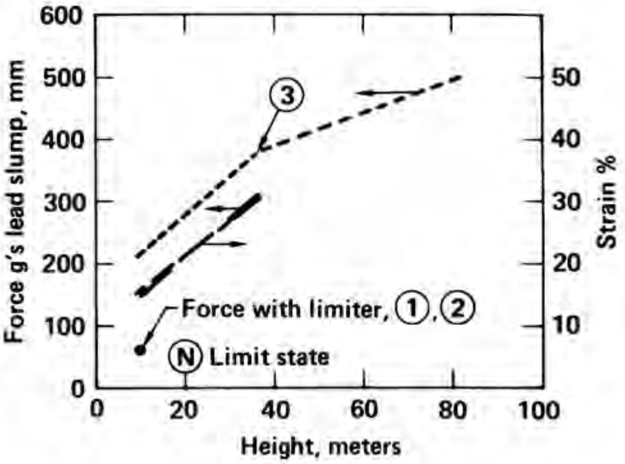


Fig. 6. Truck cask drop onto unyielding surface.

silty clay cannot cause significant damage to the cask even at heights up to 140 meters. Damage beyond the first and second limit states occurs to the cask for drops over 10 meters onto hard soil represented by rockfill and soft rock represented by concrete. For all practical purposes, hard rocks such as granite appear to be an unyielding surface to the cask. An improved material model for rocks and concrete which includes fracturing was recently incorporated into DYNA. Additional calculations are being performed and the resultant loads on rock and concrete are expected to be reduced.

3. The generic lead truck cask was dropped onto a concrete target to obtain the structural response of the cask. The impact forces, strains, and stresses were compared with those estimated using the equivalent damage technique. The comparison showed that the equivalent damage technique is conservative and can be used to estimate the cask response to real surface impacts.

PROBABILITY ANALYSIS

The results of the static force evaluations showed that only a few targets remained which could potentially cause damage to a truck cask in excess of 10 CFR 71 acceptance conditions. The remaining targets and their frequencies are listed in Table III. The estimated magnitudes and exceedance frequencies for impact velocities derived from the truck accident and grade crossing accident velocities are also listed. When a specific target is impacted at a specific velocity by a truck cask, a specific impact force results. The impact forces for five surface types were derived from Fig. 7 for each velocity of interest and tabulated in Table III.

Given that a truck accident has occurred, the conditional probability of exceeding a specific impact force can be estimated from

$$P(\geq F_o)_a = \sum_{IJ}^{NM} P(\geq V_i)\, P(T_j)$$

where F_o is the impact force, $P(\geq V_i)$ is the conditional probability that the impact velocity is exceeded, and $P(T_j)$ is the conditional probability that a particular target is impacted. For each specified force, the probability of exceeding it was calculated for each of the velocities and targets listed in Table III. The conditional probability of exceeding a specific force was then calculated by summing the specific force probabilities for the targets and velocities. The results of the summation are plotted in Fig. 8. The results show that at least 99 percent of all accidents will have forces less than those resulting from 10 CFR 71 test conditions. Only 2 out of 10,000 accidents will result in forces which may cause failure of the inner containment wall and severe lead slump.

In the year 2000, it is estimated that the number of miles of truck shipments involving spent fuel may be in the range of 20 million miles. Based on BMCS statistics a truck accident rate of 2.5×10^{-6} accidents per mile is conservatively estimated. The probability of exceeding the third limit state with severe damage to the inner wall of the cask is less than 5×10^{-4} per year or one accident every 2000 years. Under these conditions, the outer wall of the cask could provide both structural and containment functions provided that it was fabricated to the containment component requirements recommended in Ref. 10. These results apply only to end on impact and may change when the sidewise and oblique impact analyses results have been considered.

CONCLUSIONS

The impact and probability results show that current regulatory standards cover at least 99 percent of all real world accidents for limited damage to truck casks subjected to endwise impact. Severe damage to the cask inner wall is estimated to occur no more than once in every 2000 years at a transportation rate of 20 million miles per year. For other accident conditions involving puncture, fire, and crush the evaluations are in progress and will be reported in a NUREG.

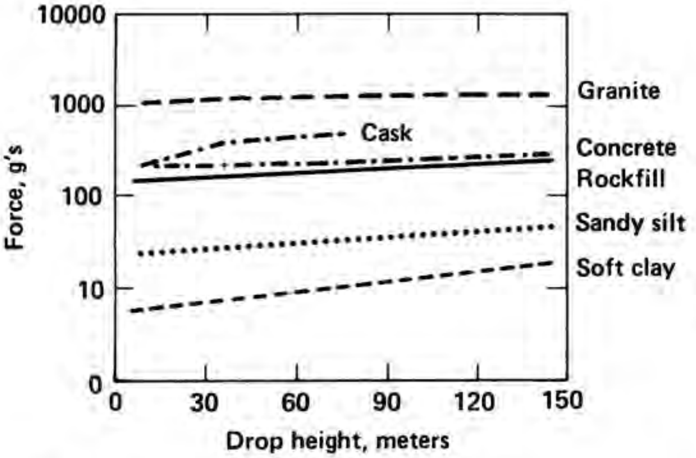


Fig. 7. Rigid cask drop onto real surfaces.

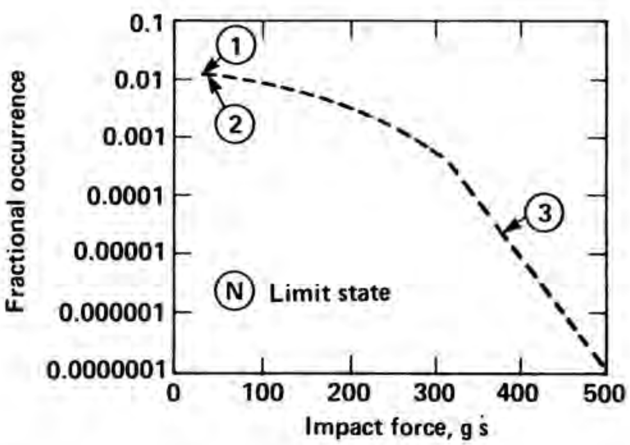


Fig. 8. Conditional probability of exceeding a specified impact force.

Table III

Conditional Probabilities for
Remaining Targets

Truck or train velocity		> 48 km/h		> 64 km/h		> 80 km/h		> 96 km/h		> 113 km/h	
Truck velocity frequency		.481		.313		.0508		.0085		.0023	
Train velocity frequency		.275		.145		.0516		.0163		.0062	
Target	Target frequency	Force g's	Probability	Force g's	Probability	Force g's	Probability	Force g's	Probability	Force g's	Probability
Train*	1.96 E-4	139	5.39 E-5	185	2.84 E-5	232	1.01 E-5	270	3.19 E-6	315	1.22 E-6
Columns	4.82 E-4	< 43	2.05 E-4	< 240	1.34 E-4	< 247	2.17 E-5	< 254	3.64 E-6	< 260	9.84 E-7
Abutments	1.15 E-5	< 43	5.53 E-6	< 240	3.60 E-6	< 247	5.84 E-7	< 254	9.78 E-8	< 260	2.65 E-8
Marsh/soft clay	8.70 E-3	6	4.18 E-3	6	2.72 E-3	7	4.42 E-4	7	7.40 E-5	8	2.00 E-5
Soft soil/silt	1.36 E-2	32	6.54 E-3	33	4.26 E-3	35	6.91 E-4	38	1.16 E-4	39	3.13 E-5
Hard soil/rockfill	1.92 E-2	43	9.33 E-3	125	6.07 E-3	140	9.86 E-4	155	1.65 E-4	170	4.46 E-5
Soft rock/concrete	4.40 E-3	43	2.12 E-3	240	1.38 E-3	247	2.23 E-4	254	3.74 E-5	260	1.01 E-5
Hard rock	2.40 E-3	43	1.15 E-3	298	7.50 E-4	312	1.21 E-4	381	2.04 E-5	420	5.52 E-6

*All impacts are end on except train which is sidewise to cask. Based on CALTRANS data the frequency of grade crossing accidents is .0196% for state highways and 0% for Federal interstate highways (no grade crossings).

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