

Why the Nine Metre Drop Test Bounds the Impacts from Most Severe Accidents

NWMO TR-2014-04

March 2014

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ABSTRACT

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Abstract

The International Atomic Energy Agency (IAEA) nine metre drop test is the primary means of assuring that transportation packages for radioactive materials can withstand the impacts of severe accidents. In general, the nine metre drop test bounds a severe real-life accident because the peak force experienced by the package during the drop test is greater than the peak force generated in a foreseeable accident. The results from a demonstration crash involving a 140 metric ton railroad locomotive travelling at 100 mph and a transportation package certified to IAEA standards were used for the severe accident scenario. Designing packages to withstand the drop test almost always results in a package that is much stiffer than objects they may collide with during an accident, including trains, trucks and concrete abutments. This means that very little of the energy of an accident is absorbed by the package. A comparison of the forces generated in a nine metre drop and those in a service crash test shows that the IAEA drop test bounds the impacts of a severe real-life accident.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	iii
1. INTRODUCTION	1
1.1 Why the Nine Metre Drop Test was Adopted	1
2. WHY THE NINE METRE DROP TEST BOUNDS THE IMPACTS FROM MOST SEVERE ACCIDENTS	1
3. A REAL EXAMPLE – OPERATION SMASH HIT	3
4. SUMMARY	7
REFERENCES	8
APPENDIX A: OPERATION SMASH HIT – CASE STUDY.....	9

LIST OF FIGURES

	<u>Page</u>
Figure 1: Energy Absorbed in a Simple Collision.....	2
Figure 2: Impact Forces for Crash and Drop Tests.....	4
Figure 3: Energy Absorbed by Cask in Drop and Crash Tests	5
Figure 4: Cask Impact Forces for Crash Test	6
Figure 5: Force Deflection Curves for Locomotive Components	7

1. INTRODUCTION

The International Atomic Energy Agency (IAEA) nine metre drop test is the primary means of assuring that transportation packages for radioactive materials can withstand the impacts of severe accidents. In general, the nine metre drop test bounds a severe real-life accident because the peak force experienced by the package during the drop test is greater than the peak force generated in the accident. Designing packages to withstand the drop test almost always results in a package that is much stiffer than objects they may collide with during an accident, including trains, trucks and concrete abutments. This means that very little of the energy of an accident is absorbed by the package.

1.1 Why the Nine Metre Drop Test was Adopted

In 1964, the IAEA adopted a nine metre drop test as the primary means of assuring that transportation packages for radioactive materials could withstand the impacts of severe accidents (IAEA, 1965). An overriding objective in adopting the nine metre drop test was to ensure that the criteria used to approve the design of transportation packages would be clear, consistent and reproducible among IAEA member states. Prior to 1964, IAEA regulations required that transportation package designs withstand a “maximum credible accident relevant to the mode of transport” (IAEA, 1961b) - a requirement that member states found difficult to interpret and implement consistently. To address this difficulty, the IAEA incorporated the nine metre drop test in its 1964 transport regulations based largely on the recommendation of a panel of international experts from IAEA member states. The nine metre drop test was selected because it was felt “that a direct drop of 30 ft (9.2 m) on a hard surface which is representative of glancing blows of 60 mph (100 km/hr) at 60° to the normal or 45 mph (75km/hr) at 45° is a reasonable test” for the type of accidents likely to be experienced in rail or highway accidents (IAEA, 1961a).

2. WHY THE NINE METRE DROP TEST BOUNDS THE IMPACTS FROM MOST SEVERE ACCIDENTS

At first glance it may seem counterintuitive that a nine metre drop test, where the terminal velocity of a falling package is 13 metres per second (30 mph), could bound the impacts in accidents where a package and transportation vehicle could collide at much higher velocities. It is readily apparent that a heavy transportation vehicle moving at high speed has a much higher kinetic energy than that generated by a transportation package in a nine metre drop test. For example, a 140 metric ton locomotive travelling at 45 m/sec (100 mph) has a kinetic energy of about 140 MJ, whereas a 48 metric ton cask falling 9 metres develops a terminal velocity of 13 m/s and a kinetic energy of about 4.4 MJ. The conclusion that must be drawn is that some transportation accidents have the potential energy to result in greater damage than that caused in a nine metre drop test, but only if sufficient energy can be absorbed in deforming the package.

There are two important factors that tend to limit the amount of energy that is actually absorbed by large transportation packages during a severe accident. The first is that most of the original kinetic energy is transferred to the kinetic energies of the impacting transportation vehicles, package trailer and package after the impact. As shown in the example presented in following

paragraphs, the residual kinetic energies of the impacted components can account for up to 75 percent of the accident's original kinetic energy. The remaining energy, i.e., the difference between the initial and post-impact kinetic energies, is the amount available to be absorbed by the transportation vehicle (e.g., truck, locomotive or ship), package trailers or the package itself. The second important factor is the hardness or “stiffness” of the package. The stiffness is important because it ultimately determines the amount of energy a package absorbs, and the amount of damage a package sustains. This stems from the fact that force, energy and deformation (damage) are intimately related. The energy that a package absorbs can be derived from the equation for work (work = applied force x distance) where the energy absorbed is equal to the work done on the package, and the deformation of the package is equivalent to the distance that the force operates over.

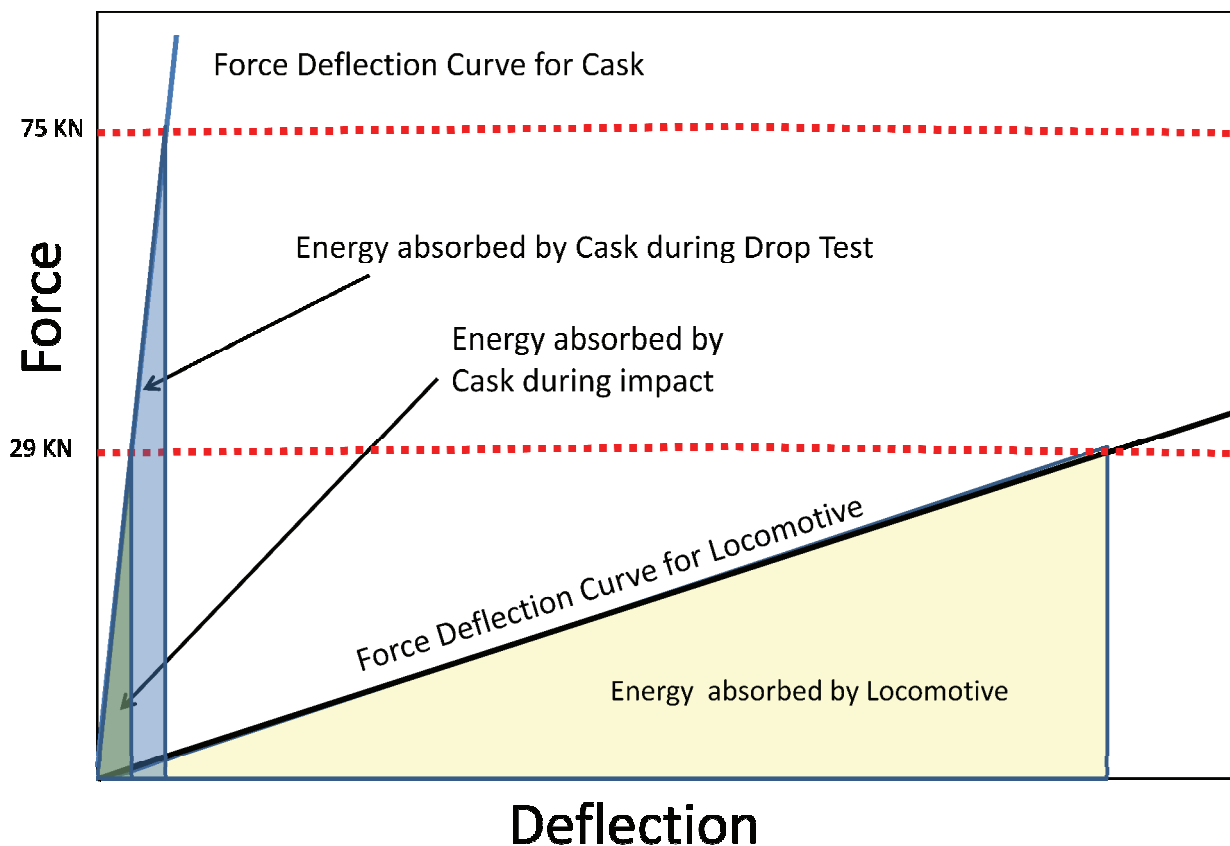


Figure 1: Energy Absorbed in a Simple Collision

Figure 1 represents an illustration of how the stiffness of a shipping cask could affect the relative amount of energy absorbed by a cask and a locomotive in a simplified collision. The stiffness of a package can be expressed by a force deflection curve – a plot of the amount of force needed to cause a specific amount of deformation (i.e., deflection). Similarly, the stiffness of a colliding vehicle, such as a locomotive, can also be expressed by its own force deflection curve.

The area under each curve represents the energy that is absorbed by each component for a given force. The magnitude of that force is limited by the fact that the absorbed energies (the sum of the areas under both curves) cannot exceed the total collision energy available (i.e., the difference between the initial and post-impact kinetic energies), and that the force on the package and locomotive must be the same magnitude at any instance (per Newton's third law, for every force applied there is an equal and opposite reaction force). As Figure 1 illustrates most of the available energy is absorbed in deforming the locomotive because it is less stiff than the package.

The nine metre drop test bounds most severe accidents because transportation packages are designed to be much stiffer than objects they may collide with, including trains, trucks and concrete abutments (see references (Ammerman, 1992), (Bonzon, 1976), (Droste, 1998) and (Gonzales, 1986) for more detailed discussions on the comparisons of impacts with surfaces of varying hardness). Some transportation package designs include impact limiters, which are non-rigid components designed to deform in an accident to absorb impact energy. The stiffness of the package is derived largely from the fact that a package (and impact limiters if part of the design) must absorb the total energy of a nine metre drop with very little deformation to the package. This gives the package a very steep force-deflection curve and results in a large peak force during the drop test. On the other hand, the peak force on a package during an accident (and resulting absorbed energy) is limited because most available energy is consumed in deforming the impacting vehicle and package trailer.

Because the drop energies and package stiffness are a function of individual package designs, it is difficult to generalize on the level of protection provided by nine metre drop test without knowledge of the individual package design and the prospective accident. To address this concern a number of countries have conducted large scale crash tests. One example is the series of tests conducted by SANDIA in the 1970's (Huerta, 1983) and (Huerta, 1976). Another is Operation Smash Hit, conducted by the Central Electricity Generating Board (CEGB) in the United Kingdom. This example is discussed in the next section to illustrate the how the IAEA nine metre drop test protects against severe real-life accidents.

3. A REAL EXAMPLE – OPERATION SMASH HIT

In 1984, the CEGB conducted a rail crash test of a full-sized Magnox spent fuel cask, termed Operation Smash Hit. A major objective in conducting the rail crash test was to compare the impact forces on a Magnox cask resulting from a nine metre drop test with those resulting from a severe rail accident. In brief, the crash test consisted of a 140 metric ton Class 46 locomotive traveling at 44.7 metres/sec (100 mph) colliding with a stationary 47 metric ton Magnox cask attached to a 13 metric ton flatrol rail car. The results from the rail crash test were then compared to results obtained from a nine metre drop test performed on an identical Magnox cask. To facilitate comparison, the drop and crash tests were conducted so that that the Magnox casks would be impacted on the same location – the cask lid edge. A more complete description of the crash and drop tests is given in reference (IME, 1985) and is illustrated in Appendix A.

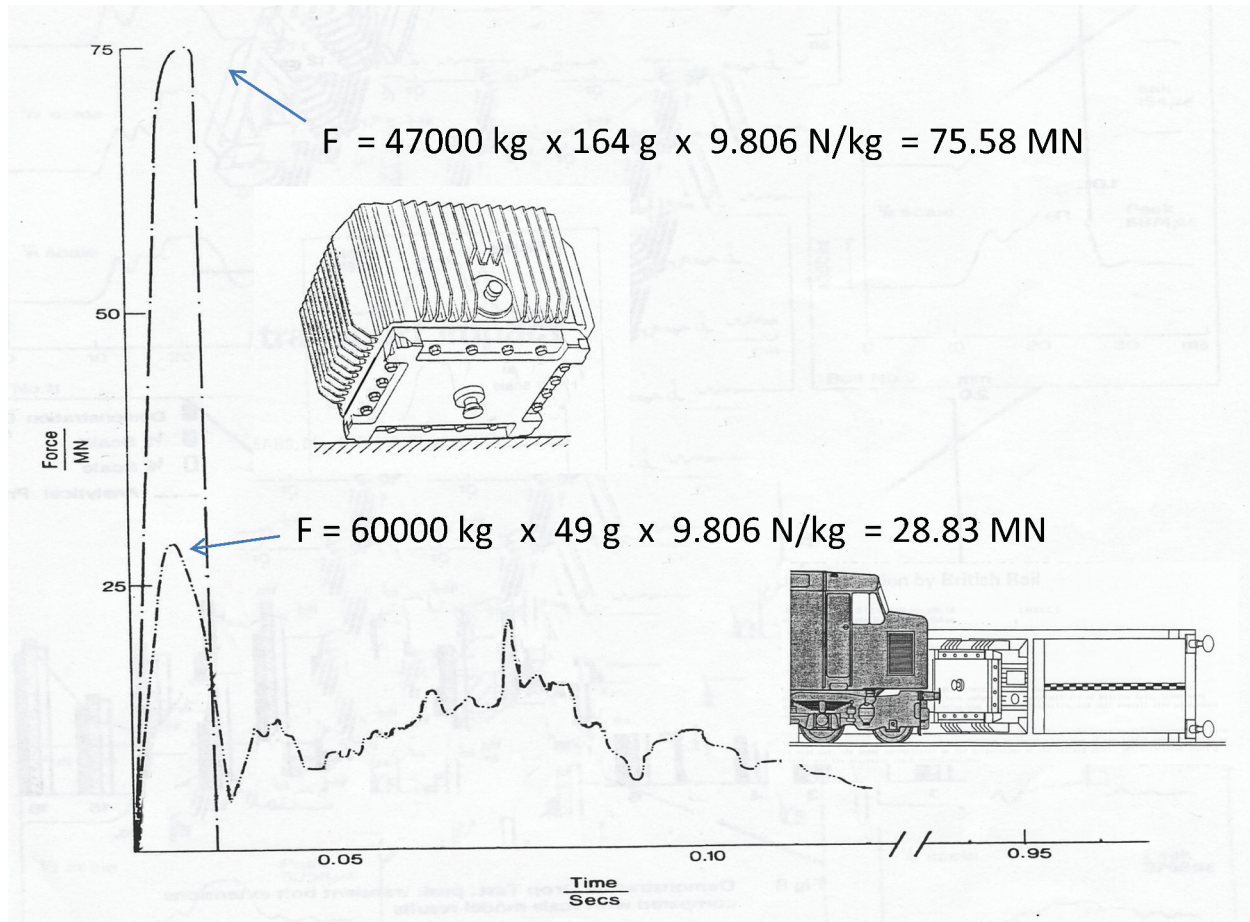


Figure 2: Impact Forces for Crash and Drop Tests

The impact forces for both the drop and crash tests were determined using data from multiple accelerometers attached to the cask bodies. The force-time histories of the nine metre drop and rail crash tests, shown in Figure 2, were derived by multiplying the measured cask decelerations by either the mass of the cask or combined mass of the cask and flatrol as appropriate. During the nine metre drop test, the cask experienced a maximum deceleration of 164 g which corresponds to a peak force of 75 MN. The peak force imparted to the cask during the crash test, based on a maximum deceleration of 49 g for the cask and flatrol, was approximately 29 MN or roughly forty percent of that experienced during the nine metre drop test.

Because the peak force experienced by the cask during the drop test was greater than the peak force experienced during the crash test, it also follows that the energy absorbed by the cask in the drop test was larger than the energy absorbed in the crash test. The energy absorbed by the cask during the nine metre drop was calculated from the cask's initial potential energy as approximately 4.14 MJ. Because the cask was dropped onto an "unyielding surface" virtually all of the energy was assumed to be absorbed in deforming the cask. A simple force deflection curve can be derived for the cask in the lid edge drop orientation based on the measured cask

deformation of 0.104 metres. The force deflection curve for the cask is shown in Figure 3, and assumes a linear relationship with the deformation of 0.104 metres occurring at the maximum measured force of 75 MN. The general shape of the curve can be verified based on comparing the area under the larger triangle ($0.5 \times 75 \text{ MN} \times 0.104 \text{ m} = 3.9 \text{ MJ}$) and comparing it with the energy calculated from the drop test (4.14 MJ). Since the drop test and crash test occurred in the same orientation, the force deflection curve can be used to estimate the energy absorbed by the cask during the crash test. The energy absorbed by the cask during the crash test, represented by the area under the smaller triangle, turns out to be approximately 1.6 MJ.

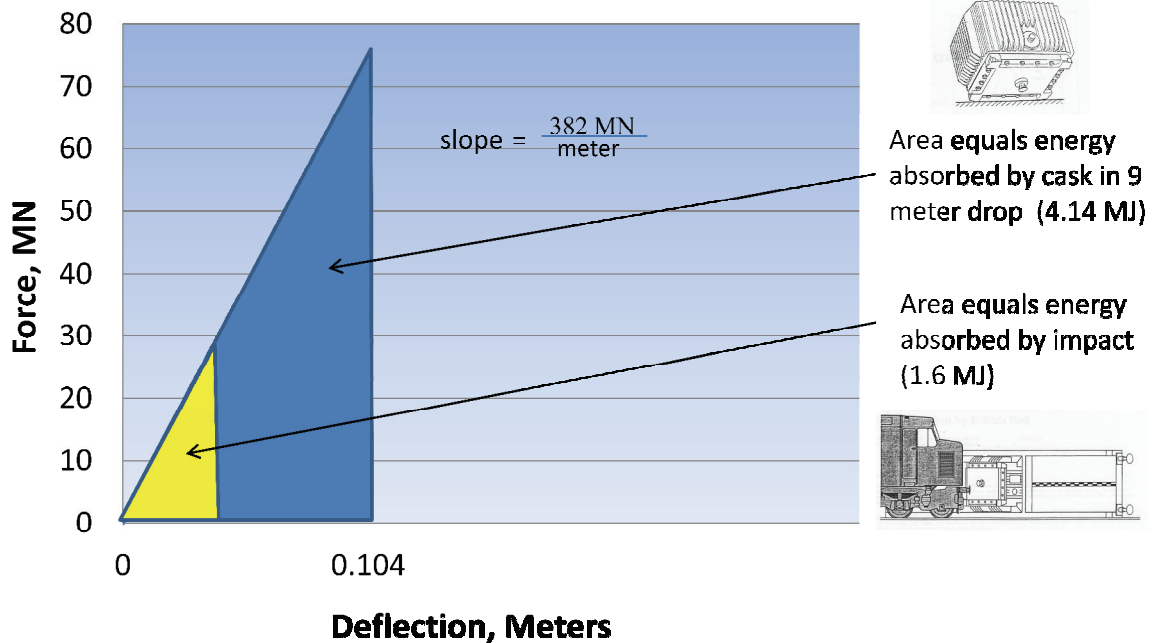


Figure 3: Energy Absorbed by Cask in Drop and Crash Tests

The estimated energy absorbed by the cask, 1.6 MJ, represents less than two percent of the original kinetic energy of the accident. A 140 metric ton locomotive traveling at 44.7 metres/sec (100 mph) starts out with a kinetic energy of approximately 140 MJ. It was estimated that approximately seventy percent of the accident's original kinetic energy was transferred to the post impact kinetic energies of the locomotive, and cask and flatrol. The post impact kinetic energies were determined by applying the law of conservation of momentum, and assuming that the locomotive, and flatrol and cask combination came out of the initial impact with the same velocity, 31.3 m/s. This assumption, which was consistent with the velocities measured during the crash test from high speed cameras, minimizes the estimated magnitude of the post impact kinetic energies (98 MJ), and thus places an upper limit on the amount of energy, 42 MJ, available to deform the both the locomotive and cask. The energy that was estimated to be

absorbed by the cask, 1.6 MJ, is only about four percent of the energy that was available to deform the both the locomotive and cask.

While it is impossible to accurately measure the exact amount of energy absorbed in deforming the locomotive, it is reasonable to assume that a much larger percentage of the total deformation energy was absorbed in damaging the locomotive than in deforming the cask. This was visually verified by observing that there was very minor damage to the Magnox cask, and major crushing of various components of the Class 46 locomotive. An additional indication of where the crash energy was being absorbed can be derived by examining the nature of the varying impact forces on the Magnox cask as shown in Figure 4. Figure 4 superimposes the measured impact forces on the cask with depictions of the cask-locomotive interactions at various key points during the impact. The fact that the impact forces show multiple peaks and valleys indicates that the locomotive did not act like a monolithic body. It shows that the impact force on the cask fluctuates as it engages various components of the locomotive, each with its own stiffness and energy absorbing characteristics. At $t = 0$ ms the cask makes initial contact. The impact forces rises to a peak at around $t = 8$ ms when the cask engages the front plate. Other peaks in impact force occur at $t = 25$ ms when the cask is interacting with the front drive unit, and at $t = 75$ ms when the cask impacts the leading set of wheels.

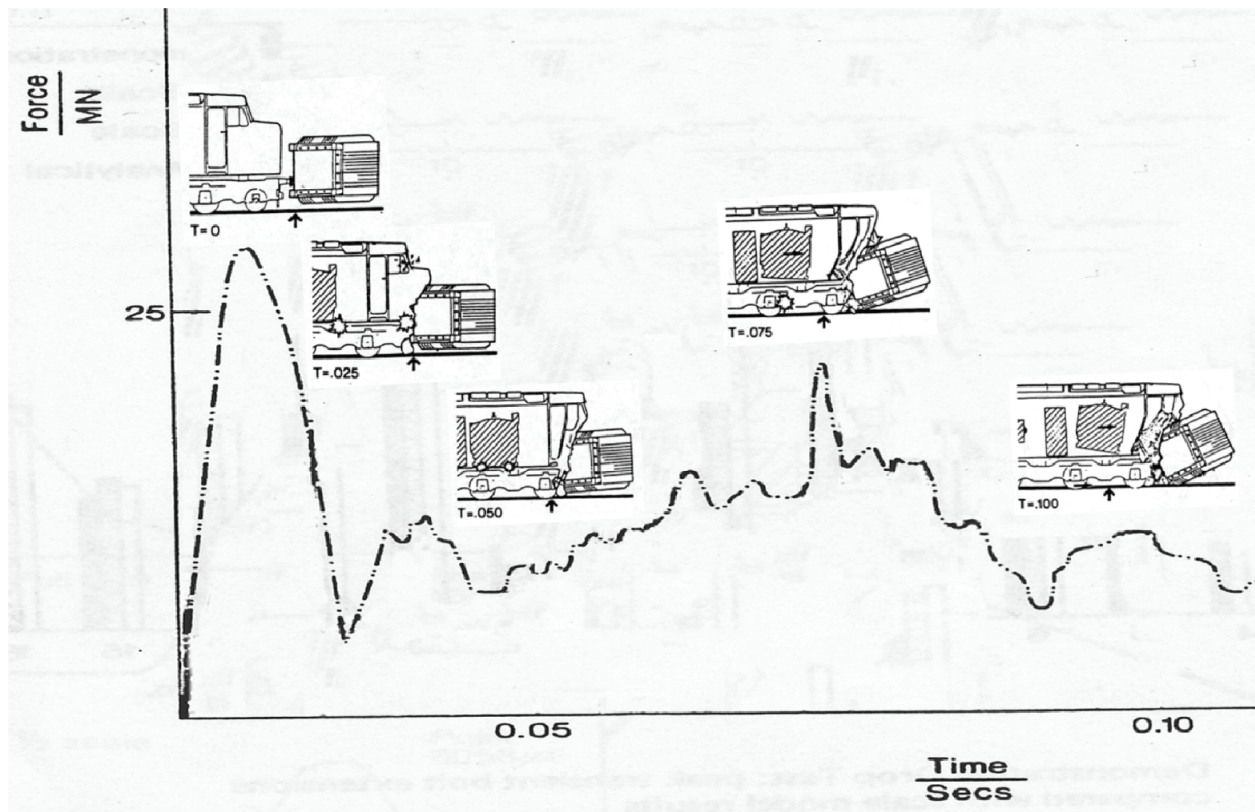


Figure 4: Cask Impact Forces for Crash Test

Although the amount of energy absorbed by each locomotive component could not be accurately measured during the crash, the energies were estimated by the use of force deflection curves in the pre-crash predictions. The force deflection curves for the major locomotive components and Magnox cask are shown in Figure 5. As can be seen in the figure the deformation energies predicted (i.e., the areas under the curves) are much larger for the locomotive components than for the Magnox cask. The pre-crash predictions for forces on the Magnox cask, based on these force deflection curves were consistent with the actual ones measured (Figure 4) during the crash test.

4. SUMMARY

In summary, a comparison of the nine metre drop and crash test shows that the IAEA drop test can bound the impacts from a severe real-life accident. The peak force experienced by the Magnox cask during the drop test (75 MN) was greater than the peak force (29 MN) generated in the rail accident. Also, the deformation energy absorbed by the Magnox cask during the drop test was greater than the deformation energy absorbed by the cask in the accident. The energy absorbed by the Magnox cask in the crash test was only a small percentage of the energy available because the Magnox cask was designed to be much stiffer than objects that it may collide with.

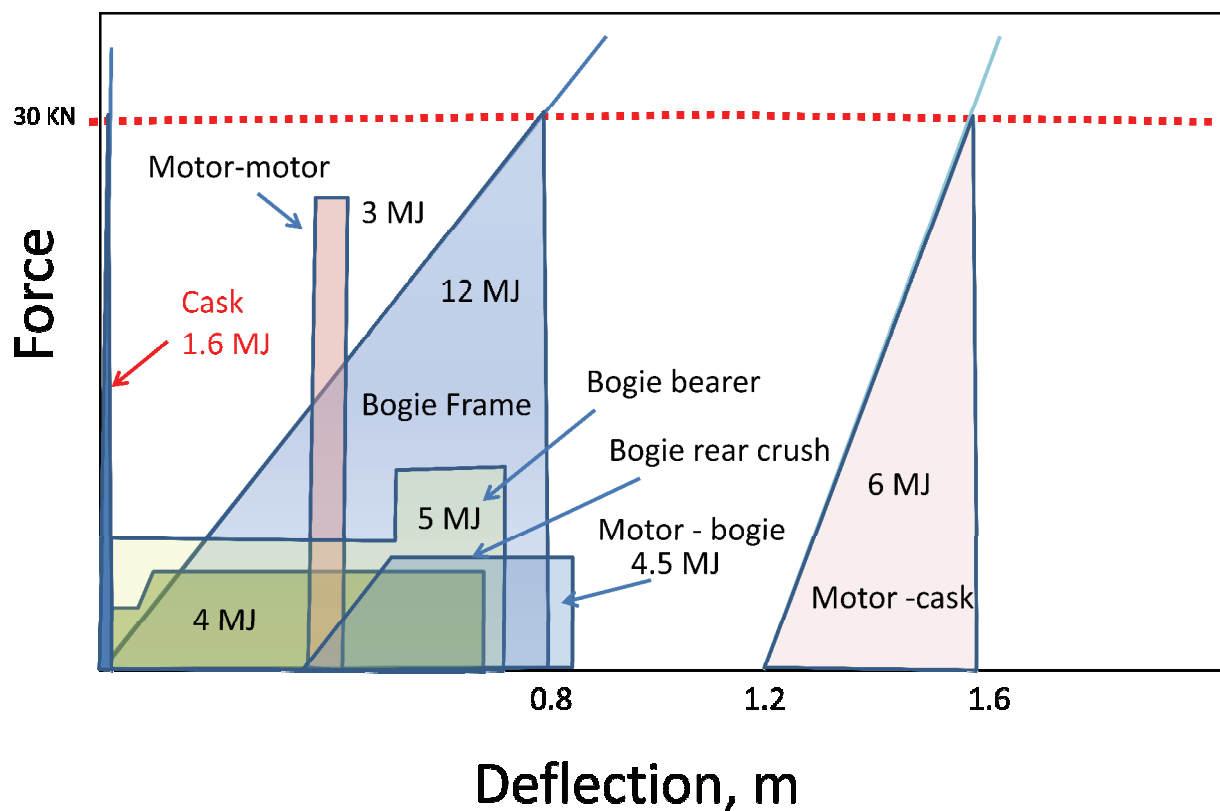


Figure 5: Force Deflection Curves for Locomotive Components

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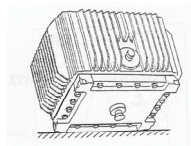
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APPENDIX A: OPERATION SMASH HIT – CASE STUDY

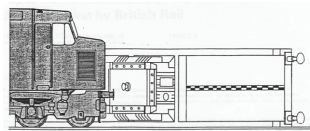
Why the Nine Meter Drop Test bounds the Impacts from Most Severe Accidents



Operation Smash Hit



vs.



- The 9 meter drop test bounds a severe real-life accident when:
 - The peak force experienced by the cask during the drop test is greater than the peak force generated in the accident.
 - The deformation energy absorbed by the cask during the drop test is greater than the deformation energy absorbed by the cask in the accident.

Impact Force from a Nine Meter Drop Test



$PE = mgh$
 $KE = 0$

$m = 47000 \text{ kg}$

$V = \sqrt{2gh} = 13.28 \text{ m/s}$

9 meters

Maximum cask deceleration = **164 g**

Measured value →

Unyielding Surface

$KE = 4.14 \text{ MJ}$
 $PE = 0$

Energy Absorbed by Cask

$E = \frac{1}{2} mv^2 = 4.14 \text{ MJ}$

Average Impact Force

$F_{avg} = \frac{\frac{1}{2} mv^2}{d}$

$F_{avg} = \frac{\frac{1}{2} mv^2}{d} = \frac{4.14 \text{ MJ}}{0.104 \text{ M}} = 39.8 \text{ MN}$

Measured value →

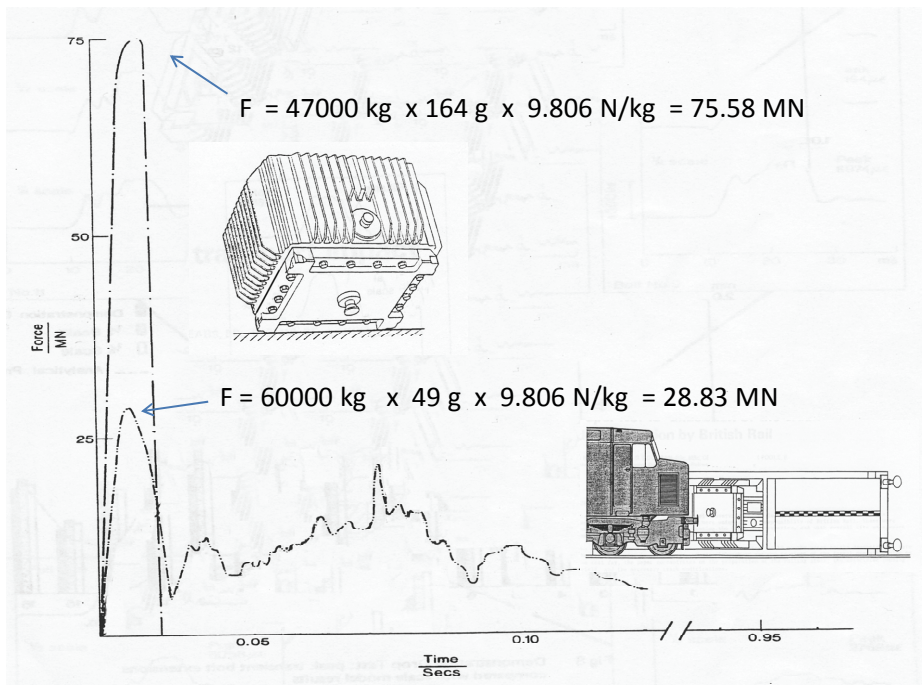
Maximum Impact Force

$F = ma$

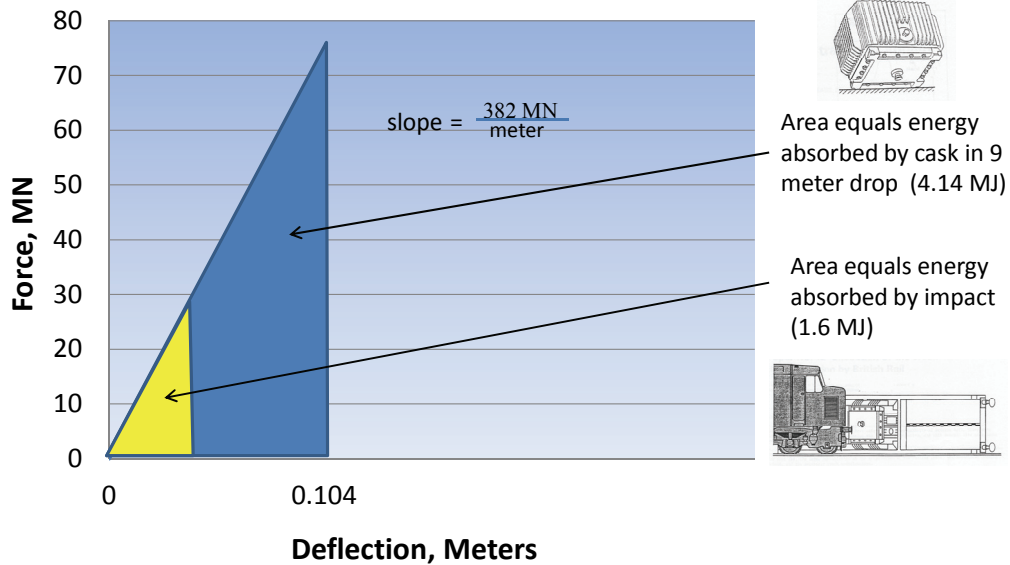
$F = 47000 \text{ kg} \times 164 \text{ g} \times 9.806 \text{ N/kg}$

$F = 75,584,648 \text{ N}$ or 75.58 MN

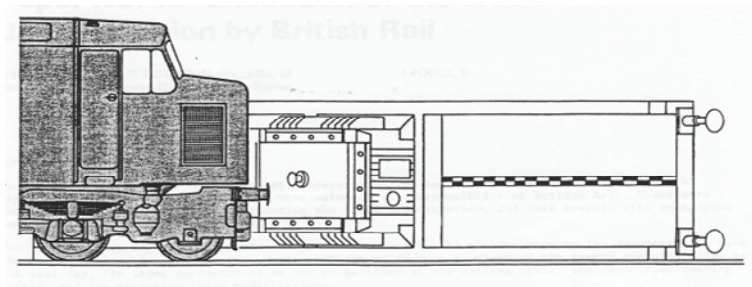
Test Results for Drop Test and Impact



Force Deflection Curve for Cask



Energy Balance for an Inelastic Collision



$$\frac{1}{2} m_T v_{T1}^2 = \frac{1}{2} m_T v_{T2}^2 + \frac{1}{2} m_C v_{C2}^2 + E_T + E_C$$

Total Kinetic Energy of Locomotive = Final Kinetic Energy of Locomotive + Final Kinetic Energy of Cask + Energy Absorbed by Locomotive + Energy Absorbed by Cask

Energy Balance for an Inelastic Collision

Therefore the Energy Absorbed by the Cask is :

$$E_C = \frac{1}{2} m_T v_{T1}^2 - \frac{1}{2} m_T v_{T2}^2 - \frac{1}{2} m_C v_{C2}^2 - E_T$$

$$E_C = 139.9 \text{ MJ} - 68.5 \text{ MJ} - 29.4 \text{ MJ} - E_T$$

$$E_C = 42 \text{ MJ} - E_T$$

Only 30 % of the initial kinetic energy is available to deform the locomotive and cask.

Approximately 70 % of the initial kinetic energy is converted to the final kinetic energy of the locomotive and cask.

Conservation of Momentum

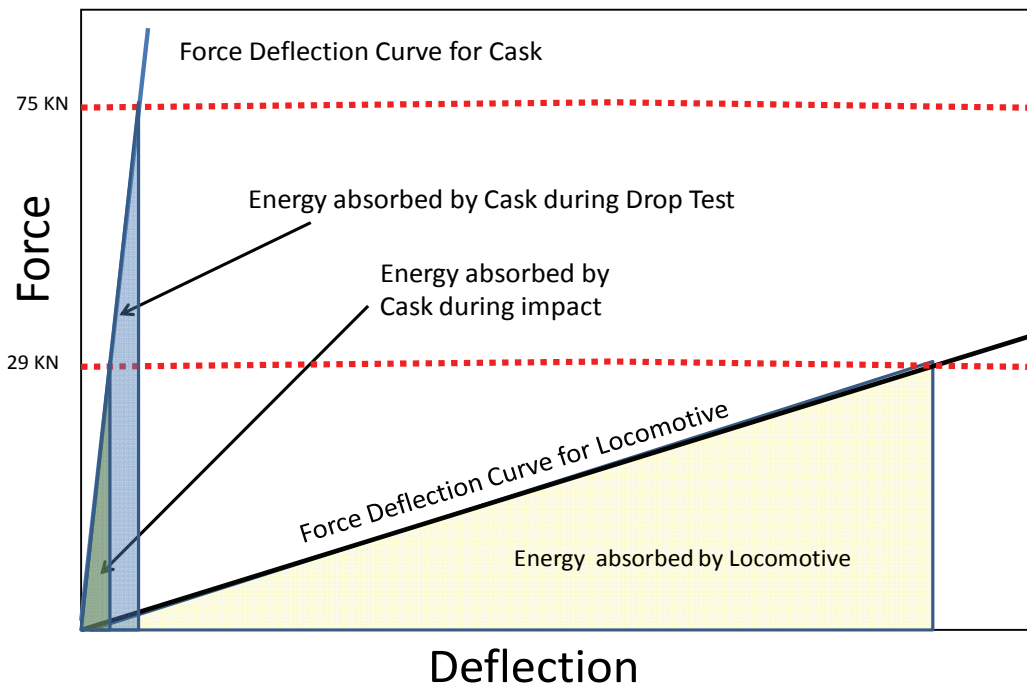
$$m_T v_{T1} = m_T v_{T2} + m_C v_{C2}$$

Assume $v_{T2} = v_{C2} = v_{\text{final}}$

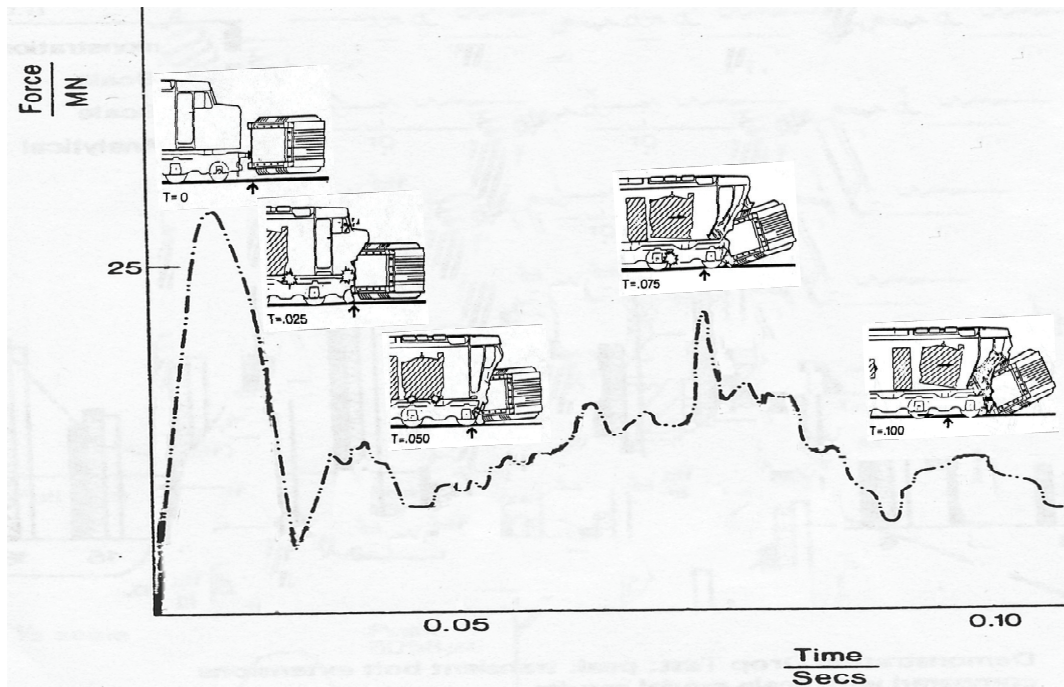
$$v_{\text{final}} = \frac{m_T}{m_T + m_C} \times v_{T1}$$

$$v_{\text{final}} = 31.3 \text{ m/s}$$

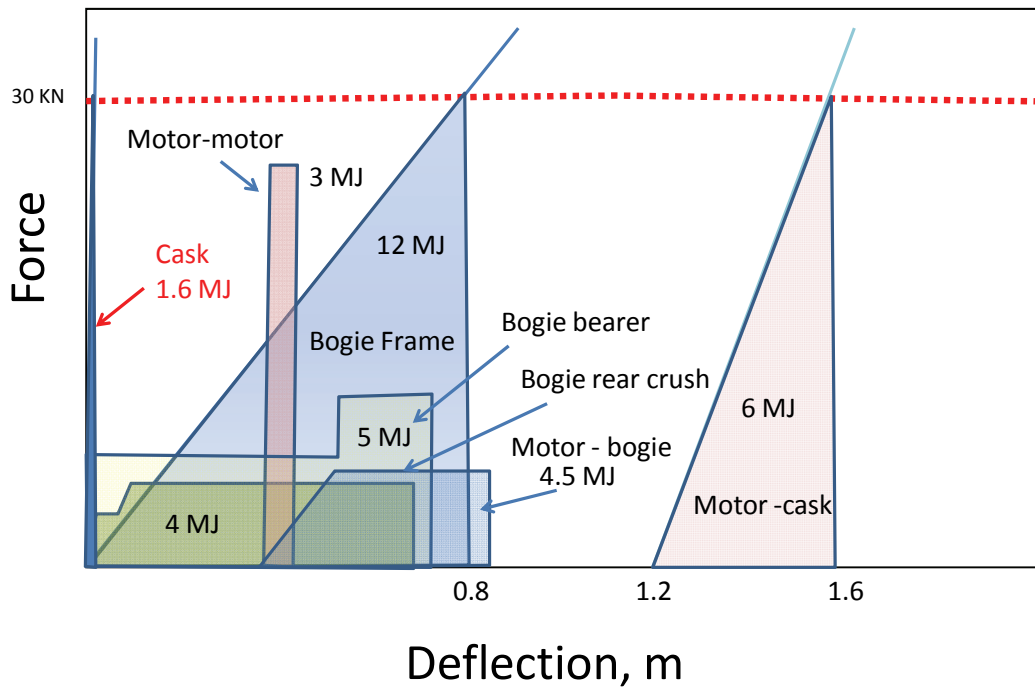
Energy absorbed during Collision



Test Results for Crash Test



Energy absorbed during Collision



Operation Smash Hit

	Peak Force (MN)
Thirty-foot drop test on lid edge	61
Thirty-foot drop test on lid corner (CG over corner)	75
Crash test predictions (unconstrained)	25 – 47
Crash test predictions (constrained)	59
100 mph crash with locomotive	29

Nine Meter Drop Test bounds the Impacts from Most Severe Accidents

- The peak force during the drop test (75 MN) was greater than the peak force (29 MN) generated in the rail accident.
- The deformation energy during the drop test was greater than the deformation energy absorbed by the cask in the accident.
- The energy absorbed by the Magnox cask in the crash test was only a small percentage of the energy available because the Magnox cask was designed to be much stiffer than objects that it may collide with.