

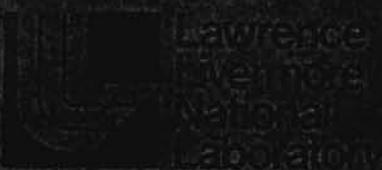
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Mechanical Analysis of a
Transportation Accident Involving
Empty Shipping Casks for
Radioactive Materials Near Hilda,
South Carolina, in November 1982

MAJOR CONTRIBUTORS: Carl F. Walters and Howard H. Wiley

Prepared for
U.S. Nuclear Regulatory Commission



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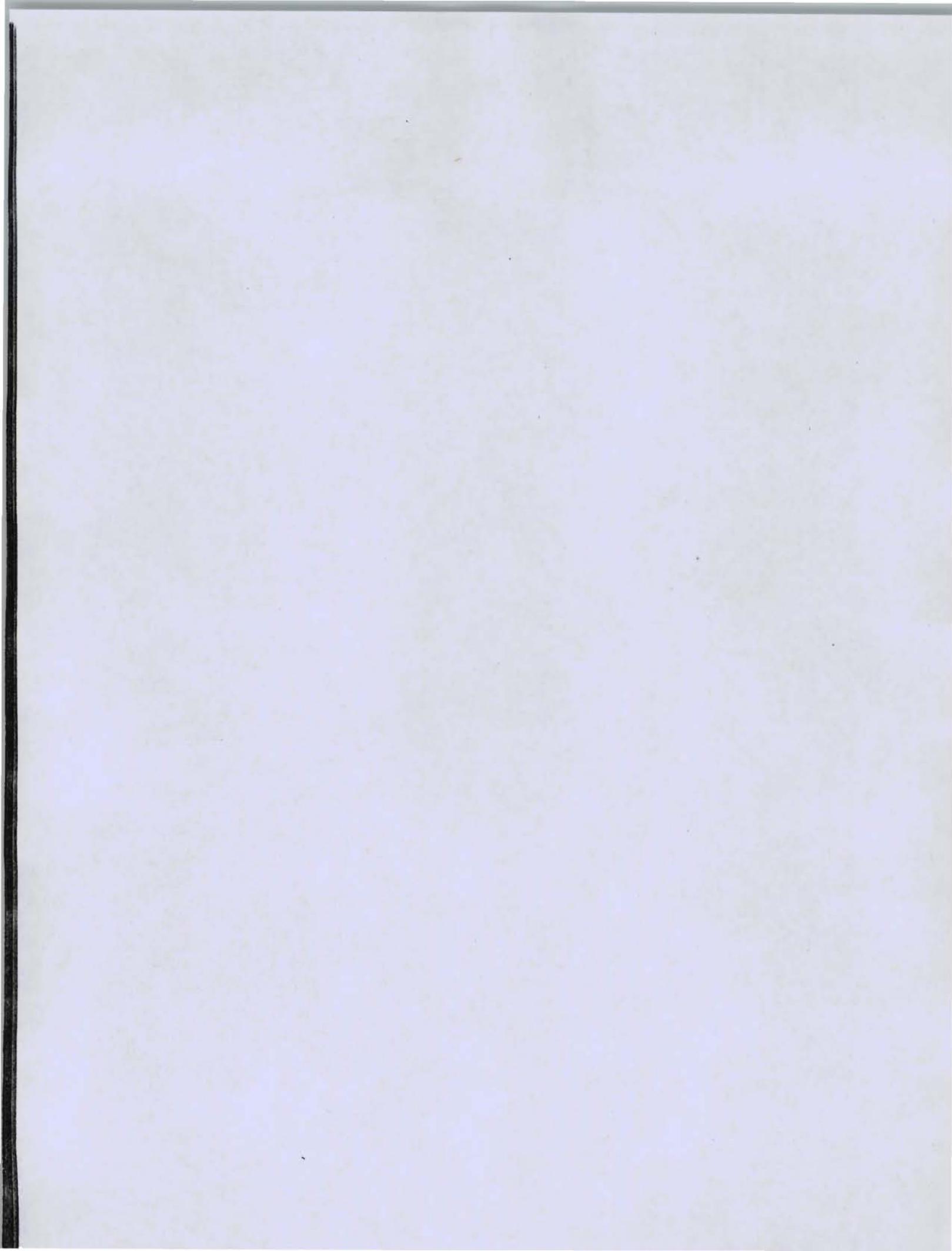
Mechanical Analysis of a Transportation Accident Involving Empty Shipping Casks for Radioactive Materials Near Hilda, South Carolina, in November 1982

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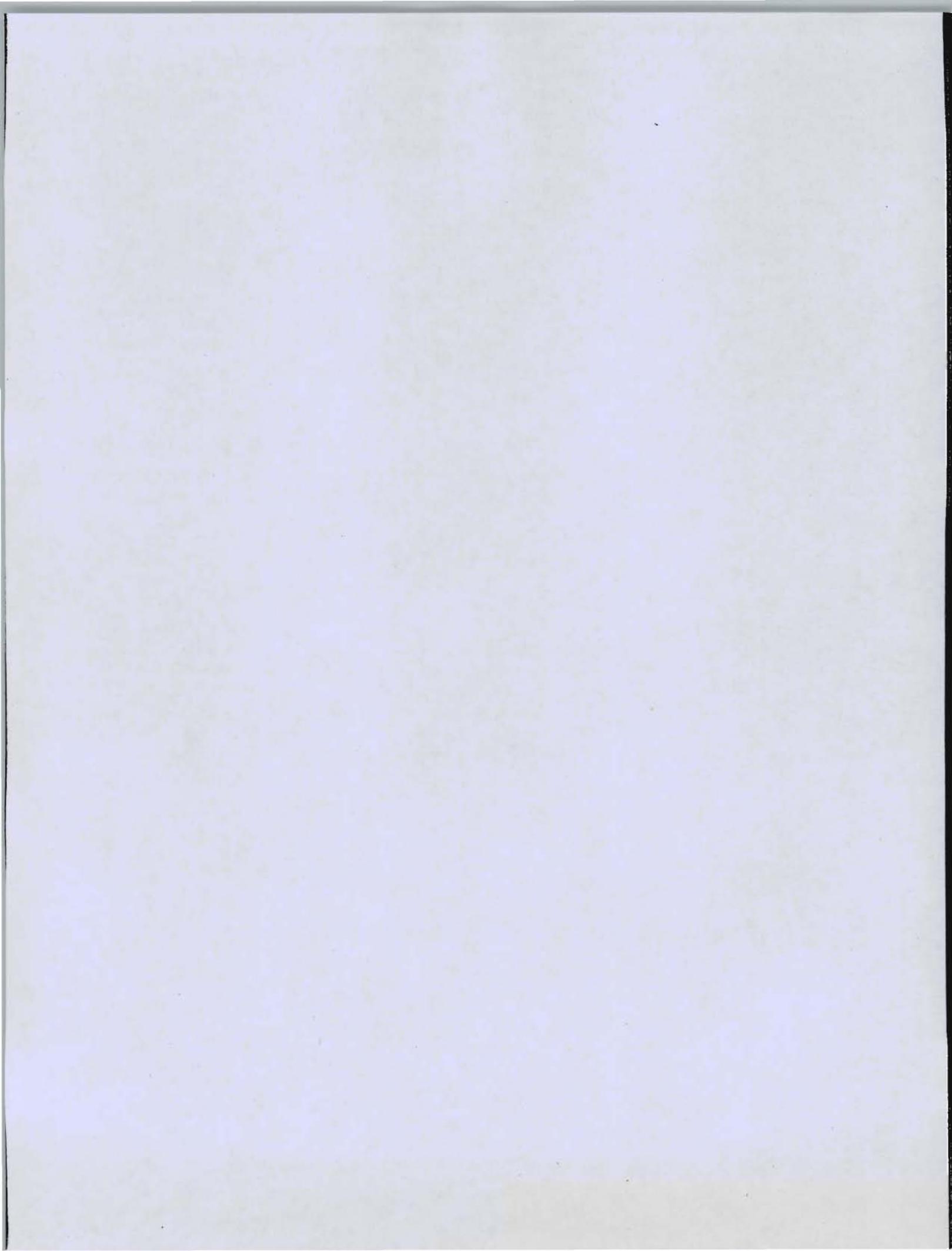
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ABSTRACT

An accident involving a passenger automobile and a tractor-trailer carrying two empty shipping casks for transporting low-level radioactive materials occurred on November 3, 1982, near Hilda, SC. The purpose of this report is to document the mechanical circumstances of the accident, and to assess the types and magnitudes of accident environments to which the casks were subjected.

The report contains two major parts. The first concerns the accident description, which includes fact-finding and the inferred accident scenario. The second part deals with the mechanical analysis of the accident, consisting of estimates of the impact loads and an assessment of the response of the casks and their tie-down systems. Discussions of results and recommendations are also included.



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EXECUTIVE SUMMARY

A mechanical analysis is performed of an accident involving a passenger automobile and a tractor-trailer carrying two empty shipping casks for transporting low-level radioactive materials. The accident occurred on November 3, 1982, at a rural intersection of State Highways 70 and 304 near Hilda, SC.

The collision caused the tractor-trailer to overturn, and the shipping casks became detached from the trailer. Damage to the tractor-trailer and automobile was severe, but damage to the casks was inconsequential. Neither fractures nor significant deformations were observed on the casks after the accident.

In the analysis we examine the mechanics of the accident, estimate the load environment to which the casks were subjected, and evaluate the response of the casks and their tie-down systems. We show that the estimated loads for the inferred accident scenario would not cause the casks to fail. However, in agreement with observation we show that the cask tie-down systems would fail under the estimated impact loads.

The casks were empty at the time of the accident, but our analysis indicates that the casks would not have failed had they been filled.

MECHANICAL ANALYSIS OF A TRANSPORTATION ACCIDENT
INVOLVING EMPTY SHIPPING CASKS
FOR RADIOACTIVE MATERIALS NEAR HILDA, SOUTH CAROLINA, IN NOVEMBER 1982

INTRODUCTION

Background

On November 3, 1982, an accident occurred involving a passenger automobile and a tractor-trailer carrying two empty shipping casks used for transporting low-level radioactive materials. The accident took place at a rural intersection of State Highways 70 and 304 near Hilda, SC.

The truck had earlier completed a delivery at the Chem-Nuclear Systems, Inc., low-level nuclear waste burial facility in Barnwell, SC, and was returning to the Union Carbide plant at Tuxedo, NY, with the empty casks. The two casks were being carried on a flat-bed trailer. Extensive damage resulted to both vehicles, and the driver of the truck was killed. The driver and a passenger in the automobile were not seriously injured.

During the accident, the tractor-trailer overturned and the shipping casks were thrown from the trailer. Damage to both casks was inconsequential, resulting in no release of radioactive materials.

It is estimated that there are about 300 000 shipments a year in this country of low-level radioactive materials.¹ The total volume of material involved annually is estimated to be about two million cubic feet. Many of these shipments are made in casks similar to the ones involved in this accident. In this report, we analyze the mechanics of this accident and evaluate the response of the casks to the estimated load environments.

The U. S. Nuclear Regulatory Commission (NRC) has published two reports describing transportation accidents involving natural uranium concentrate used in the production of fuel for nuclear power plants. In these two cases, the material was contained in sealed 55-gal drums being transported in an enclosed trailer. In both cases, the tractor-trailer overturned throwing some of the drums free and spilling a small percentage of the uranium concentrate being carried. The amount and level of radioactive materials released was small, and in neither case was a serious public hazard created.^{2,3}

In addition, two transportation accidents, each involving the use of two shipping casks for spent nuclear fuel, have been documented.¹ In one case the casks were empty at the time of the accident, and in the other they contained spent fuel. The casks used to contain spent nuclear fuel differ in design from those involved in the Hilda accident. In neither case was any radioactive material released.

Study Objectives and Scope

The Nuclear Regulatory Commission is vitally interested in the safety of transporting radioactive materials, including the development of safe procedures and systems for this activity. The Hilda accident provides data for the successful performance of these shipping casks under these loading conditions.

The objectives of the study are:

- To develop the scenario concerning the mechanical circumstances of the accident.
- To assess the types and magnitudes of accident load environments to which the casks were subjected.
- To evaluate the response of the shipping casks and tie-down systems to the estimated load environments.

The study was organized as follows:

- Determine the most probable accident scenario from the available information.
- Determine the characteristics of the casks and their arrangement on the trailer.
- Analyze the mechanics of the truck rollover.
- Estimate the impact loads imposed on the casks.
- Evaluate the cask response to the estimated load environments.
- Estimate the forces in the cask tie-down system.
- Perform metallurgical analyses on some of the D-ring tie-down devices which were used on the trailer.
- Estimate the hypothetical load environment which would have occurred if the casks had been loaded at the time of the accident.

ACCIDENT DESCRIPTION

Background

The accident occurred at about 6:00 p.m. on November 3, 1982, at the intersection of State Highways 304 and 70 near Hilda, SC. Personnel from the emergency response team of the Chem-Nuclear Systems, Inc., waste burial facility in nearby Barnwell, SC, where the truck had earlier made a delivery, arrived at the accident scene within 10 min of notification of the incident. The news media became aware of the accident shortly thereafter and, despite the presence of officials at the scene, there were numerous false reports of a "radioactive spill." These stories apparently continued for some time in the broadcast media, and persisted in misleading reports appearing the next day in several newspapers. It was thus some time before the fact that there had not been a radioactive spill became widely known.

The Lawrence Livermore National Laboratory (LLNL) was requested by the NRC to collect the accident data on November 12, 1982. A fact-finding trip was conducted by an LLNL engineer on November 14-17. Because of the delay between the incident and the investigation, it was not possible for LLNL personnel to view the accident scene before the site was cleared.

At the time of the fact-finding trip, the roadway at the accident site had been repaired and the damaged vehicles moved. The casks had been taken to the Union Carbide plant in Tuxedo, NY, where they were to be reused. The damaged tractor had been taken to the Tri-State Motor Transit Co. Terminal in Barnwell, SC, and the flat-bed trailer was moved to the Tri-State headquarters in Joplin, MO. Tri-State Motor Transit was the trucking contractor to Union Carbide. Accounts of the accident were obtained from a traffic report recorded by the investigating officer of the South Carolina Highway Patrol, and from articles appearing in The Barnwell People-Sentinel, a local newspaper, on November 11, 1982.⁴

The following is a summary of accident events determined from the available accounts.

- The accident occurred at about 6:00 p.m. on November 3, 1982.
- The roads were wet from rains earlier in the day, but it was not raining at the time of the accident.
- The tractor-trailer was eastbound on State Highway 70 near Hilda, SC, when it struck a Mercury sedan which was entering the intersection of State Highways 70 and 304. It is believed the automobile was attempting a right turn from northbound 304 to eastbound 70. There are stop signs on Highway 304, but none for Highway 70, at this intersection.
- The tractor-trailer overturned after the collision with the automobile. It eventually came to a stop upside down at a right angle to the roadway in a drainage ditch on the south side of State Highway 70. The total distance from the initial point of impact to the final resting point was about 300 ft. The tractor and trailer were severely damaged, and the driver was killed. The tractor-trailer combination remained attached.

- The automobile received damage to the left front and left rear corners. The vehicle came to rest a few feet onto the shoulder of the roadway at a right angle to State Highway 70. There was one passenger in the automobile besides the driver; neither was seriously injured.
- As a result of the impact of the casks with the road pavement when the tractor-trailer overturned, the cask tie-down assemblies failed, allowing the casks to become detached from the trailer. One cask came to rest about 100 ft from the initial point of impact, in the lane of on-coming traffic on State Highway 70. The other cask stopped near the final resting place of the tractor. Apparently, neither cask struck any objects other than the road or ditch banks when thrown free, and both received only minor damage.
- The only surviving witnesses to the accident were the automobile driver and passenger.
- The investigating Highway Patrol officer estimated the speed of the truck at the time of the collision to be about 45 to 55 mph.

A diagram of the accident scene is shown in Fig. 1. Figures 2 and 3 are photographs of the damaged tractor-trailer and automobile, respectively, taken shortly after the incident.

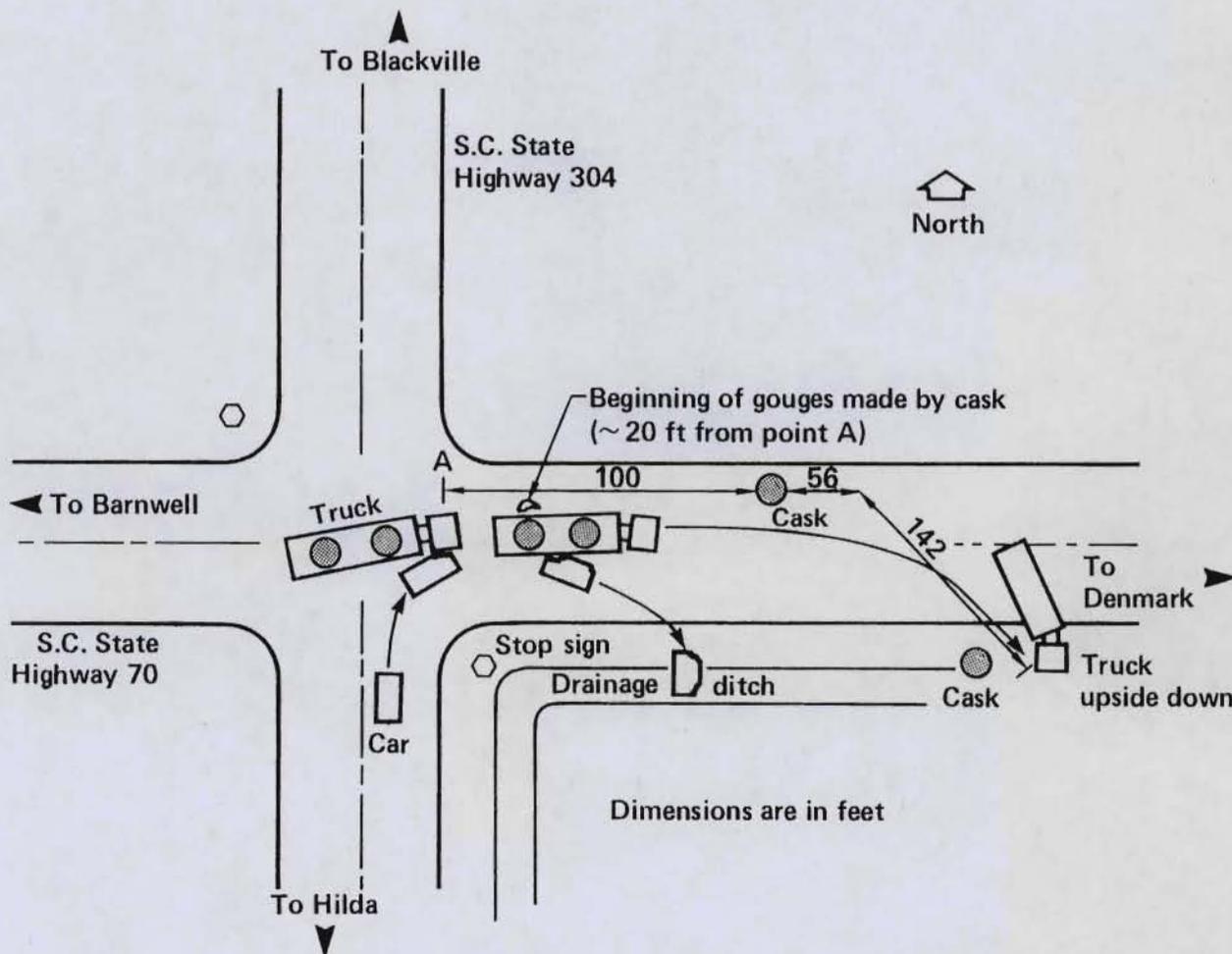


Figure 1. Diagram of the accident scene.

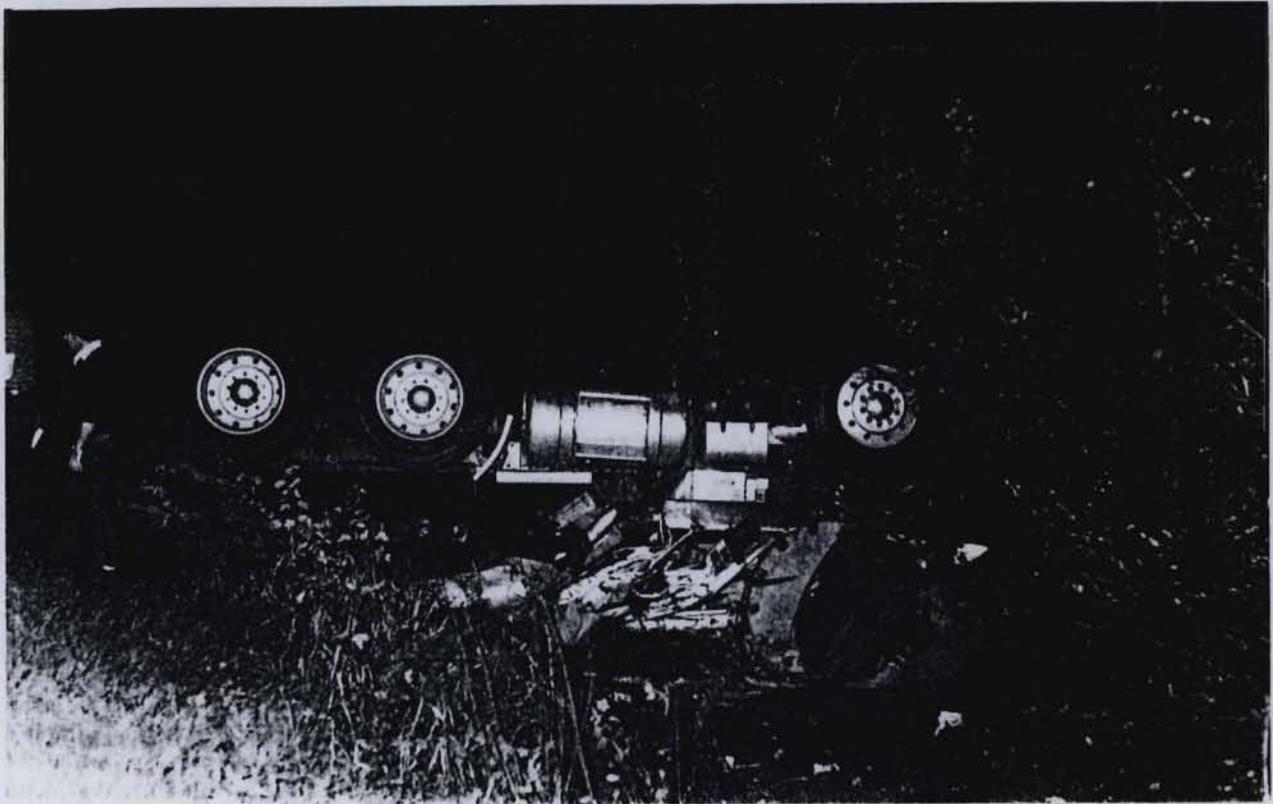


Figure 2. Two views of the damaged tractor.

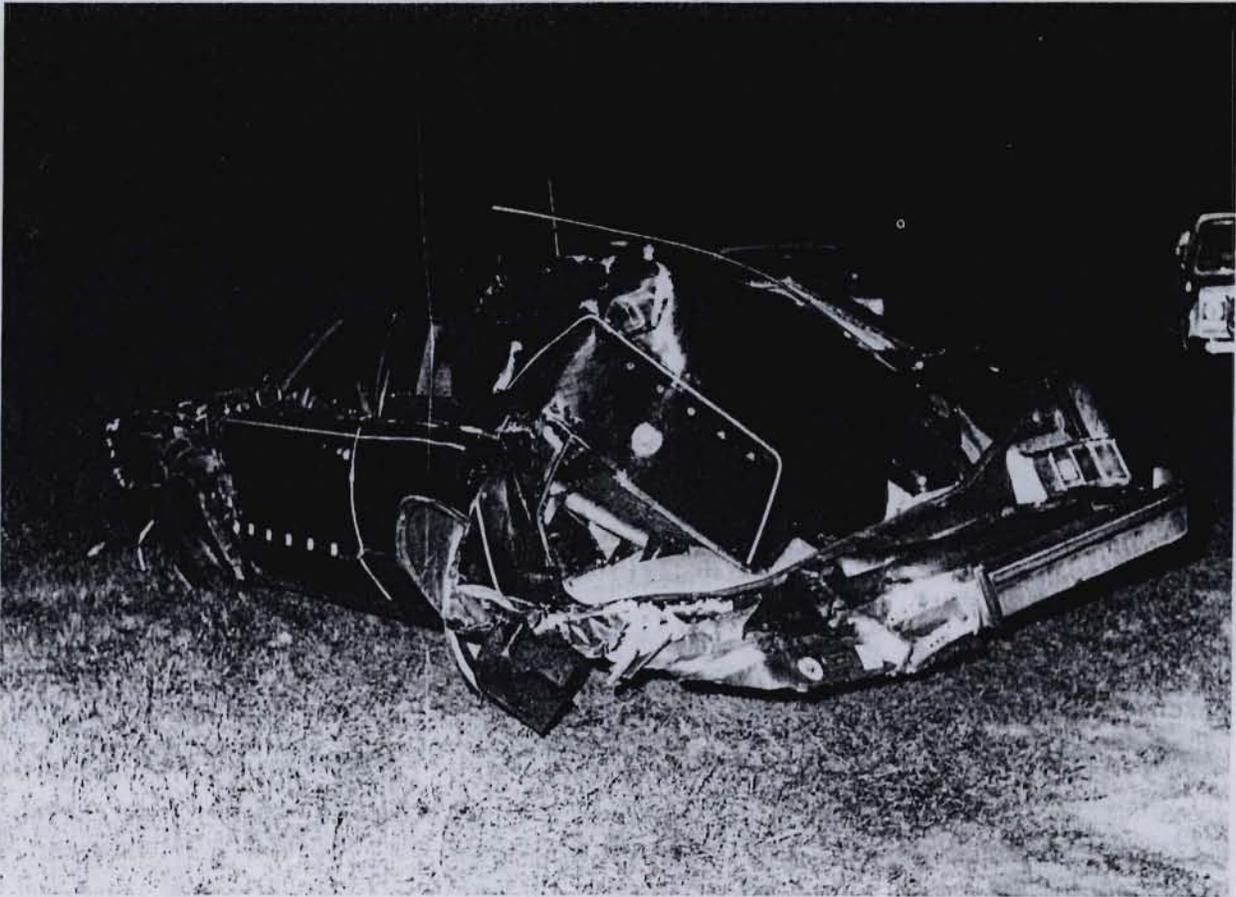


Figure 3. The rear of the automobile was severely damaged.

Fact-finding Trip

A fact-finding trip was conducted by an LLNL engineer during November 14-17, 1982. The following locations were visited:

- (1) Barnwell/Hilda, SC (accident site).
- (2) Tuxedo, NY (site where casks were taken).
- (3) Joplin, MO (site where trailer and eventually tractor were taken).

The accident scene had been cleaned up and the roadway repaired before the arrival of the LLNL engineer, but physical evidence remained which was helpful in reconstructing the accident scenario.

Markings which remained on the road surface show that the tractor-trailer overturned shortly after the initial impact with the automobile and slid along the centerline of the road for about 156 ft. The tractor-trailer then began sliding in a curved path to the right, moving off the road. The tractor-trailer eventually came to rest upside-down with the tractor in the drainage ditch on the south side of State Highway 70. The trailer remained attached to the tractor and damaged a portion of the highway as it slid off the edge of the road. The front of the trailer was in the ditch, and its rear

remained on the highway pavement. The damaged pavement was repaired with a patch measuring 24 by 4 ft.

When the truck overturned, one of the casks struck the road, leaving an indentation about 3- to 4-in. deep in the pavement. The rear cask became detached from the trailer and eventually came to rest about 100 ft beyond the highway intersection in the lane of on-coming traffic. The front cask later became detached from the trailer and came to rest near the tractor. Figure 4 is a photograph showing the normally used cask tie-down method, as used in a subsequent shipment. The cable assembly used to attach the casks to the trailer includes a 5/8-in.-diam steel rope.

The casks were examined by the LLNL engineer at the Union Carbide plant in Tuxedo, NY, where they had been returned. The casks had been cleaned of the dirt and asphalt of the collision, and had been polished with sandpaper prior to the visit by the LLNL engineer. It did not appear that any other repair had been performed. The only visible damage was that on each cask, one of the six tie-down lugs had been bent slightly out of its original plane. The lugs project 3-1/2 in. beyond the cask wall in a plane parallel to the length of the cask. One lug was tangentially deflected 7/8 in. on one cask, and 1/2 in. on the other. Because they had been moved, it was not possible to determine which cask had been placed at the front or rear end of the trailer.



Figure 4. The loaded trailer showing cask tie-down method.

The damaged trailer and, eventually, the tractor were taken to the Tri-State Motor Transit facility in Joplin, MO. The trailer was examined by an LLNL engineer on December 7, 1982.

There was considerable damage to the wood planks comprising the floor of the trailer. As seen in Fig. 5, a semicircular hole was punched into the flooring near the front cask. This indentation was slightly off-center (toward the trailer's front left corner) from the original cask position. There were also indentations made by the front cask as it moved toward the rear of the trailer, and indentations made by the rear cask near the rear end of the trailer. These indentations had no recognizable shape. Severe deformation of the trailer's steel cross beams at these locations also was observed.

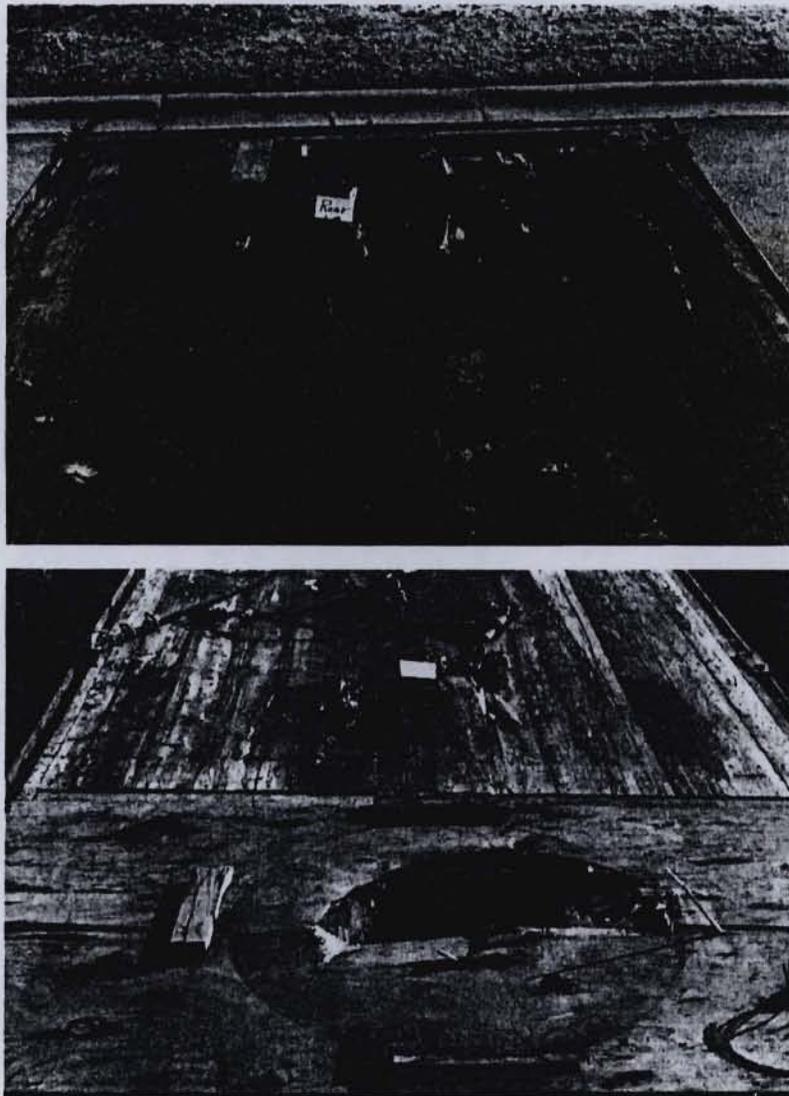


Figure 5. Holes were punched into (a) the rear of the trailer bed and (b) into the front part.

A diagram of the damaged trailer is shown in Fig. 6. The cask tie-down cables had been attached to the trailer using lugs called "D-rings." These consist of a 1-in.-diam steel rod in the shape of an inverted U which is welded to a steel plate that rests on the trailer bed. The legs of the U are threaded near their ends and project through a trailer tie-down rail. As can be seen in Fig. 7, which shows some of the damaged D-rings, they are secured to the trailer with two nuts and another steel plate on the bottom of the tie-down rail.

In two of the D-ring locations, welded steel cylindrical spacers were used. The spacers were welded to the trailer tie-down rail, and the cask tie-down cables attached directly to them. The rings which had been replaced by spacers were the center rings for the front cask.

Of the 10 D-rings used, 2 were broken, 7 were bent by various amounts, and 1 was missing after the accident.

The cable assemblies are made by tying the cable ends into a loop with metal clips connected to a turnbuckle and ratchet binder. The ratchet is used by the truck driver to tighten the cables when securing the casks on the trailer. Failure of the cable assemblies to restrain the casks would result from a failure of either the ratchet binder, clips, cable, or D-ring. All of the failure modes were observed in at least some of the assemblies.

Four of the damaged D-rings were removed from the trailer for further examination. These are labeled L2, L4, R2, and R3 in Fig. 6. The results of these analyses are discussed in a later section of this report. Also, it was noted that asphalt remained in the D-ring in the right rear corner of the trailer, and the left tandem dual wheel was damaged and the outside tire was flat. The cause of the damage to the wheel remains unexplained. The spare tire rack on the underside of the right side of the trailer was also bent, apparently as a result of the automobile striking it.

Inferred Accident Scenario

The following is the probable sequence of events during the accident as inferred from observations:

1. Truck driver swerves to left on seeing the automobile pulling into lane of traffic from right.
2. Tractor strikes front left corner of automobile. Right front tire of tractor is punctured.
3. Because front right tire is flat, tractor begins to move to right.
4. The force of impact causes the car to spin so that its rear end moves under the trailer and hits the spare tire rack.
5. Rear right tires of trailer strike and roll over left rear corner of car, causing right rear end of trailer to lift upward, eventually causing both tractor and trailer to overturn.
6. Automobile is knocked aside and comes to rest on right shoulder next to road.
7. Rear cask strikes pavement as tractor-trailer overturns.
8. Tie-down cables for rear cask break, allowing cask to be thrown free. Cask comes to rest in lane of on-coming traffic after traveling about 100 ft.

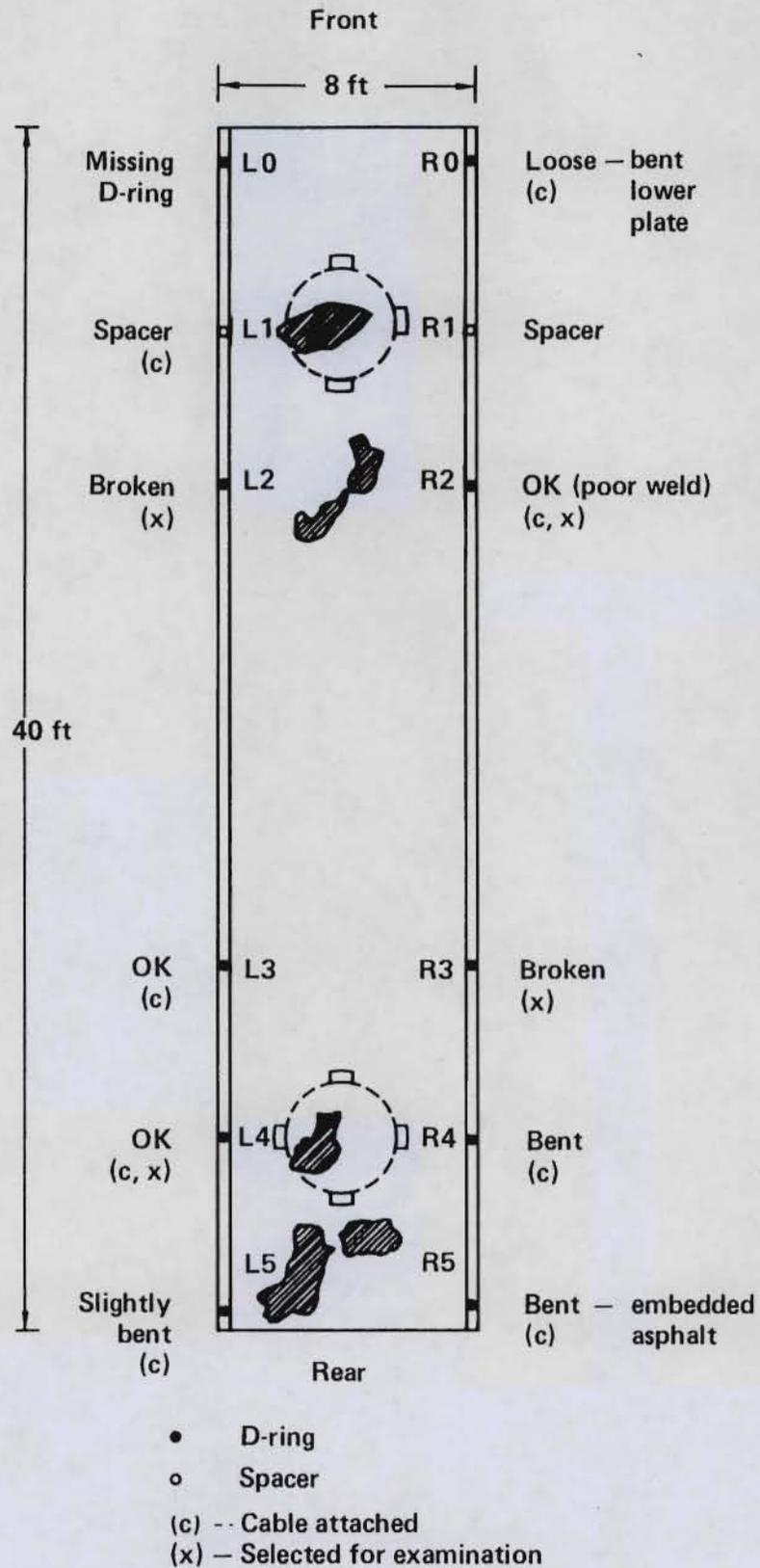


Figure 6. Diagram of the damaged trailer showing location and condition of tie-down devices.

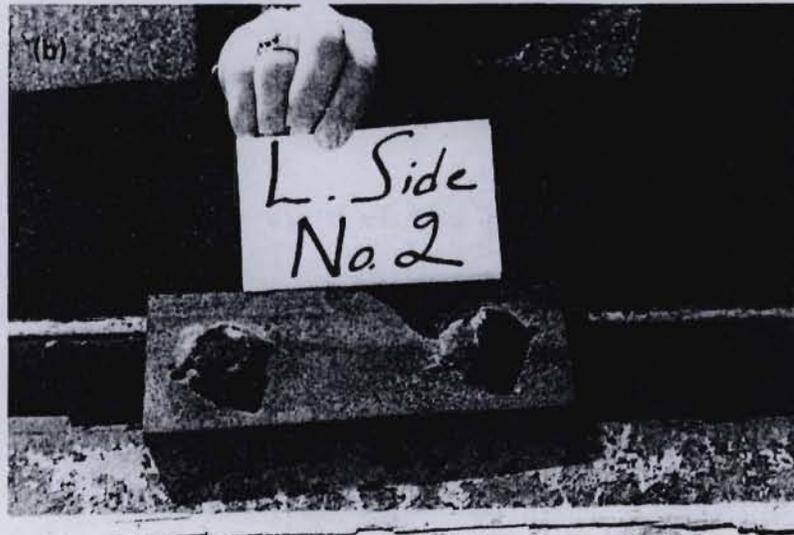
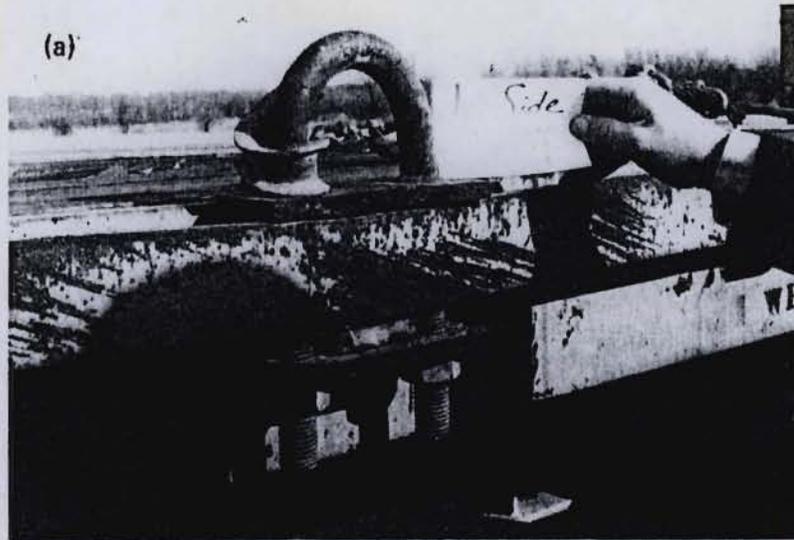


Figure 7. Various degrees of damage were observed in the D-rings: (a) undamaged; (b) D-ring broken off at weld to steel plate;

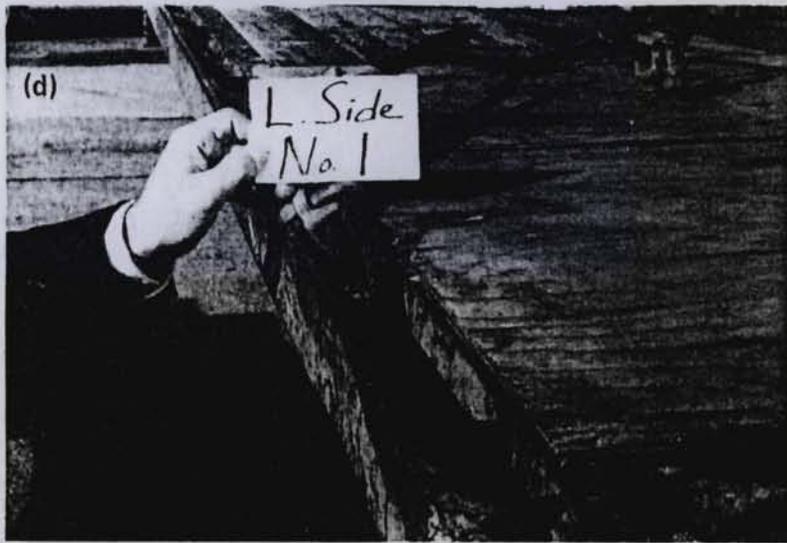


Figure 7. Various degrees of damage were observed in the D-rings: (c) D-ring severely bent; (d) one of two places where D-rings were replaced by spacers. This spacer was undamaged.

9. Right rear corner of trailer strikes the pavement, leaving embedded asphalt in D-ring assembly.
10. Tractor-trailer continues to slide (upside down) on pavement with front cask still attached.
11. Tractor-trailer slides off road to the right towards drainage ditch.
12. Front tie-down cables break, releasing front cask.
13. Front of tractor-trailer comes to rest in ditch in upside-down position at approximate right angle to the road. Total distance from initial impact is about 300 ft.
14. Front cask comes to rest near final resting point of tractor-trailer.

MECHANICAL ANALYSIS FOR THE SHIPPING CASK ACCIDENT

Description of Casks and Loaded Trailer

The shipping casks involved in this accident were designed by Battelle Memorial Institute. They are NECO shipping cask model B3-1 (Ref. 5) with the NRC certificate of compliance No. 6058 (Ref. 6). The casks are cylindrical in shape. A diagram of the cask is shown in Fig. 8. Each cask has an empty weight of approximately 20 500 lb.

The basic cask body (excluding tie-down lugs) has a diameter of 41.0 in. and height of 57.0 in. It consists of two concentric stainless steel shells which form an annular region which is filled with chemical (pure) lead. The internal storage cavity is 26.5 in. in diameter and 43.0 in. high (sufficient size for a 55-gal barrel). The lead-filled annulus is 6-in. thick with equally thick sections of lead on top and bottom. The stainless steel shell of the cask is a laminate construction consisting of a 1/2-in.-thick inner layer and a 1/4-in.-thick outer layer. The laminate construction is used to improve the cask's thermal resistance to external fire exposure.

To minimize hazard in the event of a cask failure, the radioactive contents are cast in concrete which is then placed into the cask cavity. The weight of the cask when full is about 22 200 lb.

A diagram of the loaded tractor-trailer is shown in Fig. 9. The two shipping casks are each attached to the trailer with six tie-down cables which extend symmetrically from the top of the casks at 60° spacings and connect to the sides of the trailer. To prevent sliding, wood blocks are nailed to the trailer floor at the base of the casks.

As seen in Fig. 9, the flat-bed trailer is 40-ft long and 58-in. high. The tractor has a wheelbase of 157 in. The tractor and trailer weigh 18 800 and 14 800 lb, respectively, and the empty shipping casks each weigh 20 500 lb. The loaded rig weighs a total of 74 600 lb with empty casks, and 78 000 lb with full casks. It is of interest to note that the useful payload weight is 3 400 lb, or less than 5% of the total.

ANALYSIS OF ACCIDENT LOADS

Truck Rollover Mechanics

In this section, we present a simplified analysis of the mechanics of the truck rollover. Results of the analysis are used in subsequent calculations

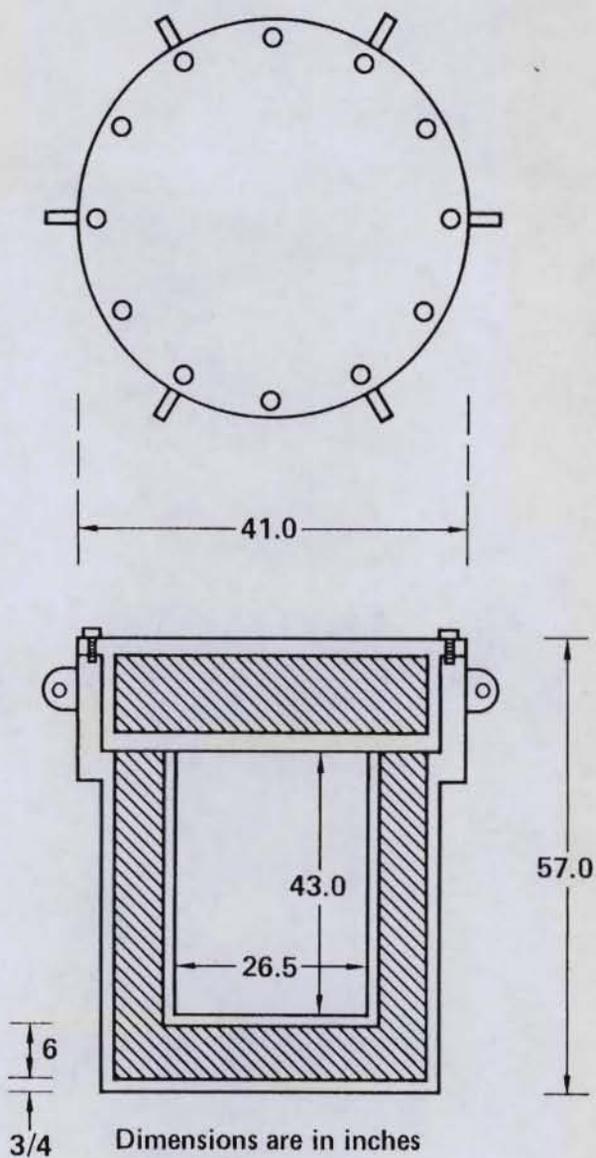


Figure 8. Diagram of the shipping cask.

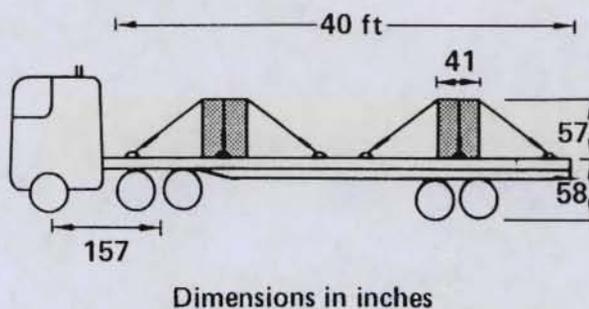


Figure 9. Position of casks on the trailer.

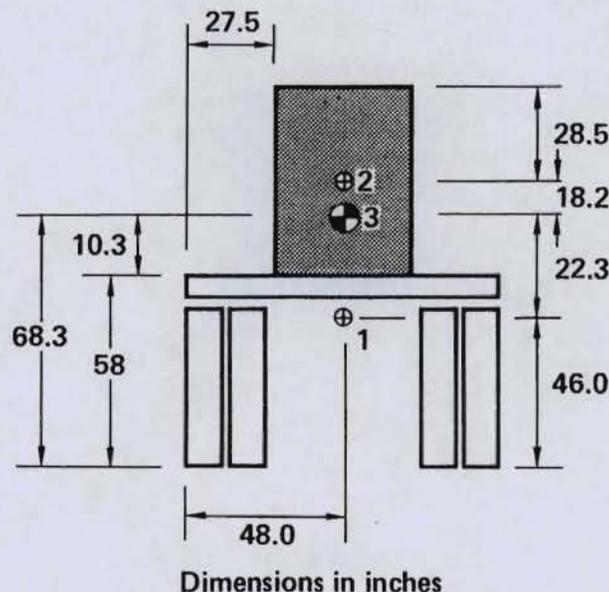
to determine the impact forces which occurred when the casks struck the road pavement.

The mass distribution of the loaded rig is depicted in Fig. 10. The 33 600-lb tractor-trailer has a center of mass approximately 46.0 in. above the ground, and the two shipping casks weigh a total of 41 000 lb with center of mass at about their geometric center. When placed on top of the 58.0-in.-high flat-bed trailer, the loaded rig has a center of mass about 68.3 in. above the ground.

The modeled rollover is depicted in Fig. 11(a)-(d). For simplicity, we use a two-dimensional analysis and assume that the entire mass system rotates as a rigid body in the plane perpendicular to the direction of travel. As shown in the figure, the collision with the automobile is modeled as a force which imparts an impulse to the outside corner of the right wheel. This impulse causes the system to rotate about the opposite wheel at point A.

The minimum angle of rotation θ needed to initiate rollover is shown in Fig. 11(a). At this point, the truck center of mass is at its maximum height. For the mass distribution of the trailer and casks used in this case, $\theta = 35.1^\circ$.

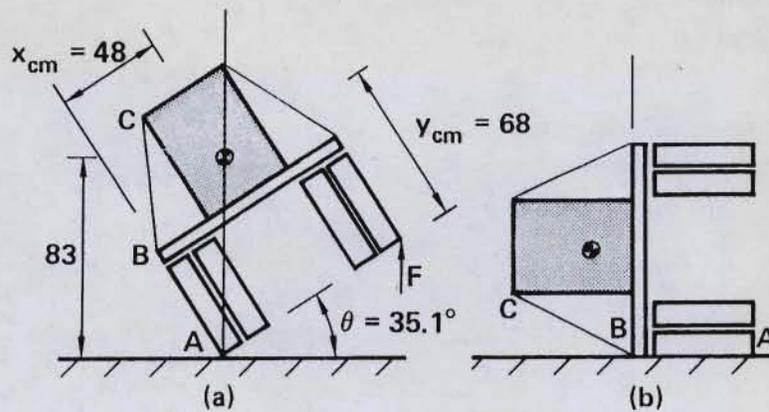
After moving beyond the critical angle, the truck continues to rotate about point A until the left top corner of the trailer strikes the pavement at point B, as shown in Fig. 11(b). The truck then rotates about point B until the top edges of the casks strike the pavement at point C [Fig. 11(c)]. We assume that the casks initially remain attached to the trailer, so the center of mass location does not change until the moment when the casks struck the pavement.



Center of mass locations

- 1 – Position for the empty tractor-trailer.
- 2 – Position for the empty casks.
- 3 – Position for the loaded tractor-trailer.

Figure 10.. Assumed mass distribution for the loaded trailer.



Dimensions are in inches

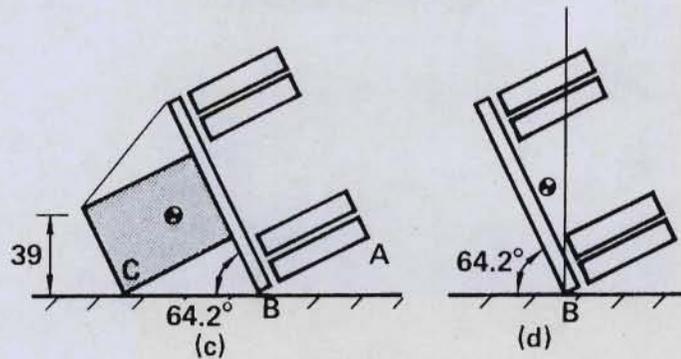


Figure 11. Assumed sequence of positions during the truck rollover.

As was the case in the accident, we assume that all the cask tie-down assemblies fail as a result of impact with pavement (it will be shown in a later section that the estimated impact forces exceed the rated breaking strength of the cables). Although the evidence suggests that the front cask remained attached to the trailer for some time after the initial collision, we assume for simplicity that both casks strike the pavement simultaneously and are thrown free.

Assuming that both casks are released immediately after the initial impact with the road pavement, the tractor-trailer would become unloaded as shown in Fig. 11(d), and would pivot about point B. For the unloaded trailer, the critical angle of rollover is 76.0° (which is the angle measured from the road surface to the trailer bed when the trailer center of mass is at its highest point). As seen in Fig. 11(d), the position of the trailer center of mass at the moment the casks are released is 64.2° , which is beyond the critical rollover point. Thus, the tractor-trailer would continue to roll over until it overturns completely. This is an inevitable result, assuming the casks are released, and given the physical characteristics of the tractor-trailer involved in this accident.

The rotational kinetic energy of the truck just prior to the impact of the casks with the pavement is an important parameter, since it determines the magnitude of the impact force. The actual kinetic energy during the accident cannot accurately be determined, but an estimate of its minimum value can be made.

The minimum rotational kinetic energy needed to cause the loaded trailer to overturn is equal to its potential energy when its center of mass is at its highest point. That is,

$$KE = (I\omega^2/2) = (mG)(h - h_0) \quad , \quad (1)$$

where

- KE = kinetic energy (ft-lb)
- I = mass moment of inertia (ft-lb-s²)
- ω = angular velocity (rad/s)
- m = mass (slugs)
- G = acceleration due to gravity (ft/s²)
- h_0 = initial center-of-mass height (ft)
- h = center-of-mass height (ft).

For the tractor-trailer involved in this accident, $h_0 = 68.3$ in., and for the highest center-of-mass location, $h = 83.4$ in. The tractor-trailer weighs 74 600 lb, so its mass is 2 317 slugs. Inserting these values into Eq. (1) gives a value of 94 400 ft-lb for the minimum rotational kinetic energy needed to initiate the truck rollover.

The rotational kinetic energy of the truck just prior to the impact of the casks with the road is equal to the change in potential energy between the positions shown in Figs. 11(a) and 11(c). In this case, $h = 83.4$ in. and $h_0 = 39.8$ in.; and according to Eq. (1), the kinetic energy is 277 000 ft-lb.

Equation (1) can also be used to calculate the rollover velocities by assuming conservation of energy and angular momentum when the truck first begins to rotate about point A, and then about point B.

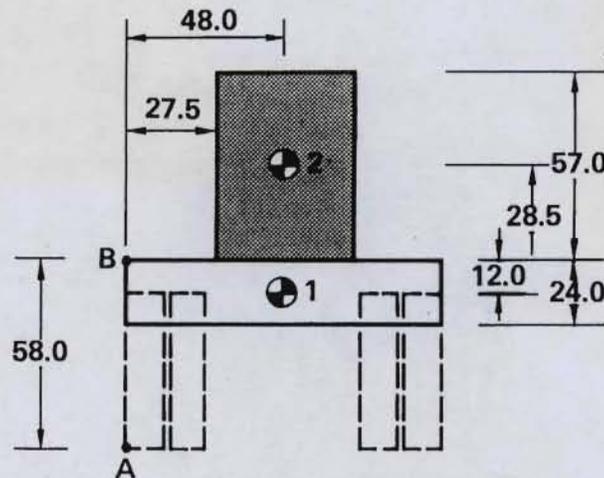
The moment of inertia of the loaded trailer is estimated by considering the composite body (tractor-trailer and cask) shown in Fig. 12. For simplicity, we represent the tractor-trailer as a simple rectangular body of uniform composition with center of mass 12.0 in. below the top of the trailer bed. The moment of inertia for the loaded truck is then the summation of that for tractor-trailer and cask,

$$I = \sum \left[(m)(b^2 + l^2)/12 + md^2 \right] \quad , \quad (2)$$

where

- I = mass moment of inertia (ft-lb-s²)
- m = mass (slugs)
- b = height of body (ft).
- l = length of body (ft)
- d = distance of center of mass to point of rotation (ft).

Inserting the previously specified parameter values into Eq. (2) yield values of 1.84×10^7 ft-lb-s² for the moment of inertia when rotating about point A, and 7.90×10^6 ft-lb-s² for rotation about point B. Solving Eq. (1) for ω yields a value of 0.101 rad/s (5.80 deg/s) for the initial angular velocity



Dimensions are in inches

- 1 Center of mass for the tractor-trailer
- 2 Center of mass for the cask

Figure 12. Assumed mass distribution for the calculation of the mass moment of inertia of the truck.

for rotation about point A, and 0.236 rad/s (13.5 deg/s) for the initial angular velocity for rotation about point B. The angular velocity at the moment just prior to impact at point C is 0.265 rad/s (15.2 deg/s).

In this accident, the greatest risk to the integrity of the casks probably occurred as a result of the impact with the road when the truck overturned. It is apparent, therefore, that the safety of the shipping procedure could be improved by reducing the risk of rollover. The possibility of a rollover, of course, depends greatly on the vehicle mass distribution, and in particular, to the position of the center of mass. We therefore investigate the effect on the roll stability of a vehicle with respect to the position of its center of mass.

In the foregoing modeled rollover analysis, it was assumed that the rollover occurred as the result of an impulse applied to the rear wheel of the trailer, and that the truck continued to travel in a straight course. This model was used since the evidence from the accident suggested that this was the primary cause of the rollover. However, rollover can also occur as a result of dynamic forces when a vehicle is turned sharply. This type of evasive action would be expected in an accident such as this, but we did not analyze this action in the foregoing since it is not possible to precisely determine the reactions of the truck driver to the impending collision from the physical evidence that remained. In the actual accident, both rollover modes were probably involved, and are examined below.

In the case of rollover due to an applied impulse, it is seen in Eq. (1) that the energy, and thus the magnitude of the impulse required, is directly proportional to the change in height of the center of mass. The change in height of the center of mass, as illustrated in Fig. 11(a), is equal to

$$\Delta h = (h - h_0) = \left(x_{cm}^2 + y_{cm}^2 \right)^{1/2} - y_{cm} \quad (3)$$

where

- Δh = change in height of center of mass (ft)
- x_{cm} = horizontal distance of center of mass to point of rotation (ft)
- y_{cm} = vertical distance of center of mass to point of rotation (ft).

Since the magnitude of the impulse needed to initiate rollover is directly proportional to Δh , one can assess the effect of the-center-of mass position on vehicle roll stability by considering this parameter. One cannot directly relate the possibility of rollover in this case to other single factors such as vehicle speed, since the magnitude of the impulse of collision will also depend on other things such as the amount of deformation which occurs in the wheel and in the body which is struck.

For the loaded tractor-trailer in this accident, $x_{cm} = 48.0$ in., $y_{cm} = 68.3$ in., and $\Delta h = 15.2$ in. Figure 13 shows the effect on Δh when the center-of-mass height y_{cm} is varied from one-half to twice its baseline value. The data are normalized by dividing the values of y_{cm} by 68.3 in., and the resulting values of Δh by 15.2 in. As can be seen in the figure, for example, if the baseline center-of-mass height is decreased by 50%, Δh increases by about 63%.

The dynamic forces acting on a vehicle during a turn are shown in Fig. 14. In the figure, we consider the general case where the curve is superelevated (banked), but assume that the velocity through the turn remains constant. For the curvilinear motion, the centripetal force (assumed to act through the

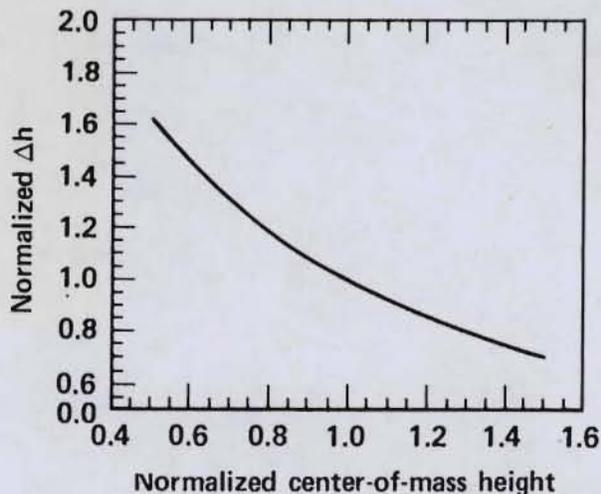


Figure 13. Normalized change in Δh vs normalized center-of-mass height.

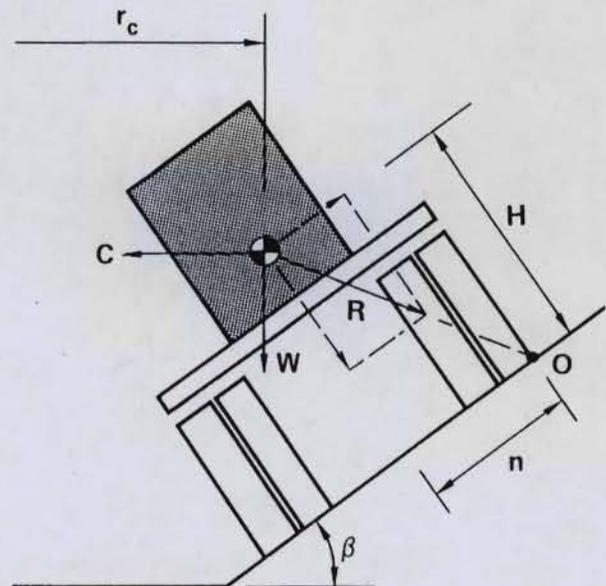


Figure 14. Dynamic forces acting on the tractor-trailer during a turn.

center of mass) is held in equilibrium by the sum of the side-force reactions on the tires. That is,⁷

$$C = m r_C \omega^2 = \frac{Wv^2}{Gr_C} \quad , \quad (4)$$

where

- C = centripetal force (lb)
- m = vehicle mass (slugs)
- r_C = radius of curve (ft)
- ω = angular velocity (rad/s)
- W = vehicle weight (lb)
- v = translatory velocity (ft/s)
- G = acceleration due to gravity (ft/s²).

The vehicle will begin to tip if the resultant of the reaction forces R pass through the tire contact point O, shown in Fig. 14. Equating moments about point O yields

$$(n)(C \sin \beta + W \cos \beta) - (H)(C \cos \beta - W \sin \beta) = 0 \quad , \quad (5)$$

where

- H = center-of-mass height (ft)
- n = distance between point O (Fig. 14) and center of mass (ft)
- C = centripetal force (lb)
- W = vehicle weight (lb)
- β = superelevation angle (deg).

Equating expressions (4) and (5) gives

$$v_{\max} = \left[\frac{Gr_C (n + H \tan \beta)}{(H - n \tan \beta)} \right]^{1/2} \quad , \quad (6)$$

where

$$v_{\max} = \text{maximum safe velocity (ft/s)}.$$

Simplifying Eq. (6) for the case of a level road ($\beta = 0$), yields

$$v_{\max} = \left[\frac{Gr_C n}{H} \right]^{1/2} \quad . \quad (7)$$

Therefore, for the case of a level road and a given radius of curvature, the maximum safe velocity decreases as the square root of the center-of-mass height. For example, if the center-of-mass height were reduced by one-half, the maximum safe velocity would increase by a factor equal to the square root of two. The result would be an increase in safe velocity of about 41%.

These evaluations show that the risk of rollover can be reduced significantly by lowering the vehicle's center of mass.

Estimate of Impact Loads on Casks

The calculation of the impact loads imposed on the casks is made using simplified energy and work considerations. The determination of the actual forces of impact is a difficult problem since this is not an elastic collision.

For objects traveling at relatively low velocities impacting terrestrial media (i.e., like rock or asphalt), the object will not rebound elastically or embed itself in the material, but will undergo a "cratering" process in which the object creates a "burrow" for itself as material is displaced. During this time, the dynamic forces are not in equilibrium and the surfaces of interaction are constantly changing. The impacting object will ultimately bounce out of the crater with a fraction of its initial impact velocity.

During the time of the collision, forces are generated by the impacted media, as shown in Fig. 15, which will be nonuniform in direction and magnitude. However, it may be argued that when taken over the time span from the initial impact to the time the downward velocity of the body is stopped, the total work done on the body by the vertical components of the forces is equal to its initial downward kinetic energy.

If this were a perfectly elastic collision, the impacted media would return to its original shape providing an upward force propelling the impacting object back upward with its original kinetic energy. If it were a perfectly inelastic collision, the impacted media would remain in its deformed state and the object would remain embedded. In the inelastic case, the kinetic energy of the object would be completely converted to work of deformation. The collision being considered here falls somewhere between these extremes.

Based on the preceding arguments, one can estimate the magnitude of the vertical component of the average impact force on the object during the time of its downward travel by equating the work done by the force to the object's downward kinetic energy just prior to impact. A method to estimate the horizontal component of the impact force will be discussed later.

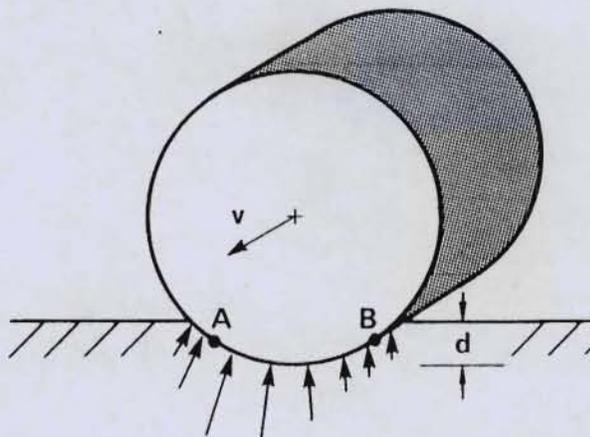


Figure 15. Idealized impact forces over surface of interaction for an oblique impact.

For the overturning vehicle, the impact force at the point of contact with the road produces a torque about the point of rotation O, as shown in Fig. 16. The work done by this torque is equal to the kinetic energy of rotation just before impact. Thus, the torque is equal to

$$\tau = (I\omega^2/2)/\theta \quad , \quad (8)$$

where

- τ = torque (ft-lb)
- I = mass moment of inertia (ft-lb-s²)
- θ = angular displacement (rad)
- ω = angular velocity (rad/s).

Since the angular displacement during the impact event is small, the following approximation is valid:

$$\tau = (F)(L) \cong (F)(d/\theta) \quad , \quad (9)$$

where

- F = impact force (lb)
- L = moment arm (ft)
- d = vertical displacement at impact point (ft).

By combining Eqs. (8) and (9), we obtain the following equation for the average impact force:

$$F \cong (I\omega^2/2d) \quad . \quad (10)$$

In subsequent calculations involving the cask response, we wish to know the peak value of the impact force rather than the average value just calculated. From impact tests for projectiles such as spheres and cones, it is estimated

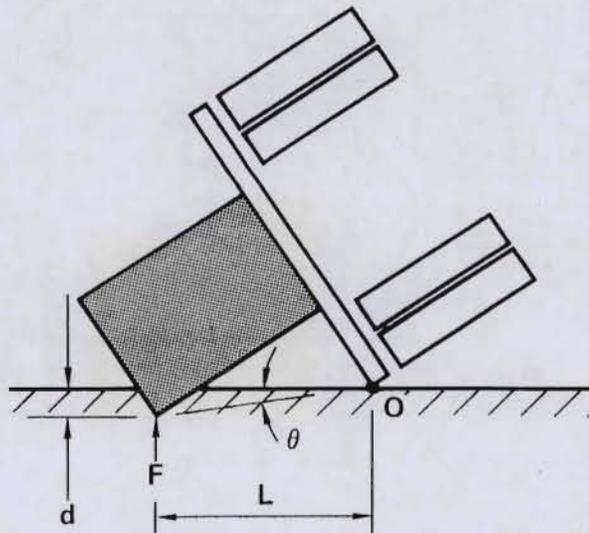


Figure 16. Impact force for the assumed tractor-trailer rollover.

that the effective peak force will be about two to three times the average value.⁸ In the case being considered here, the cask is cylindrical and strikes the pavement on its top edge. Test data are not available for this type of impact, but based on the available information, we believe that the foregoing factor can be applied in this case as well.

For oblique impacts such as that shown in Fig. 15, forces in the horizontal direction are also generated. Their magnitude is estimated on the basis of the following considerations.

Impact forces in a media such as asphalt are the result of compressive stresses generated in the material as it is crushed. The rate at which the material can be crushed, and the resulting resisting force, is limited by its acoustic impedance, which is a measure of the speed of transmission of stress waves in the media. For most impacts, this limiting rate is achieved.

In Fig. 15, the material surrounding point A is being crushed about equally in both the downward and horizontal directions (to the left). Thus, it can be argued that the resisting forces at this point will be roughly the same in both directions. However, since the object is moving to the left in the figure, the material at point B is only being crushed in the downward direction.

From the preceding, one sees that only half of the surface of the object embedded in the impacted media will be subjected to a horizontal force. Thus, when taken over the entire media interface, the sum of the forces will have a horizontal component equal to about half the vertical component. In the following analyses, we assume this to be true.

From the analysis of the truck rollover mechanics, it was found that the minimum rotational kinetic energy just prior to impact was 277 000 ft-lb. The analyzed system included the two casks and the tractor-trailer. Although the rear cask apparently struck the road before the front cask, we assume for simplicity that the tractor-trailer overturned with both casks striking the road pavement simultaneously.

Thus, the rotational energy corresponding to the impact force for each cask is half the foregoing value, or 138 500 ft-lb.

Inspection of the accident site showed that the impact of the cask with the pavement left an indentation about 3- to 4-in. deep.⁹ Inserting these parameter values into Eq. (10) yields impact forces of 554 000 and 415 000 lb, respectively.

When analyzing impact forces, it is common to express them in terms of "acceleration units," g, according to the following equation:

$$F = Wg = (W)(a/G) \quad , \quad (11)$$

where

- F = force (lb)
- W = Weight (lb)
- g = acceleration unit
- a = acceleration (ft/s²)
- G = acceleration due to gravity (ft/s²).

For the overturning truck, W equals 37 300 lb (weight of one cask and one-half of the tractor-trailer). Thus, the preceding impact forces correspond to 14.9 and 11.1 g, respectively.

As discussed previously, the effective peak force is estimated to be 2 to 3 times larger than the average force. Using these factors and the foregoing average values of the impact force, we find a minimum estimate of 22 g and a maximum estimate of 45 g. Therefore, the estimated impact acceleration is 33.5 ± 11.5 g.

Because of the imprecise nature of our estimate, we round off our result and assume in all subsequent calculations that the vertical impact acceleration is 30 g. This corresponds to a vertical impact force of 1.12×10^6 lb. Also, as just discussed, we assume a horizontal force of one-half this value, or 5.60×10^5 lb, in the direction opposite the truck's travel.

It should be emphasized that this calculation is based on the estimated minimum rollover velocity. The actual rollover velocity and energy cannot accurately be determined from the available information.

ANALYSIS OF THE CASKS AND THEIR TIE-DOWN SYSTEMS UNDER IMPACT LOADS

Cask Response

When the tractor-trailer overturned in this accident, the casks struck the road pavement on their top edges. For an edge impact, the most probable cask failure modes which could lead to a radioactive release are loss of the lead shielding due to deformation during impact, and failure of the cask cover bolts. These two cases are analyzed below. The evaluations are based on analyses contained in Ref. 5.

A bounding calculation of the cask shielding deformation is based on energy considerations. The kinetic energy of the cask during impact must be absorbed by the cask shell and shielding material (lead), or by the impacted media. For the bounding calculation, we assume that the impacted media is unyielding, and neglect the presence of the stainless steel shell. Thus, all the kinetic energy of the cask just prior to the collision must be absorbed by the lead shielding. Based on data from impact tests using lead, the capacity to absorb energy can be expressed as⁵

$$E = V k \quad , \quad (12)$$

where

- V = volume of material displaced (in.³)
- k = energy absorbed per unit volume 10 000 in.-lb/in.³ for lead)
- E = absorbed energy (in.-lb).

Therefore, the volume of displaced material is equal to

$$V = KE/k \quad , \quad (13)$$

where

- KE = kinetic energy of cask just prior to impact (in.-lb).

For an edge impact, the volume of deformed material can be represented as shown in Fig. 17. The volume of displaced lead is

$$V = (D/2)^3 (\tan \alpha) \left(\sin \theta - \frac{\sin^3 \theta}{3} - \theta \cos \theta \right) , \quad (14)$$

where

- D = cask diameter (in.)
- α = angle between cask centerline and vertical (rad)
- θ = angle between cask centerline and edge of displaced volume (rad).

Equating expressions (13) and (14) yields

$$KE/k = (D/2)^3 (\tan \alpha) \left(\sin \theta - \frac{\sin^3 \theta}{3} - \theta \cos \theta \right) . \quad (15)$$

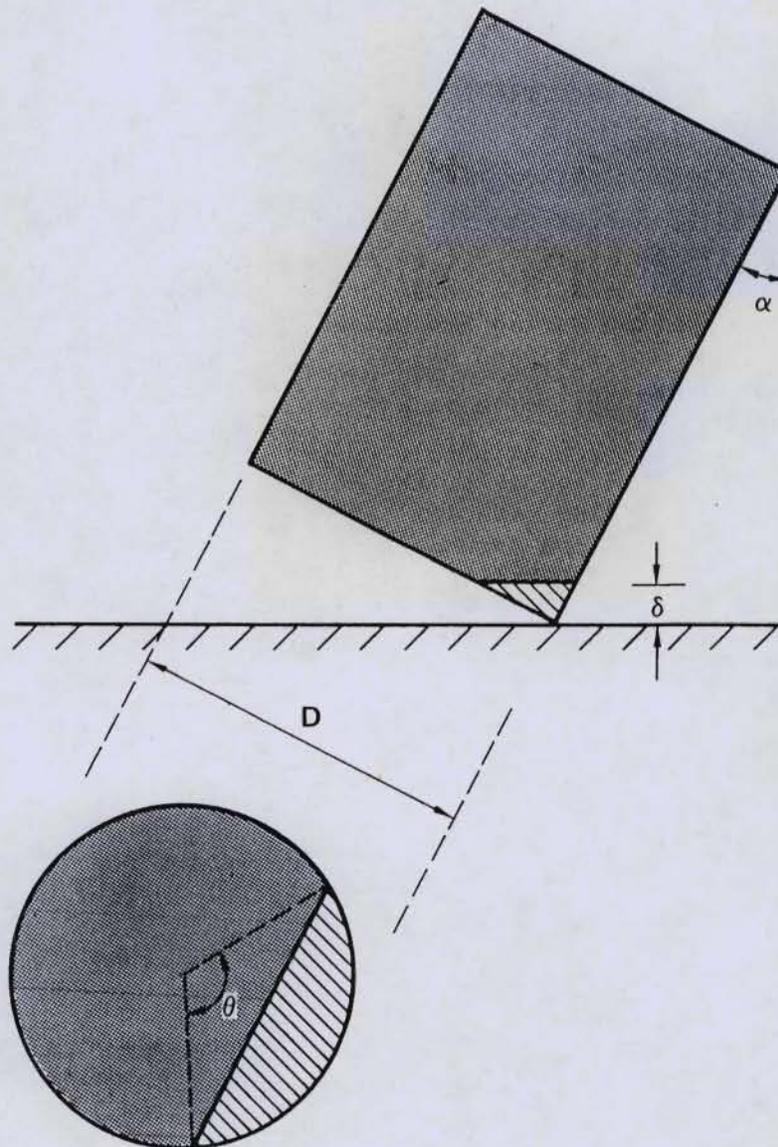


Figure 17. Deformation of the cask by an edge impact.

The kinetic energy of each cask just prior to impact was estimated in the previous section to be 138 500 ft-lb, or 1.66×10^6 in.-lb, and the diameter of the lead shielding is 39.5 in. From the configuration of the loaded casks when they strike the road, it is found that

$$\alpha = 1.12 \text{ rad } (64.2^\circ) .$$

By trial and error, we find from Eq. (14) that

$$\theta = 0.61 \text{ rad } (35.0^\circ) .$$

Based on the foregoing geometry, the depth of deformed material, as shown in Fig. 17, is

$$\delta = 0.82 \text{ in.}$$

The amount of deformation (calculated as an upper bound) is less than 14% of the 6-in. thickness of lead. The casks were designed to safely withstand an 82% deformation of the lead shielding for an edge impact.⁵

For the empty casks, the impact force resulting from the mass of the cask cover will produce both tensile and shear stresses in the cover bolts. These stresses are evaluated below.

If the weight of the cover is conservatively assumed to act at point A, as shown in Fig. 18, the maximum tensile load on the bolts can be estimated.

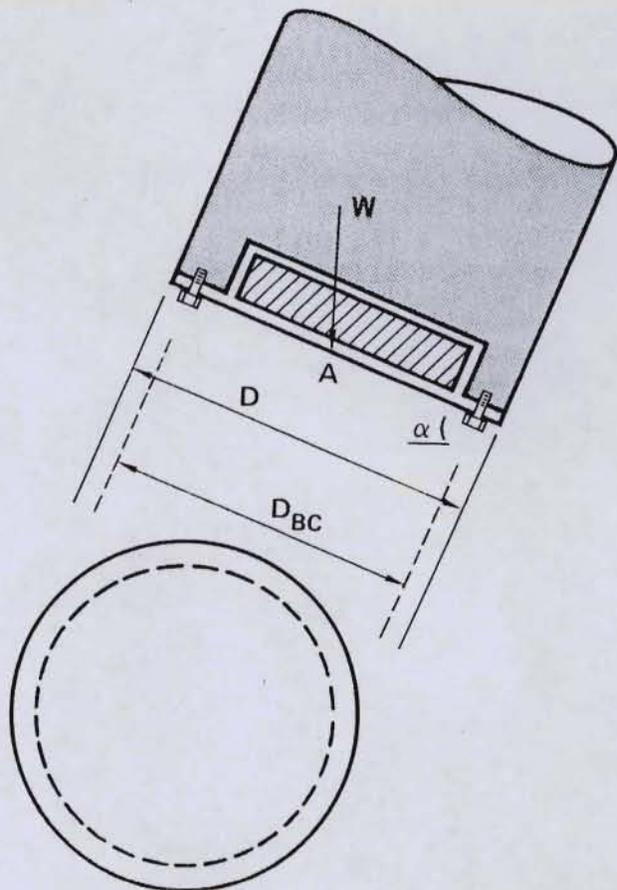


Figure 18. Assumed loading due to the mass of the cover for an edge impact of the cask.

Assuming that slippage does not occur between the cover and the cask at their interface, the largest bolt tensile stress occurs in the bolt farthest from the point of impact, and is given by the following equations:

$$\sigma = (Wg)(\cos \alpha)/nA + (Mc/I_0) \quad , \quad (16)$$

$$M = (Wg)(\cos \alpha)(D/2) \quad , \quad (17)$$

$$c = (D + D_{BC})/2 \quad , \quad (18)$$

$$I_0 = \Sigma (I_C + Ad^2) \quad , \quad (19)$$

where

- σ = bolt tensile stress (lb/in.²)
- W = weight of cover (= 3 460 lb)
- a = impact acceleration (f/s²)
- g = acceleration unit
- D = cask diameter (= 41.0 in.)
- D_{BC} = bolt circle diameter (= 37.0 in.)
- I_C = area moment of inertia for one bolt about its neutral axis (= 0.0319 in.⁴)
- I_0 = effective area moment of inertia for all bolts (in.⁴) ,
- A = effective area of one bolt (= 0.633 in.²)
- d = distance of each bolt from a horizontal axis through impact point (in.)
- α = angle between cask face and horizontal (deg)
- n = number of bolts (= 12).

For the assumed accident scenario, $\alpha = 64.25^\circ$, and $g = 30$. Inserting the above parameter values into Eqs. (16) through (19) yields

$$\begin{aligned} M &= (9.24 \times 10^5) \text{ in.-lb} \\ c &= 39.0 \text{ in.} \\ I_0 &= 4\,490 \text{ in.}^4 \\ \sigma &= (Wg)(\cos \alpha)/nA + Mc/I_0 = 14\,000 \text{ psi.} \end{aligned}$$

The tensile strength of the ASTM-type A325 bolts used with the casks is 120 000 psi,⁵ which is well above the calculated stress.

The margin of safety is equal to

$$\text{margin of safety} = \frac{120\,000}{14\,000} - 1 = 7.6 \quad .$$

The shear stress for the bolt is given by

$$\sigma_{sh} = (Wg)(\sin \alpha)/nA \quad . \quad (20)$$

Inserting the previously specified parameter values into Eq. (20) yields

$$\sigma_{sh} = 12\,300 \text{ psi} \quad .$$

The shear strength of the A325 bolts is 89 000 psi,⁵ and the margin of safety is

$$\text{margin of safety} = \frac{89\,000}{12\,300} - 1 = 6.2 \quad .$$

Estimate of Tie-Down Cable Forces

During the collision of the casks with the road pavement, the shipping casks were released when the tie-down devices failed. In every case, either the trailer D-ring or tie-down cable assembly broke. To determine the safety of these devices, we estimate the impact forces generated in the cables and compare them to their breaking strengths.

The calculation of the cable forces is made using a linear spring model. That is, when loaded by a force, it is assumed the cable will stretch slightly, resulting in a resisting force which is proportional to the amount of elongation. Such an assumption is necessary since the set of forces in the cable tie-down system is statically indeterminate and could not otherwise be solved. This situation is illustrated by the simple example shown in Fig. 19.

In this example, a hinged bar is attached to four cables of unequal length, which we model as linear springs. An upward force is applied at the unhinged end of the bar, and we wish to calculate the forces created in the four cables. One finds that this system is statically indeterminate, but by using the assumed spring model for the cables, the system can be solved.

For example, for small angles of rotation the amount of elongation will be proportional to the distance from the hinged end, and similarly for the forces in the cables, if the spring constant is assumed equal for all cables. The forces in cables 2, 3, and 4 can thus be expressed in terms of their ratio to the force in cable 1. With this assumption, the problem is reduced to one unknown force and the system can be solved by summing moments about the hinged point.

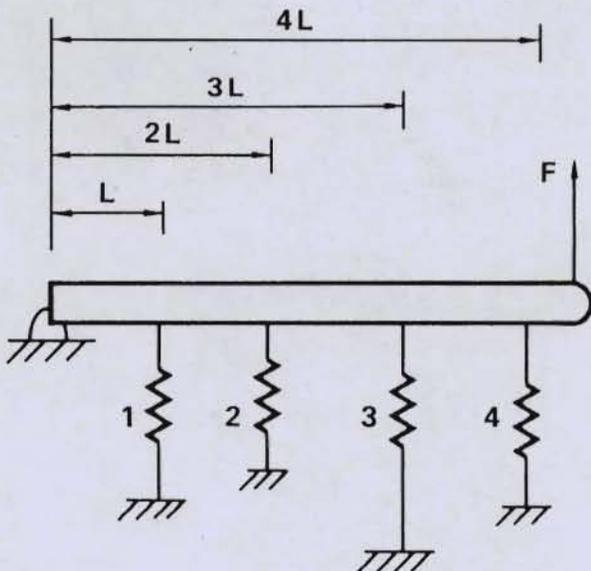


Figure 19. Example of spring system with indeterminate force distribution.

The calculated forces must then be scaled according to the ratio of the lengths of the cables. This is because the cables are of unequal lengths, and according to the linear spring assumption, the spring force is inversely proportional to its unstrung length for a given amount of elongation.

For the case of the casks and their tie-down cable assemblies, the solution is obtained in an analogous manner (except in three dimensions instead of two). The calculational method is outlined below.

1. For the application of a force on the top edge of the cask, assume that it will tip about an axis which is at the intersection of the bottom edge and the resultant of the x and y components of the applied force (x and y in the plane of the trailer bed).
2. For the case of impending tipping, calculate the incremental change on length which would occur in each of the tie-down cables by resolving the displacements in the three coordinate directions.
3. Assume a linear spring model for failure of the cables. That is, the forces created in the cables are proportional to the amount of elongation. For cables that decrease in length, the force is zero.
4. Using the assumption of step (3), express the force in each of the other cables as the ratio to one cable. This allows one to reduce the problem to only one unknown force. The system of equations is otherwise indeterminate and cannot be solved.
5. Calculate the values of the forces by summing moments about the axis of rotation.
6. Using the forces calculated in step (5), determine the actual cable forces by multiplying by the ratio of cable lengths. This is based on the assumption that for a given amount of elongation, the force is inversely proportional to cable length.

The calculation of the change in length of the cables in step 2 can be evaluated by considering the case shown in Fig. 20. For small angles of rotation θ of the point B about point A, the incremental change in length in the radial direction can be ignored. The change in length in the normal direction δs is equal to

$$\delta s = l \sin \theta \cong l\theta \quad , \quad (21)$$

where

$$\begin{aligned} l &= \text{distance between point and axis of rotation (ft)} \\ \theta &= \text{angle of rotation (rad)}. \end{aligned}$$

The cask is assumed to rotate in the x-z plane as shown in the figure, so the displacement of point B in the y-direction is zero. The displacements of point B in the x- and z- directions are equal to

$$\delta x = \delta s \cdot \cos \phi = (l\theta) (H/l) = H \cdot \theta \quad , \quad (22)$$

$$\delta z = \delta s \cdot \sin \phi = (l\theta) (L/l) = L \cdot \theta \quad , \quad (23)$$

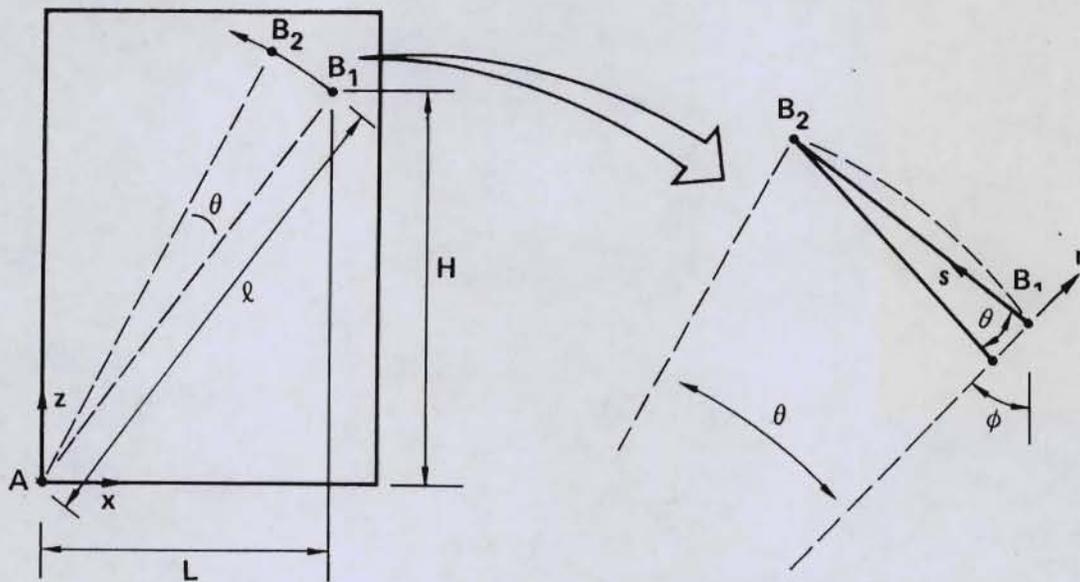


Figure 20. Geometric displacements for an incremental rotation of the cask.

where

- δx = displacement in x-direction (ft)
- δz = displacement in z-direction (ft)
- ϕ = angle between vertical and line connecting cable attachment point and axis of rotation (rad)
- H = height of cable attachment point on cask (ft)
- L = horizontal distance from cable attachment point on cask to axis of rotation (ft).

For a cable attached at point B, its change in length due to the incremental rotation is equal to

$$\delta c_i = \left[(x_i + H_i \theta)^2 + (y_i)^2 + (z_i + L_i \theta)^2 \right]^{1/2} - \left[(x_i)^2 + (y_i)^2 + (z_i)^2 \right]^{1/2}, \quad (24)$$

where

- c_i = change in length of cable i
- x_i = x-component of distance between cable attachment points on the cask and trailer
- y_i = y-component of distance between cable attachment points on the cask and trailer
- z_i = z-component of distance between cable attachment points on the cask and trailer
- H_i = height of cable attachment point on cask
- L_i = horizontal distance from cable attachment point on cask to axis of rotation
- θ = angle of rotation.

Expanding expression (24) and neglecting second order terms yields

$$\delta c_i = (a_i + b_i \theta)^{1/2} - (a_i)^{1/2} , \quad (25)$$

where

$$a_i = (x_i^2 + y_i^2 + z_i^2)^{1/2} ,$$

$$b_i = (2)(x_i H_i + z_i L_i) .$$

The ratio of changes in length for two cables, 1 and 2, is thus equal to

$$\frac{\delta c_1}{\delta c_2} = \frac{(a_1 + b_1 \theta)^{1/2} - (a_1)^{1/2}}{(a_2 + b_2 \theta)^{1/2} - (a_2)^{1/2}} . \quad (26)$$

Expression (26) can be evaluated for small angles of rotation using the following relationship:

$$\lim_{\theta \rightarrow 0} \left[\frac{\delta c_1}{\delta c_2} \right] = \left[\frac{d(\delta c)_1 / d\theta}{d(\delta c)_2 / d\theta} \right]_{\theta = 0} . \quad (27)$$

Inserting expressions (26) into (27) gives

$$\lim_{\theta \rightarrow 0} \left[\frac{\delta c_1}{\delta c_2} \right] = \frac{(b_1)(a_1)^{-1/2}}{(b_2)(a_2)^{-1/2}} . \quad (28)$$

Expression (28) can now be used in step 4 of the previously outlined calculational procedure to express the forces in each of the cables as the ratio to one cable (this is an interim result which assumes that the cables are of equal length and have the same spring constant). The system of forces can then be solved by summing moments about the axis of rotation at point A. The cable forces can finally be determined in step 6 by scaling the results in step 5 by the ratio of unsprung cable lengths.

The cask tie-down configuration used on the trailer involved in this accident is shown in Fig. 21. For the impact force shown, it is assumed the cask will tip about the cable attachment point at A. The actual intersection of the cask edge and the resultant of the assumed impact force is a small distance (0.25 in.) from point A, but we assume that the cask rotates about this point since this simplifies the calculation greatly by virtue of symmetry.

The assumed impact force has components of 1.12×10^6 lb (30 g) in the direction perpendicular to the roadway, and 5.60×10^5 lb (15 g) in the direction parallel to the road. The orientation of this force with respect to the cask is as shown in the figure. The magnitude, point of application, and direction of the impact force were determined in previous sections of this report.

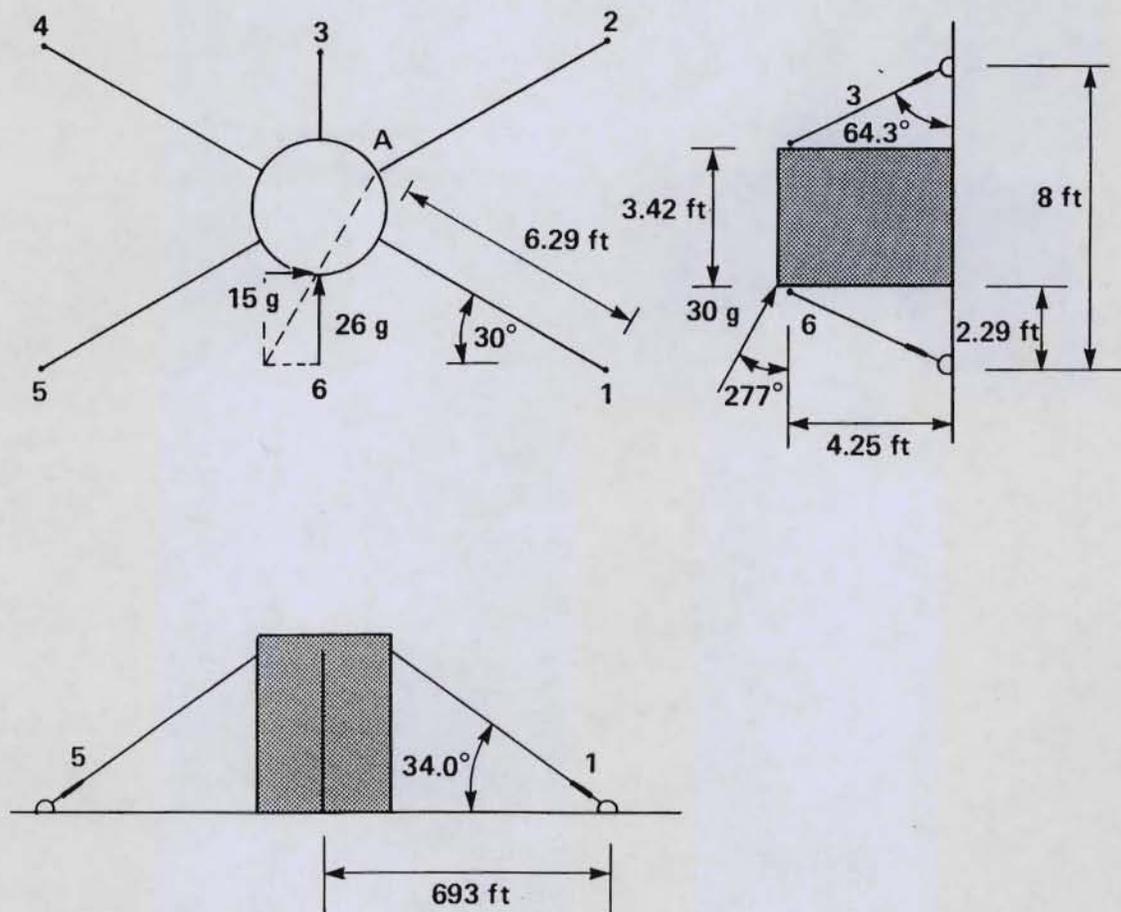


Figure 21. Configuration of the cask tie-down cables and the assumed impact force.

For the assumed impact mode, it is found that only cables 4, 5, and 6 will be loaded. For the numbered cables the estimated loads in pounds are

1	0
2	0
3	0
4	139 000
5	236 000
6	223 000

The maximum estimated cable load is 236 000 lb. The tie-down cables are 5/8-in. rope made of plough steel with a breaking strength of about 26 000 lb,¹⁰ while the ratchet binders used to connect the cables to the trailer D-rings break, according to their manufacturer, at 23 000 lb.⁹ Since these ratings are well below the estimated loads, the cables would be expected to fail in an accident such as this involving a rollover.

The foregoing analysis neglects the cable preload imposed by the ratchet binder. The resulting preload adds to the cable stress but was neglected in the preceding calculations since the magnitude of the preload is not known. The actual amount of preload imposed on the cables is not specified in the

shipping procedures, and thus can vary depending upon the judgment of the individual shipper. We believe the preload can be a significant factor in determining the safety of the cables and it should be specified in a uniform set of procedures when transporting this type of cask.

TEST RESULTS FOR D-RING TIE-DOWN DEVICES

Three of the D-rings from the damaged trailer were examined using conventional metallographic techniques to determine their cause of failure. The selected D-rings are labeled L2, L4, R2, and R3 in Fig. 6.

No information was available on the type of material used to make the D-rings, but their microstructure resembles that of AISI 1018 steel. Figure 22 shows the microstructure for one of the rings.

All of the examined rings failed in the steel rod in the heat-affected zone just above the junction of the weld bead and the top side of the support plate (for example, see Fig. 7(b)). Figure 23 shows the structure of the metal at weld junction for one of the samples. The darker material in the upper left corner is the weld bead, while the lighter material is the base metal. The dark ring in the base metal adjacent to the weld bead indicates overheating into the austenite range during welding, and the subsequent formation of martensite. Hardness measurements confirmed the presence of martensite in the samples. Martensite is brittle and would be a probable nucleation site for cracks which could lead to failure during high loads such as those experienced in the accident.

The welds were generally of poor quality. In addition to the overheating problem described, the welds contained numerous large pores and showed lack of adherence between the weld bead and base metal over large areas. These defects are illustrated in Figs. 24 and 25. Figure 23 also shows a notch (crack) at the root of the weld bead. The basic joint configuration is conducive to crack formation at the root of the weld during cooling.

A tensile test was conducted on one of the D-rings, which survived the accident without apparent damage, to determine its breaking strength. The tested D-ring is labeled L4 in Fig. 6.

The load was applied to the ring by gripping the midpoint of the rod between the two welds to the plate and pulling perpendicular to the surface of the plate. The rod failed at a stress of 56 000 psi. The applied load was 88 000 lb. The failure occurred in the heat-affected zone of the weld, as was the case in the accident for the other D-rings. The rated ultimate strength of AISI 1018 steel is 75 000 to 80 000 psi.⁵ Based on the rated strength of 75 000 psi, the D-ring would fail with an applied load of 118 000 lb. Thus, it is apparent that the welding caused a significant degradation in the strength of the rod. This conclusion is also supported by the results of the metallurgical analysis.

HYPOTHETICAL LOADING CONDITIONS FOR FULL CASKS

In the previous analyses, we have assumed that the casks are empty, in accordance with the actual accident. However, it is of interest to repeat the analyses assuming that the casks were loaded to predict whether they would have failed in this case.

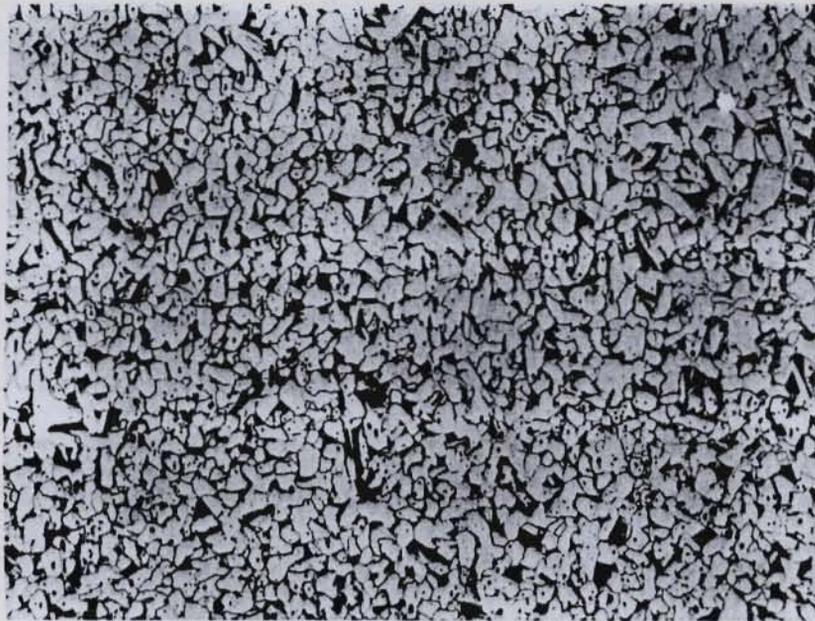


Figure 22. Microstructure of the D-ring material (100X).

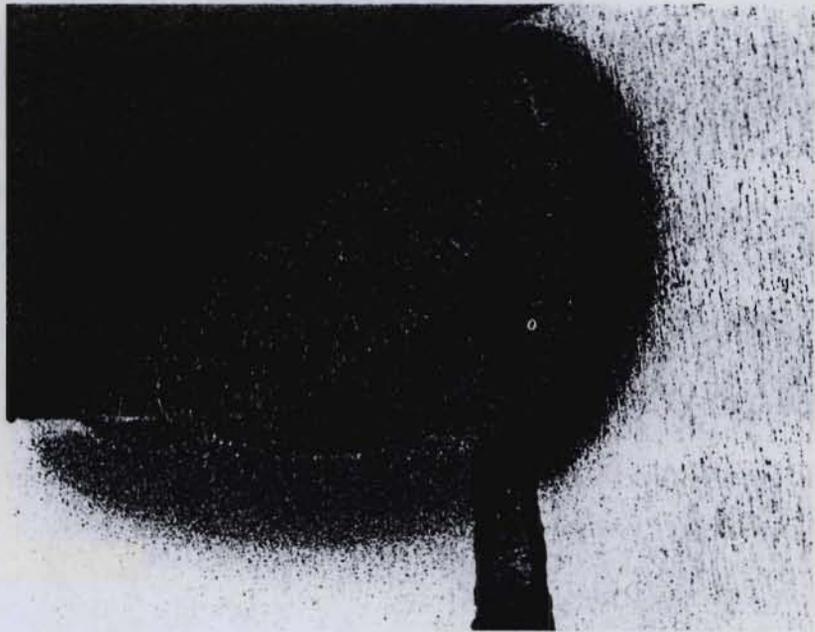


Figure 23. Structure of the metal near weld bead for the D-ring sample showing presence of martensite (10X).

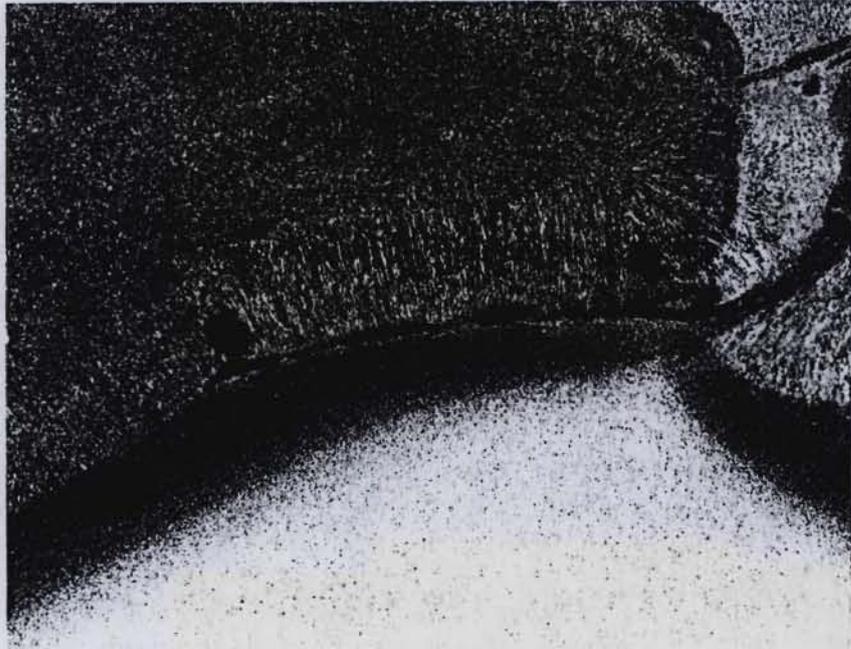


Figure 24. Structure of the metal near weld bead for the D-ring sample showing unfilled voids (10X).

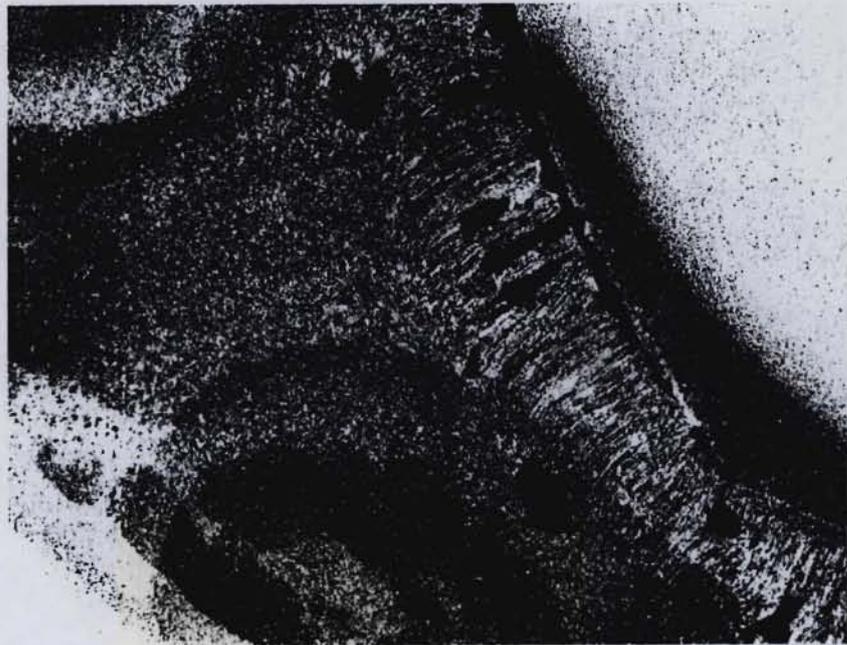


Figure 25. Structure of the metal near weld bead for the D-ring sample showing lack of adherence between weld and base metal (10X).

The empty shipping casks weigh about 20 500 lb, compared to 22 200 lb when they are filled with radioactive material encased in concrete. The results of the analyses using the higher cask weight are summarized in Table 1.

Table 1. Comparison of analyses results for empty and full shipping casks.

	Empty casks	Full casks
Weight of casks (lb)	20 500	22 200
Weight of contents (lb)	0	1700
Center-of-mass height for loaded trailer (in.)	68.3	69.1
Rotational kinetic energy just prior to impact (ft-lb)	277 000	285 000
Angular velocity just prior to impact (deg/s)	15.2	15.4
Vertical impact acceleration (g)	30	30
Horizontal impact acceleration (g)	15	15
Vertical impact force (lb)	1.12×10^6	1.21×10^6
Horizontal impact force (lb)	5.60×10^5	6.06×10^5
Fraction of cask lead shielding deformed by impact	0.14	0.15
Margin of safety for tensile stress in cask cover bolts	7.6	4.8
Margin of safety for shear stress in cask cover bolts	6.2	3.8
Tie-down cable forces by cable number (lb)		
1	0	0
2	0	0
3	0	0
4	139 000	150 000
5	236 000	256 000
6	223 000	241 000

As can be seen from the analysis results, the conclusions are unchanged from the case with empty casks. That is, neither the empty nor loaded casks will fail due to the impact when the truck overturns, but the cask tie-down assemblies will fail in both cases.

SUMMARY AND CONCLUSIONS

Our investigation of this accident showed that the shipping casks did not receive significant damage despite the apparent severity of the accident. Neither fractures nor significant deformations to the casks were observed. The casks were empty at the time of the accident, but the analysis indicates that the casks would not have failed had they been filled.

We believe that the greatest risk to the integrity of the casks occurred when they struck the road pavement when the tractor-trailer carrying them overturned. As a result, the cask tie-down cable assemblies failed. The casks apparently did not strike each other or any other objects when they were thrown free of the trailer.

The most probable failure mechanisms for an edge impact on the casks are loss of the lead shielding material due to deformation, and failure of the bolts used to attach the cask to its cover. These two cases were analyzed and it was found that the estimated loads were well below those which would cause failure.

However, in agreement with observed fact, our analysis shows that the cask tie-down devices will fail under the estimated impact loads for the inferred accident scenario. It was not possible to estimate from the available information the fraction of the tractor-trailer's total kinetic energy at the time of the collision which was dissipated by the tie-down system.

The following is a summary of specific results of the accident analysis.

1. The estimated cask accelerations during the impact of the casks with the road pavement are 30 g vertically and 15 g horizontally, with respect to the road.

For an edge impact, the casks were designed to safely withstand an acceleration of 53 g.

2. The estimated impact forces for the empty casks based on the calculated accelerations are 1.12×10^6 lb vertically and 5.60×10^5 lb horizontally.
3. Based on the assumed impact acceleration, the amount of deformation in the cask's lead shielding is estimated to be 14%. The casks were designed to safely withstand an 82% deformation of the lead shield for an edge impact.
4. Based on the assumed impact acceleration, the bolts used to attach the cask to its cover would not fail. The margins of safety are 7.6 for the tensile load, and 6.2 for the shear load.
5. The largest calculated cable force for the assumed impact load is 236 000 lb. This is well above the breaking strength of 26 000 lb for the cables, and 118 000 lb for the D-rings if properly welded.

6. Results of a tensile test on one of the D-ring assemblies that appeared to be undamaged after the accident showed that it failed at a load of 88 000 lb. This is less than its expected strength of 118 000 lb.
7. Poor welds probably contributed to the failure of some of the D-ring assemblies used to connect the cask tie-down cables to the trailer.

The following recommendations are made to further improve the safety of transporting these shipping casks.

1. Use a trailer that allows the load to be lower, thus reducing the risk of rollover.
2. Require that more specific tie-down procedures and devices be employed when securing the casks to the trailer for shipment.

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16. ABSTRACT (200 words or less) An accident involving a passenger automobile and a tractor-trailer carrying two empty shipping casks for transporting low-level radioactive materials occurred on November 3, 1982, near Hilda, SC. The purpose of this report is to document the mechanical circumstances of the accident, and to assess the types and magnitudes of accident environments to which the casks were subjected. The report contains two major parts. The first concerns the accident description, which includes fact-finding and the inferred accident scenario. The second part deals with the mechanical analysis of the accident, consisting of estimates of the impact loads and an assessment of the response of the casks and their tie-down systems. Discussions of results and recommendations are also included.					
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