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Yucca Mountain Site Characterization Project

Effects of a Potential Drop of a Shipping Cask, a Waste Container, and a Bare Fuel Assembly During Waste-Handling Operations

C. L. Wu, J. Lee, D. L. Wu, L. J. Jardine
Bechtel National, Inc.
50 Beale Street
San Francisco, CA 94105

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
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EFFECTS OF A POTENTIAL DROP OF A SHIPPING CASK, A WASTE CONTAINER,
AND A BARE FUEL ASSEMBLY DURING
WASTE-HANDLING OPERATIONS

by

C. L. Wu, J. Lee, D. L. Wu, L. J. Jardine

Bechtel National, Inc.
50 Beale Street
San Francisco, CA 94105

for

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Under Sandia Contract: 52-9817

Sandia Contract Monitor
C. V. Subramanian
Principal Investigator
C. V. Subramanian
Nuclear Waste Engineering Projects Division

ABSTRACT

This study investigates the effects of potential drops of a typical shipping cask, waste container, and bare fuel assembly during waste-handling operations at the prospective Yucca Mountain Repository. The waste-handling process (one stage, no consolidation configuration) is examined to estimate the maximum loads imposed on typical casks and containers as they are handled by various pieces of equipment during waste-handling operations. Maximum potential drop heights for casks and containers are also evaluated for different operations.

A nonlinear finite-element model is employed to represent a hybrid spent fuel container subject to drop heights of up to 30 ft onto a reinforced concrete floor. The impact stress, strain, and deformation are calculated, and compared to the failure criteria to estimate the limiting (maximum permissible) drop height for the waste container. A typical Westinghouse 17 x 17 PWR fuel assembly is analyzed by a simplified model to estimate the energy absorption by various parts of the fuel assembly during a 30 ft drop, and to determine the amount of kinetic energy in a fuel pin at impact. A nonlinear finite-element analysis of an individual fuel pin is also performed to estimate the amount of fuel pellet fracture due to impact.

This work was completed on May 1990.

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EXECUTIVE SUMMARY

Scope

This study investigates the effects of potential drops of a typical shipping cask, a waste container, a bare fuel assembly, and an individual fuel pin during the waste-handling operations at the potential Yucca Mountain repository.

The waste-handling process for the waste-handling building (one stage, no consolidation configuration) is examined. Several waste-handling scenarios involving cask and container impacts are described, estimates are made of the maximum loads imposed on different parts of a cask or container, and methods of mitigating the effects of these impacts are discussed.

Impact analyses are performed to estimate the limiting drop height of a waste container (the maximum height it can fall without unacceptable damage) and to assess the potential damage to a bare fuel assembly/individual fuel pin in the event of an assembly/pin drop. For the case of a spent fuel assembly, the mechanism of fuel pellet pulverization is discussed.

Cask and Container Drops During Waste-Handling Operations

For a shipping cask, the following cases were considered: toppling, rolling off a cask transfer car and landing in a horizontal position on the floor, swinging against a wall or a 2 in. dia. object, and falling 2 ft. The results of these load envelope studies indicate that maximum stresses occur when the cask rolls off a transfer car and strikes the floor. These maximum (compressive) stresses are about 21,000 psi and 19,000 psi for a truck cask and a rail cask, respectively. Because these stresses do not exceed the allowable stress* (21,000 psi) for 304L stainless steel, neither truck cask nor rail cask should fail.

* The allowable compressive stress is taken to be 60 percent of the yield stress.

For an empty container, the following cases were considered: dead load, ovaling due to stacking, swinging like a pendulum, impacting the hot-cell walls, impact between containers, swinging against a stationary 2 in. dia. and 1 ft dia. object, and striking a concrete floor after free-falling 2 ft or 34 ft. The results of this load envelope study indicate that the maximum stresses occur as a consequence of a free fall from the maximum drop height of 34 ft or of an impact on the hot-cell walls. These stresses are about 26,000 psi (compressive) and 22,000 psi (bending). The bending stress is less than the allowable stress (23,000 psi) for 304L stainless steel; the compressive stress is slightly greater than the allowable stress (21,000 psi) for 304L stainless steel, but will not result in a fracture of the container.

For a loaded container, the following cases were considered: dead load; swinging like a pendulum; impacting the hot-cell walls; swinging against a stationary 0.2 in. dia. or 6 in. dia. object; free-falling 2 ft onto the floor, a 6 in. dia. object, or a 2 in. dia. object; and seismic loads. The results of the load envelope study indicate that the maximum stress occurs when the container impacts the hot-cell walls or a 2 in. dia. stationary object. The value of this stress is about 81,000 psi (bending), which is almost four times as great as the allowable stress for 304L stainless steel, but not great enough to result in a fracture. (The ultimate strength of this material is 85,000 psi, and the critical fracture strength is 228,000 psi.)

There are several ways of mitigating the effects of a potential drop. These mitigation techniques, which are based on the load analysis and potential drop heights, include equipment rearrangement, structural modifications, and the use of energy-absorbing materials.

Determining the Limiting Drop Height of a Loaded Container

Investigations were carried out to determine a loaded (spent fuel) waste container's limiting drop height, defined as the maximum vertical distance the container can fall without being shortened through impact by more than 1.0 in. and without undergoing an effective plastic strain greater than 0.15. A literature search was conducted to collect

published information. Next, three finite-element impact analyses using the computer program, DYNA3D, were performed for drop heights of 30 ft, 7.5 ft, and 5.0 ft. The results of these analyses were compared with the results of experimental tests, described in the literature, involving a 30 ft drop of defense high-level waste (DHLW) canisters. It was found that:

- o The results of the DYNA3D analysis for a 30 ft drop of a loaded spent fuel container agree with those of the experimental drop tests for a DHLW canister.
- o The limiting drop height of a loaded spent fuel container is about 3.8 ft.

To obtain a more detailed analysis, future studies of the effects of impact on a loaded spent fuel or DHLW waste container are recommended. These studies should cover:

- o The effect of container impact orientation, especially impacts directly on the pintle of the container
- o The effect of total container weight on the limiting drop height
- o The effect on the limiting drop height of (1) interactions between the fuel assemblies and (2) interactions between the fuel assemblies and the container
- o The effects of impacts on sharp objects and for various target conditions

Analysis of an Accidental Drop of a Typical Bare Fuel Assembly or of an Individual Fuel Pin

The analysis of an accidental drop of a fuel assembly or a fuel pin proceeded as follows: (1) a literature search was performed; (2) hand calculations were carried out to estimate the energy absorption by the various parts and fuel pins of a fuel assembly; and (3) a finite-element

impact analysis was conducted by employing the computer program, DYNA3D, for an individual fuel pin within a fuel assembly. In both the hand calculations and the finite-element analysis, a 30 ft drop was assumed.

As a result of these studies, the following conclusions were drawn:

- o The friction between fuel pins and the grid spacers dissipates only a small amount of the impact energy, approximately equal to 3 percent of the total kinetic energy imparted to the fuel pins.
- o The bottom 1.3 in. of fuel pellets (which is less than 1 percent of the total volume) fractures.
- o The zircaloy cladding fails in the region where the fractured fuel pellet bulges out radially (0.15 to 0.45 in. from the bottom of the fuel pellet).
- o There is no failure in the bottom end plug of the fuel pin.

Further studies on the effect of impacts on fuel assemblies and fuel pins are recommended. These studies should investigate the effect of buckling on the failure of fuel pellets and the zircaloy cladding. A simplified finite-element model can be created for the fuel assembly and its numerous fuel pins. Instead of performing a hand calculation using the energy balance method, one can conduct a finite-element impact analysis of the entire fuel assembly to determine the energy absorption of the bottom nozzle. In this way, the effect of the bottom nozzle on the dynamic response of fuel pins can be accounted for more realistically. The effects of nonperpendicular impact and of impacts on various target conditions should also be investigated.

Fuel Pellet Pulverization

The studies on fuel pellet pulverization performed by Argonne National Laboratory were reviewed. These studies included a series of drop-weight impact tests of representative materials such as pyrex glass, Macor glass ceramic, and sintered UO₂ ceramic.

All results showed that the fracture particulate proper, which included all particles of respirable size (i.e., diameters less than 10 microns), and which contained more than about 90 percent of the total surface area, had a straight-line size distribution when plotted on lognormal graphical coordinates.

It was found the volume fraction of particles with diameters less than 10 microns is directly proportional to input energy density. No significant difference between axial and diametrical impact was found.

Further studies are recommended which examine and develop the relationships and possible correlations between the laboratory-scale results on small specimens and the finite-element analysis results for a single full-scale spent fuel rod.

1.0 INTRODUCTION

1.1 General

The objective of this study is to investigate the effects of a potential drop of a shipping cask (hereinafter referred to simply as "a cask"), a waste container (hereinafter referred to simply as "a container"), and a bare fuel assembly in the waste-handling building (WHB) during waste-handling operations. The drop may occur because of a malfunction of handling equipment, a seismic event, etc. Estimates of the radiological consequences of a drop in the WHB are required to support preclosure radiological safety analyses.

Casks and containers are handled by various types of equipment. The maximum loads imposed by the handling equipment on the casks and containers have to be estimated to provide information needed for conceptual design. This study estimates the maximum equipment loads and defines the design conditions for the casks and containers during normal waste-handling operations.

If a bare fuel assembly is dropped within a hot cell, it may strike the concrete floor or other objects, the fuel pins may be damaged, and a certain amount of the spent fuel may be fractured or pulverized. This can cause radioactive spent fuel particles or dust to become airborne, resulting in a possible radiological safety problem. To perform an adequate radiological safety analysis of the hot cell confinement system, the amount of fuel pulverized from the event must be estimated. The phenomenon of fuel pellet pulverization is discussed in this report, but no estimate is given.

In this report, frequent reference is made to three types of drop heights: (1) limiting drop height (the maximum permissible vertical distance that an object may fall without unacceptable damage), (2) potential drop height (the most probable drop height,

based on the current surface facility design), and (3) maximum drop height (the unobstructed height from the lowest floor elevation along the travel path of the cask or container, to the highest elevation to which the bottom of the cask or container can be lifted).

1.2 Scope

In this study, load envelopes for casks and containers are estimated, and the drops of a cask or container and a bare fuel assembly are investigated. The following activities are included:

- o Investigating various types of casks, containers, and fuel assemblies and selecting one of each type as typical for use in this study
- o Evaluating the waste-handling process, which was assumed to be, for the purpose of this report, one stage without consolidation (Ref. 1), and estimating the envelope of maximum forces imposed upon various parts of a typical cask and container as they are handled by different equipment during normal operations
- o Evaluating the limiting drop heights of the container (including a qualitative consideration of the range of impact angles on flat surfaces, blunt and sharp objects, and the likelihood of penetration during the drop) and comparing these values with potential values as the containers are moved through various waste-handling operations in the WHB
- o Identifying the equipment and areas in the WHB subject to potential impacts and proposing equipment rearrangements or structural modifications to mitigate the potential impact effects.

- o Evaluating the characteristics and feasibility of using energy-absorbing materials to reduce the effects of an impact in the identified areas of the WHB subject to potential cask and container drops
- o Performing a literature search related to the analysis of a drop of a fuel assembly
- o Studying the accidental drop of a typical nuclear fuel assembly during the waste-handling operations and the effect of the assembly drop on fuel pins and fuel pellets, including
 - Estimating the amount of energy absorbed upon impact by a typical fuel assembly and by the individual fuel pins and fuel pellets
 - Investigating the behavior of the fuel pellets and establishing the basis for estimating the amount of pulverization of the spent fuel using existing and limited experimental impact data for fuel pellets

Preliminary hand calculations were performed to estimate the load envelopes and potential drop heights of the cask and waste container during the repository operation. The same type of calculations were made to estimate the energy absorption by various parts of the fuel assembly and to determine the impact velocity of an individual fuel pin. Finite-element models using nonlinear material properties were employed in computations for the structural responses of the drop of container and fuel assemblies to assess the potential damage to the container and the fuel. These calculations involve a great deal of simplification of the complicated physical systems, but provide a rough estimate of the design parameters and system response during impact. The preliminary results of this study are suitable for the conceptual design effort in the design studies for the cask and container, as well as for the radiological safety studies. As the design

progresses, more accurate results may be needed and more sophisticated modeling and analyses will be required.

The fuel consolidation operations, if adopted at the repository, may introduce additional complexity to the analyses for drop of fuel pins, assemblies, and containers, and should be studied as part of further preclosure radiological safety analysis.

1.3 Contents

Section 2.0 of the study report describes the assumptions, operational considerations, analyses, and results for developing the load envelopes and potential drop heights of a cask and a container.

Section 3.0 discusses the assumptions, the literature search, and the estimate of the limiting drop height of a (loaded) container.

Section 4.0 analyzes the accidental drop of a typical bare fuel assembly or of an individual fuel pin.

Section 5.0 discusses fuel pellet pulverization.

Section 6.0 presents the conclusions and recommendations.

Section 7.0 lists the references.

Section 8.0 is an appendix containing RIB and SEPDB information.

2.0 CASK AND CONTAINER DROPS DURING WASTE-HANDLING OPERATIONS

2.1 Assumptions

2.1.1 Waste-Handling Operations

The waste-handling operations considered in this study are based on the one stage, no consolidation configuration of the WHB. The material block flow diagram that describes waste-handling operations is shown in Figure 2-1.* The operations themselves are described in Subsection 2.2.

2.1.2 Casks

In accordance with the NNWSI requirements, casks are designed either for vitrified defense high-level waste (DHLW) or for spent fuel. The reference cask concept (Ref. 2) is shown in Figure 2-2. The casks will be used to carry the designated waste forms in a legal weight shipment using either truck carrier or railcar. A specific cask concept for spent fuel is assumed for this study. Information for the assumed concept is shown in Figures 2-3 and 2-4.

2.1.3 Containers

As identified in Blocks 3.1 and 3.20 of Figure 2-1, two types of containers are used for the repository operations: one for packaging fuel assemblies and the other for the DHLW canisters. The hybrid spent fuel containers used for the fuel assemblies are assumed for this study. Information for the assumed container is summarized in Figure 2-5. The material for the container is assumed to be austenitic stainless steel 304L. Although there are other stainless steel alloys and other metals being considered for the container, they are not considered in this study.

* In this section, the figures are placed at the end, after the text and tables.

2.1.4 Material Properties

For the purpose of this study, it is assumed that the steel parts are made of AISI 304L stainless steel and that 4,000 psi concrete is used for structures. Pertinent physical properties of these materials are given below.

Strengths

- o Stainless steel AISI 304L (Refs. 3,4)
 - Yield strength (F_y) @ 2% 35,000 psi
 - Ultimate strength 85,000 psi
 - Critical normal fracture strength* 228,000 psi
 - Shear yield strength 20,207 psi
- o Concrete
 - Compressive strength (f'_c) 4,000 psi

Young's Modulus (E)

- o Stainless steel (Ref. 4) 28×10^6 psi
- o Concrete (Ref. 5) $57,000 (f'_c)^{1/2} = 3.6 \times 10^6$ psi

Critical Impact Velocity (Ref. 6)*

- o Stainless steel 200 fps

2.1.5 Functional Parameters

The following functional parameters are assumed in this study:

Traveling Speeds

- o Maximum crane speed 60 fpm

* The critical normal fracture strength is defined as the fracture strength of a material under a multiaxial state of stress. It may be expressed as a function of the critical impact velocity, which is a physical property of a material defined as the velocity of impact at which a specimen of the material fractures at the point of impact (Ref. 6).

- o Stop (or start) mode
 - Brake applied at the speed of 30 fpm
 - Distance of travel for complete stop 3 ft

Construction Tolerance

- o General ± 0.0625 in.

Transfer Fixtures

- o Casks Lifting yoke
- o Empty containers Fixture
- o Loaded containers Grapple

2.2 Description of Waste-Handling Operations

Major waste-handling operations during the preclosure period include receiving, preparing, storing, and emplacing waste forms (consisting of spent fuel and DHLW). Only the waste-handling operations in the surface facilities are considered in this investigation.

2.2.1 Waste Receiving and Cask Transfer

Waste is shipped to the repository in casks transported either on trucks or on railcars. All casks, trucks, and railcars are initially inspected and surveyed for radioactive contamination and are checked for security purposes before they enter the waste receiving and inspection area. If contaminated, truck casks and rail casks can be transferred to either the waste-handling building or the decontamination building for removal of the exterior contamination.

In the cask receiving and shipping area of the WHB, the cask shipments are received and the casks are prepared for transfer to the hot cells for waste unloading. After removal of the tiedowns, the cask is transferred, by means of the overhead bridge crane, from the truck trailer or railcar to a cask transfer car - illustrated in Figure 2-6 (Ref. 2). The cask is checked for radioactive contamination, and if no significant contamination is present, its outer cover is removed, followed by the inner lid bolts. A hot cell adapter is attached to the cask to facilitate mating with the hot cell fuel receiving port. The transfer car then moves the cask to a position under the cask unloading cell for the unloading of the waste. After the inner cask lid has been removed, the fuel assemblies or waste canisters are unloaded from the cask through the unloading port into the hot cell.

After unloading, the cask cavity is visually inspected and the spacers and inner lid reinstalled. The cask is returned to the preparation area, where the outer cover is reinstalled. The cask is then transferred, if necessary, to the decontamination station for exterior cleaning. Finally, it is returned to the receiving area for offsite shipment.

Figure 2-7 shows the steps involved in receiving the waste, transferring it to the waste-handling building, and unloading it from the cask. During the transfer operations, the casks are assumed to be handled by means of lifting yokes. In the absence of any specific details for the repository operation, the schematic lifting yoke shown in Figure 2-8 (Ref. 7) is assumed for this study.

2.2.2 Transfer of Empty Containers

Empty containers are transferred on a monorail (Figure 2-9) from the storage area to the transfer air locks. From the air locks, the containers are transported on transfer cars into hot cells A and B (see Figures 2-10 and 2-11). In the hot cells, the empty

containers are transferred to weld stations using the overhead cranes and transfer fixtures. Since no details are currently specified for the repository operation, the fixture designed for the Waste Isolation Pilot Plant (WIPP), shown as Figure 2-12, is used in this study as a specific reference in order to estimate the loads on the waste containers.

2.2.3 Transfer of Loaded Containers

Figure 2-13 shows the steps involved in packaging both vitrified DHLW and spent fuel. After an empty container has been transferred to the weld station, the waste forms from the unloading operations or from storage are placed in it. Figures 2-14 and 2-15 show the conceptual layout for both weld and inspection stations at the WIPP facilities, which are used in this study as a reference configuration. At the weld station, the container weld surface is prepared and the lid welded to the container. The loaded container is then transferred to the inspection station for weld inspection. After the inspection, the container is transferred to the leak test station for a leakage check. If faulty welds are discovered, the container is returned to the weld station for repair.

After the container has been successfully inspected and leak-tested, it is transferred to the decontamination station (Figures 2-10 and 2-11), where it is cleaned. Then, it is shuttled off and removed from the floor port by means of a crane. If further cleaning is required, the container is checked for contamination and returned to the decontamination station. The clean containers are then moved on the transfer cars to the transfer station, through a tunnel connecting the hot cell with the surface storage vault and out-transfer bay. As shown in Figure 2-16, two container transfer machines (CTMs) are provided to move the container from the transfer cars at the transfer station to the storage racks in the storage vault.

When a container (in a cask) is selected to be stored in the subsurface storage area, it is transferred by the CTM from the surface storage vault back to the transfer station. An underground transporter, shown in Figure 2-17, picks up the container from the shielding cask at the transfer station, rotates the container to the horizontal position, and transports it to the underground storage location for disposal. The cask can be rotated to the vertical for loading, as indicated in Figure 2-18.

During transfer operations in the surface facilities, the loaded containers are assumed to be handled by cranes and manipulators with attached grapple assemblies which match the container's pintle configuration. Since no detailed designs exist for the surface facilities, the crane and manipulator and grapple assembly designed for the WIPP waste-handling facilities are assumed in this study and are shown in Figures 2-19 and 2-20.

2.3 Estimate of Load Envelopes and Potential Drop Heights

2.3.1 Typical Handling Operation

From the discussion in Subsection 2.2, each major waste-handling operation (i.e., receiving, unloading, welding, inspection, testing, or decontamination process) can be described as a typical unit operation. The typical operation, illustrated in Figure 2-7 or 2-13, is performed as follows:

- o Remove the cask or container from the first work station and prepare it for transfer.
- o Transfer the cask or container to the next work station via overhead cranes or monorails.
- o Place the cask or container in a designated position at this work station for waste handling prior to moving it to the next work station.

2.3.2 Bases for Establishing Load Envelopes

2.3.2.1 Casks

At any station, the cask is assumed to be restrained by a holding frame on the top of a transfer car. During the handling operation, the possible loads imposed upon the cask are from tool parts dropping onto the cask as a result of an abnormal movement of the crane and manipulator. However, this type of loading is judged not to be critical because of the very small mass of the tools dropping against the massive cask and the fairly small drop heights of these tools. This small drop height is attributed to the fact that all the tools are used close to the cask.

If the cask is not properly constrained, sudden car movements may cause it to topple and strike the transfer car top. The cask can also roll out of the car and drop onto the concrete floor, in which case the critical load is the force due to the impact of the cask body on the concrete floor.

During the transfer of casks between stations, it is assumed that the casks will be carried by lifting yokes and moved to the designated position. The moving speed of the cask is assumed to be 60 fpm (see Subsection 2.1.5). On this basis, four cases were assessed and are used as bases for establishing load envelopes. In the design, these loading conditions will be combined with the dead load and/or other loads specified in the Regulatory Guide 7.8 (Ref. 8) as applicable. The four cases included in this study are illustrated in Figure 2-21 and are described below.

Impact Due to Toppling. The cask is assumed to be free-standing on the transfer car. Sudden movement of the car may cause the cask to pivot about the corner point (Figure 2-21A), then topple onto the transfer car. The magnitude of the impact stress at the contact surface depends on the amount of kinetic energy, which is related to car speed.

Impact Due to Rolling. As illustrated in Figure 2-21B, the cask is assumed to roll off the car top and fall in a horizontal position onto the concrete floor. The impact force depends on the height of the car top. For this study, the top of the transfer car is assumed to be 42 in. from the floor. The impact stress at the contact surface between the cask and the concrete floor can be estimated by assuming that the cask is elastic and strikes a rigid floor surface. The impact stress is proportional to the cask density, the velocity of wave propagation in the cask, and the striking velocity of the cask (Ref. 6).

Swing Impact. During travel, abnormal crane movements may cause the cask to swing against the concrete wall or a sharp object. The cask is modeled as a simple pendulum hanging by a cable of finite length (Ref. 9). At the maximum crane speed of 60 fpm, the cask carried by the moving crane will have enough kinetic energy to strike the target wall (Ref. 10). Forces on the cask can be treated as a line load or a point load, depending upon the instantaneous position of the cask with respect to the target.

Impact Due to Free Fall. In the draft version Regulatory Guide 7.8 (Ref. 8), a cask is evaluated for a 1 ft free drop vertically onto a flat unyielding surface to assess simulated damage to the cask during normal operating conditions. In this study, the cask is evaluated for a 2 ft free fall because this height is judged to be the operating height for the repository operation. The impact stress at the contact surface between the cask and the concrete floor is estimated by the method described above (Ref. 6).

2.3.2.2 Containers

At any station, the container is assumed to be stationary and restrained. During handling operations, various tool parts are handled by a manipulator above the container. Releases of these tools due to abnormal movements of the manipulator are assumed to be possible and can generate impact forces on the container.

During transfer of containers between stations, it is assumed that containers are carried by cranes traveling at a constant speed of 60 fpm. Six cases of loading, including a seismic load case, are assessed under this assumption and are used as bases for establishing load envelopes. In the container design phase, these loading conditions will be combined with the dead load, including the contents of the container. The six cases are described below; the five nonseismic cases are illustrated in Figure 2-22.

Ovaling Due to Stacking. Empty containers are assumed to be stored in a horizontal position and stacked up to 30 ft high. The dead load of the containers in the upper levels becomes a lateral load on the containers in the lower levels and it causes these containers to deform from a normally circular shape to an oval shape and produces bending stress in the container shell.

Swing Loads (Free Swing). For this case, the container is modeled as a simple pendulum hanging by a cable. Swing loads will be generated from the starting and stopping associated with crane movement. This scenario is based on the assumption that the speed of the crane carrying the container can be reduced to 30 fpm before the brake is applied. In addition, 3 ft of travel is required for complete stop of the crane.

Impact on Hot-Cell Walls. During travel, abnormal crane movements may cause the container to swing against the hot-cell wall. At the maximum speed of 60 fpm, the container carried by the moving crane can generate enough kinetic energy to strike the target wall. Forces on the target wall can be treated as a line load or a point load, depending on the instantaneous position of the container with respect to the target.

Impact Between Containers. In the hot cells, it is assumed that only one container is being handled by the overhead crane at any time. Therefore, a collision between two moving containers is not considered credible. A moving container could hit a stationary

container, but such an event is assumed in this study to be included in the hot-cell or stationary object cases. As for empty containers being handled outside the hot cells, a traveling container could accidentally swing into a stationary container. The traveling speed for this case is assumed to be 60 fpm. The system is treated as a collision between two elastic bodies (Ref. 11).

Impact Against Stationary Objects. Figures 2-14 and 2-15 illustrate types of equipment to be located in the unloading hot cells. At the weld station, for example, there will be work tables, welding heads, welding head manipulators, grinding and cutting tools, grapple assemblies, and rotating blocks. During transfer, it is possible for the container to swing into these objects and cause damage (Ref. 10). Without detailed layouts for the equipment, three types of targets are assumed in this study. They are classified as sharp, blunt, and flat targets, and are defined in Figure 2-23.

Impact Loads Due to Free Fall. The container is evaluated for a 2 ft free fall in a vertical position onto a flat, unyielding surface, such as the hot-cell floor, in order to assess the damage to the container during its normal handling operations. The evaluation is similar to the one described in Draft Regulatory Guide 7.8 (Ref. 8) for casks. As mentioned previously for the cask evaluation, this height of 2 ft is judged to be the operating height for the repository operation.

Seismic Loads. The container is evaluated for two possible loading conditions during a seismic event: container suspended from the overhead crane system, and container located in a station. In the first case, the container is assumed to be a simple pendulum; in the second case, it is assumed to be restrained at the floor level only while in a station (see Figure 2-11). The system is assumed to be a cantilever.

Table 2-1

STRESS LEVELS AT VARIOUS PARTS OF SHIPPING CASKS

Load Cases	Critical Locations	Stress Levels (psi)	Allowable Stress ^(a) (psi)
Truck casks			
Toppling impact	Shell at contact surface	153 compressive stress	21,000
Rolling impact on floor	Shell at contact surface	20,864 compressive stress	21,000
Swing impact			
a) On walls	Point Load on shell	742 bending	23,100
b) On 2 in. dia. object	Point load on shell	6.5 shear puncture	20,210 ^(b)
Impact due to 2 ft free fall	Plate at contact surface	15,820 compressive stress	21,000
Rail casks			
Toppling impact	Shell at contact surface	377 compressive stress	21,000
Rolling impact on floor	Shell at contact surface	18,850 compressive stress	21,000
Swing impact			
a) On walls	Point load on shell	2,610 bending	23,100
b) On 2 in. dia. object	Point load on shell	12 shear puncture	20,210 ^(b)
Impact due to 2 ft free fall	Plate at contact surface	14,240 compressive stress	21,000

(a) Allowable stresses are $0.6 F_y$ and $0.66 F_y$ for compression and bending, respectively.

(b) This is the shearing yield stress.

Table 2-2

STRESS LEVELS AT VARIOUS PARTS OF EMPTY CONTAINERS

Load Cases	Critical Locations	Stress Levels (psi)	Allowable Stress ^(a) (psi)	Remarks
Dead load	Shell away from pickup points	101 longitudinal tensile stress	21,000	
	Shell at pickup points	7,860 longitudinal tensile stress	21,000	
Ovaling due to stacking of containers (30 ft high in horizontal position)	Shell of the bottom container	4,858 bending	23,100	0.013 in. in diametrical change
Swing load	At pickup points	Negligible	N/A	
Impact on walls	Point load on shell	22,230 bending	23,100	
	Line load on shell	207 bending	23,100	
Impact load between containers	Point load on shell	10,270 bending	23,100	
Impact load on equipment				
2 in. dia. object	Shell wall	86 shear puncture	20,210	240 lb impact load from "impact on walls" case
1 ft dia. object	Shell wall	108 shear puncture	20,210	
Impact due to a free fall to the floor				
2 ft free fall	Plate at contact surface	6,385 compressive stress	21,000	
Free fall at the max. drop height	Plate at contact surface	26,200 compressive stress	21,000	Drop height = 33.75 ft

(a) See notes (a) and (b), Table 2-1

Table 2-3

STRESS LEVELS AT VARIOUS PARTS OF LOADED CONTAINERS

Load Cases	Critical Locations	Stress Levels (psi)	Allowable Stress ^(a) (psi)	Remarks
Dead load	Bottom plate	1,067 bending	23,100	
	shell	9,366 bending	23,100	
	Pintle lid	8,430 bending	23,100	
Swing load		Negligible	N/A	
Impact on walls	Point load on shell	80,700 bending	23,100	
	Line load on shell	440 bending	23,100	
Impact load on equipment				
2 in. dia. object	Shell	206 shear	20,210	575 lb impact load for "impact on walls" case
		80,700 bending	23,100	
6 in. dia. object	Shell	77 shear	20,210	
		21,200 bending	23,100	
Impact due to free falls				
2 ft free fall onto the floor	Plate at contact surface	11,010 compressive stress	21,000	
2 ft free fall onto a 6 in. dia. object	Bottom plate	29,800 ^(b) (144) ^(b) shear puncture	21,000	
2 ft free fall onto a 2 in. dia. object	Bottom plate	63,860 ^(b) (186) ^(b) shear puncture	20,210	
Seismic load				
At a station	Shell	2,090 bending	23,100	0.5 g
Carried by a crane	Pintle lid	11,600 bending	23,100	0.1 g

(a) See notes (a) and (b), Table 2-1.

(b) Value of stress based on the assumption that the object is elastic.

2.3.3 Load Summary

The results of the load cases for the casks and containers are summarized in Tables 2-1, 2-2, and 2-3. Table 2-1 shows the possible stress levels that would be experienced by a cask under the various loading conditions indicated in Subsection 2.3.2. Tables 2-2 and 2-3 show the results for an empty and loaded container, respectively, under the conditions indicated in Subsection 2.3.3.1. The listed stress levels have been compared with the allowable stresses shown in the tables. 2.3.3.1 Shipping Casks

Impact Due to Cask Toppling. As indicated in Table 2-1, the impact stress at the contact surface (between the cask and the top of the transfer car) is small, even though a perfect rigid surface is assumed for the target surface. The 377 psi stress level for this condition (shown in Table 2-1) is seen to be insignificant.

Impact Due to Cask Rolling. After falling off the transfer car, a truck cask is assumed to drop 42 in. The resulting impact stress at the contact surface between cask and concrete floor is 20,864 psi. Because of its smaller density,* the corresponding compressive stress for a rail cask is smaller (18,850 psi). These stress levels are less than the allowable stress of the stainless steel, but are much higher than the concrete strength. Thus, some concrete crushing is expected. Because of this crushing, the actual impact forces on the cask should be substantially reduced.

Swing Impact. For a swing impact on walls, the stress level generated from a point contact can be as high as 2,610 psi (bending) for a rail cask and 742 psi (bending) for a truck cask. The difference in stress levels is due primarily to the lower overall weight of the truck cask. These stress levels are below the allowable stress for the cask material and are not critical for design. Another load case considered is the swing impact on a sharp object (2 in. dia. assumed). The sharp object is

* Truck and rail cask densities are 0.000465 and 0.000377 lb-sec²/in.⁴, respectively.

conservatively assumed to be perfectly rigid; hence, the total impact load is absorbed by the cask shell. The shear stresses by puncture are 6.5 psi for the truck cask and 12 psi for the rail cask.

Impact Due to Free Fall. Under normal operating conditions, the potential drop height anticipated for a shipping cask is 2 ft. With a 2 ft drop, a cask may experience a maximum compressive stress of 15,820 psi at the contact surface, which is less than the allowable stress of stainless steel. However, as the concrete stress of 6,000 psi is exceeded, some concrete crushing due to the impact can be expected.

2.3.3.2 Load Summary for Containers

Dead Loads. For both empty and loaded containers, the assumed container configuration is more than adequate for the dead load conditions. The maximum stresses of 7,860 psi for an empty container and 9,366 psi for a loaded container are much less than the allowable tensile stress of 21,000 psi. (The longitudinal tensile stresses are based on a three-point pickup as shown in Tables 2-2 and 2-3.)

Ovaling. Because of the stacking of empty containers in a horizontal position, the ovaling of container can cause a diametrical change in the shell section. As indicated in Table 2-2, 30 ft high stacking yields a stress of 4,858 psi in the bottom shell and causes a change of 0.013 in. in the shell diameter. This diametrical change is not critical since the assumed allowable tolerance is 0.0625 in. (see Subsection 2.1.5).

Swing Loads. As indicated in Tables 2-2 and 2-3, a free swing due to the starting and stopping of the crane yields a maximum shock load of less than 30 lb at the container. The value is small and can be neglected in the design.

Impact on Walls. For a wall impact, the stress level is 80,700 psi for a loaded container and 22,230 psi for an empty container in the case of a point load.

For the container impact, the concrete stress at the impact surface exceeds 6,000 psi (the assumed crushing strength of concrete), including a dynamic factor of 1.5 for impact. This impact force would crush the concrete surface to some extent and substantially reduce the impact energy and the impact force transmitted to the container. The actual magnitude of impact force can be evaluated only by testing. The estimated stress level is still much less than the critical fracture stress of 228,000 psi for stainless steel (Subsection 2.1.4 and Refs. 3 and 6). This indicates that the loaded container shell may yield, but will not fracture.

Impact Between Containers. As indicated in Subsection 2.3.2.2, this case is valid only for the handling of empty containers. The stress level of 10,270 psi (Table 2-2) is considered moderate, but not critical. This stress level is conservative because it is based on a point load applied to the shell.

Impact Against Stationary Objects. It is conservatively assumed that all the stationary objects (Figure 2-23) are rigid. At impact, the total impact load is absorbed by the container shell. The shear stresses by puncture are small (see Tables 2-2 and 2-3). The maximum values are 206 psi for a sharp object and 108 psi for a blunt object. However, the bending stress is higher, of the order of 80,700 psi, in which case the container shell may yield with significant deformation, but will not fracture.

Impact Due to Free Fall. For the case of a 2 ft free fall onto a concrete floor, for a loaded container, the stress level is 11,010 psi, which is less than the yield strength of stainless steel. For empty containers, the corresponding stress is 6,385 psi. For the case where an empty container is dropped from the maximum height of 34 ft onto a concrete floor, a 26,200 psi compressive stress is produced in the bottom plate of the

container. The container may fall onto various objects on the floor. For impact with a blunt object, the shear puncture stress on a loaded container can be of the order of 29,800 psi, and for a sharp object the stress level can be as high as 63,860 psi, which is much higher than the shear yield stress. This indicates that a sharp object may puncture the loaded container. However, these high values are attributable mainly to the assumption that the target objects are perfectly rigid and unyielding; hence the container shell is assumed to absorb all of the impact energy. If target flexibility is taken into account, the impact force between the falling container and the target object should be substantially reduced (Ref. 11).

Seismic Load. During a seismic event, the loaded container is assumed to be in either a stationary or a transit mode. In the stationary mode, the container is assumed to be restrained at the floor level. The system is treated as a cantilever with a computed fundamental frequency of approximately 13 cps. An acceleration of 0.5 g is assumed and used for this evaluation. This seismic load is applied at the center of gravity of the container and results in a bending stress of 2,090 psi on the shell. When the container is in transit via the overhead crane system, the container is assumed to be a simple pendulum and its frequency is computed to be 0.3 cps. For this case, a seismic load of 0.1 g is assumed and applied at the center of gravity of the container. With the tolerance around the grapple device, a point load contact is assumed at the pintle lip, with a stress level of 11,600 psi.

2.3.4 Potential Drop Heights During Normal Operating Conditions

Using the elevations shown in Figures 2-23 and 2-24, one can identify all potential drop heights. These heights can be identified and are summarized in Table 2-4. In most areas, during normal container transfer, the drop height is limited to 2 ft above

Table 2-4
DROP HEIGHTS FOR CONTAINERS AND CASKS IN VARIOUS AREAS

Items	Drop Heights (ft)
Containers	
Transfer corridor	2 to floor
Transfer area	33.75 to floor
(between corridor and hot cell)	22.25 to transfer car
Hot cells	2 to floor
	17 to turntable at weld station
	33.75 to the lower floor at decon. station or inspection station
Transfer station at surface storage vault	32 to floor
Casks	
Receiving area	10 to floor
	2 to cask preparation area floor
	3.5 to floor (horizontally)
Hot cells	3.5 to floor (horizontally)

- Notes: 1. All drops are in the vertical position unless noted otherwise.
2. The total area where the drop height is greater than 2 ft represents a very small part of the total operation area.

the operating floor. This is judged to be the governing height for the design of casks and containers during normal operating conditions.

Angles of impact can be estimated from the type of fixtures to be used for the handling operations. One of the angles will be the maximum angle generated by swing motions identified in Subsection 2.3.2. For the free swing, the maximum angles are about 5° measured from the plumb position of the cask or container. This angle is determined by the length of the suspended cable used for handling the cask or container. For the loaded container handled by the manipulator, the tolerance allowed for the transfer fixture to handle the container is the governing factor for determining the angle of impact. Assuming a 1/8 in. gap around the pintle neck for tolerances, the restricted angle of swing is about 7° in all directions. Based on these results, the impact angle ranges from 5° to 7° measured from its plumb position.

2.4 Areas and Equipment Subject to Potential Impacts and Ways of Mitigating these Impacts

In this subsection, the equipment and the areas in the WHB that are subject to potential impacts of a cask and container are identified. Equipment rearrangements and structural modifications are suggested as potential methods for mitigating impact effects. The effect on the functional and operating requirements of the WHB is also discussed. Where equipment rearrangement or structural modifications of the WHB are not feasible, the use of energy-absorbing materials or systems is considered as an alternative to mitigate impact effects.

2.4.1 Areas Subject to Potential Impacts

Critical areas or equipment subject to potential impacts are identified in Table 2-5. Information given in the table will be used as a basis for developing schemes to mitigate damages due to impact.

Table 2-5

AREAS SUBJECT TO POTENTIAL IMPACTS

Areas	Equipment (Targets)	Impact Sources (Impactors)
Waste receiving	Floor-mounted manipulator	Casks, lifting yoke
	Wall-mounted jib-crane	Casks lifting yoke
	(Floor)	Casks lifting yoke
	(Walls)	Casks lifting yoke
	Casks	Bridge-mounted or floor-mounted manipulators
Waste unloading	Casks	Tool parts
	(Floor)	Closure
	(Walls)	Lifting adapter canisters or spent fuel assembly
	Canisters or spent fuel assembly	Tool parts Grapple or lifting adapter containers
Waste preparation	Containers	Container
	(Floor)	Container
	(Walls)	Container
	Transfer cars	Container
	Parts in weld station	Container
	Parts in weld inspection station	Container
	Parts in decon station	Container
	Parts in inspection station	Container
	HEPA filter unit	Containers or canisters/spent fuel assembly
Waste storage	Storage rack (floor)	Containers or tool parts
	Transporter	Containers or tool parts

2.4.2 Rearrangement of Equipment

Equipment that is vulnerable to potential impact (e.g., manipulators, welding heads, grinding or cutting tools) should be located close to the walls and/or away from the transfer path of casks/containers as practicable. Some of these items can have sharp points or edges which can also damage the container. To further mitigate these effects, these items should be provided with mechanisms to allow these points or edges to swing away from the traveling path of containers. For example, a manipulator arm should be folded to its downright position when it is not in use. Similarly, after material handling, a jib-crane should be located at its rest position against the structural wall.

Swing impacts due to abnormal movements of the crane system, such as overtravel, can be effectively mitigated by incorporating proper controls in the crane design. Safety features such as crane stops and limit switches can limit the crane travel to avoid possible impact on building structures and equipment. Crane-stop locations determined from the swing angle may be the most effective way to preclude any swing impact of a container against the hot-cell walls.

2.4.3 Structural Modifications

A properly designed structural system can provide some flexibility to absorb the impact energy. The reduction of impact force due to target flexibility is discussed in Subsections 2.3.3 (as well as in Ref. 10). Therefore, protective frames over critical equipment to reduce the damage potential should be evaluated as a part of structural considerations in the future designs.

For example, with a vertical drop and associated impact, a horizontal framing system (serving as a cover) can protect a manipulator from impact damages. On the other hand, if the manipulator arm swings only in a vertical plane, a vertical framing can be used to protect the manipulator from swing impacts.

2.4.4 Energy-Absorbing Systems

Energy-absorbing systems may be the most efficient way to mitigate the effects of impacts. To deal with the impact, the systems must have the following features:

- o The force produced by the impact must be limited to some safe value.
- o Kinetic energy must be irreversibly dissipated so that rebound is limited.

The above features can be obtained through the use of metal springs, elastomers, and fluid dashpots. Each has its advantages and limitations. For example, metal springs can be used inside the container to dampen the transmission of impact energy to spent fuel assemblies. This damping effect would reduce the rupture of spent fuel assemblies subject to impact from the container.

In larger areas, the provision of energy-absorbing materials becomes impractical. These areas can be protected by safety nets or grating systems specifically designed for this purpose. For example, when the transfer area (connected to the transfer air locks) for empty containers is not in use, a safety net can close the area to mitigate the potential drop into the transfer area. The concept can be effective in preventing the penetration of large objects (containers in particular), thus keeping them from striking the critical equipment located beneath the net.

Figure 2-1
Material Block Flow Diagram
for
Waste-Handling Operations

For dimensions and parameters,
see Figures 2-3 and 2-4.

Figure 2-2
Reference Cask Configuration

100-TON RAIL/BARGE SPENT FUEL CASK CONCEPT

Overall Size		
Outside Diameter (Top)	85 in.	
Outside Diameter (Bottom)	83 in.	
Overall Length	235 in.	
Weight		
Cask—Empty (Max.)	162,000 lb	
Cask—Full (Max.)	190,000 lb	
Cavity Size		
Inside Diameter	57.0 in.	
Inside Length	176.5 in.	
Shielding		
Gamma Type	Steel	
Steel Thickness		
Cask Side	10.0 in.	
Cask Top	11.0 in.	
Cask Bottom	10.5 in.	
Neutron Type	Solid, Organic Material	
Thickness	3.0 in.	
Type of Containment	Bolted Closure	
Seals	Double O-Ring	
Cavity Atmosphere	Dry Gas	
Expected Thermal Output (Max.)	13 kW	
Outer Surface Configuration	Smooth	
Trunnions		
Lifting (Top)	4 @ 90°	
Tie-Down (Bottom)	2 @ 180°	

Item	Intact Spent Fuel Assemblies (SFAs)		Square Canisters of Consolidated Rods (2:1 Consolidation)		Small-Diameter Canisters for Consolidated Rods		Large-Diameter Canisters for Consolidated Rods	
	PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR
Diameter (in.)	—	—	—	—	12.8	12.8	16.9	18.9
Side of Square (in.)	8.4	5.5	8.4	5.5	—	—	—	—
Length (in.)	160	176	152	161	158	164	160	169
Equiv. Number of SFAs ⁽¹⁾	1	1	2	2	3	7	6	17
Weight (lb)	1,450	700	2,900	1,400	5,100	4,900	10,700	13,400
Min. Age (yr) ⁽²⁾	10	10	10	10	10	10	10	10
Cask Capacity								
Number of Waste Forms ⁽³⁾	14	36	10	20	6	6	2	2
Equiv. SFAs ⁽⁴⁾	14	36	20	40	18	42	12	34
Total Cargo Weight (lb) ⁽⁵⁾	20,500	25,000	29,000	28,000	30,500	29,500	21,500	26,500
Cask Weight								
Empty (lb) ⁽⁶⁾	160,000	161,500	160,000	161,500	159,000	159,500	158,500	159,000
Full (lb)	180,500	186,500	189,000	189,500	189,500	189,000	180,000	185,500
Gross Vehicle Wt. (lb) ⁽⁷⁾	253,500	259,500	262,000	262,500	262,500	262,000	253,000	258,500
% of Allowable Weight ⁽⁸⁾	96%	99%	100%	100%	100%	100%	96%	98%

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- Notes: (1) The waste form contains the rods from this number of spent fuel assemblies.
(2) See comment in text.
(3) Cask diameter is optimized for intact fuel assemblies. This cask may be weight-limited, not quantity-limited, for other waste forms.
(4) The cask can carry the rods from this number of spent fuel assemblies.
(5) Rounded to nearest 500 lb.
(6) Includes fuel assembly or canister support baskets which vary in weight with the waste form.
(7) Assumes weight of 73,000 lb for rail car and tie-down equipment.
(8) Maximum weight for unrestricted interchange (4-axle car) is 263,000 lb.

Figure 2-3
100-Ton Rail/Barge Spent Fuel Cask Concept

TRUCK SPENT FUEL CASK CONCEPT

Overall Size						
Outside Diameter (Top)		44 in.				
Outside Diameter (Bottom)		39 in.				
Overall Length		215 in.				
Weight						
Cask—Empty (Max.)		48,000 lb				
Cavity Size						
Inside Diameter (with Shielding Liner)		22.7 in.				
Inside Length (with Shielding Liner)		176.5 in.				
Shielding						
Gamma Type		Depleted Uranium/Steel				
Equivalent Steel Thickness						
Cask Side		9.3 in.				
Cask Top		10.0 in.				
Cask Bottom		9.5 in.				
Neutron Type		Solid, Organic Material				
Thickness		3.0 in.				
Type of Containment		Bolted Closure				
Seals		Double O-Ring				
Cavity Atmosphere		Dry Gas				
Expected Thermal Output (Max.)		2.8 kW				
Outer Surface Configuration		Smooth				
Trunnions						
Lifting (Top)		4 @ 90°				
Tie-Down (Bottom)		2 @ 180°				

Item	Intact Spent Fuel Assemblies (SFAs)		Square Canisters of Consolidated Rods (2:1 Consolidation)		Small-Diameter Canisters for Consolidated Rods	
	PWR	BWR	PWR	BWR	PWR	BWR
Diameter (in.)	—	—	—	—	12.8	12.8
Side of Square (in.)	8.4	5.5	8.4	5.5	—	—
Length (in.)	160	176	152	161	158	164
Equiv. Number of SFAs ⁽¹⁾	1	1	2	2	3	7
Weight (lb)	1,450	700	2,900	1,400	5,100	4,900
Min. Age (yr) ⁽²⁾	10	10	10	10	10	10
Cask Capacity						
Number of Waste Forms ⁽³⁾	2	5	2	4	1	1
Equiv. SFAs ⁽⁴⁾	2	5	4	8	3	7
Total Cargo Weight (lb) ⁽⁵⁾	3,000	3,500	6,000	5,500	5,000	5,000
Cask Weight						
Empty (lb) ⁽⁶⁾	47,500	48,000	47,500	48,000	47,500	47,500
Full (lb)	50,500	51,500	53,500	53,500	52,500	52,500
Allowable Vehicle Weight						
Without Cask (lb)	29,500	28,500	26,500	26,500	27,500	27,500
Loaded (lb)	80,000	80,000	80,000	80,000	80,000	80,000
% of Allowable Weight	100%	100%	100%	100%	100%	100%

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- Notes: (1) The waste form contains the rods from this number of spent fuel assemblies.
(2) See comment in text.
(3) Cask diameter is optimized for intact fuel assemblies. This cask may be weight-limited, not quantity-limited, for other waste forms.
(4) The cask can carry the rods from this number of spent fuel assemblies.
(5) Rounded to nearest 500 lb.
(6) Includes fuel assembly or canister support baskets which vary in weight with the waste form.

Figure 2-4
Truck Spent Fuel Cask Concept

Figure 2-5
Hybrid Spent Fuel Container

Figure 2-6
Cask Transfer Car Used for Cask Preparation
(Ref. 2)

Figure 2-7
Pictorial Diagram of Waste Receiving
and Unloading Operations

Figure 2-8
Schematic of a Lifting Yoke
(Ref. 7)

Figure 2-9
Transfer Routes for Empty Containers

Figure 2-11
Elevations for Major Container Transfer Areas

ASSEMBLY

U.S. DOE, WIPP
 WHB 411
 Overpack Transfer Fixture
 41-H-103 Specification
 Control Drawing 41-F-300-014

Figure 2-12
 Transfer Fixture for Empty Containers

PICTORIAL DIAGRAM
OF DHLW PACKAGING

PICTORIAL DIAGRAM
OF SPENT FUEL
PACKAGING

Figure 2-13
Pictorial Diagrams of Waste Packaging

U.S. DOE, WIPP
 WHB 411
 Hot Cell Equipment Arrangement
 Drawing 41-G-450-014

Figure 2-14
 Conceptual Layouts for Welding
 and Inspection Stations - Plan

SECTION

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Figure 2-16
Typical Sections in the Waste-Handling Building

Figure 2-17
Vertical Mode Waste Transporter
in the Transport Configuration

Figure 2-18
Vertical Mode Waste Transporter with the Cask Rotated
to the Vertical Position for Loading of Containers

Figure 2-19
 Typical Grapple Assembly

(A)

(B)

(C)

(D)

Figure 2-20
Study Cases for Cask Handling

FREE SWING
(A)

SWING IMPACT
(B)

FREE FALL
(C)

IMPACT ON
STATIONARY OBJECT
(D)

CONTAINER IMPACT
(E)

Figure 2-21
Study Cases for Container Handling

FLAT TARGET

BLUNT TARGET

SHARP TARGET

Figure 2-22
Container Drop Impacts on Various Targets

TRANSVERSE SE

LONGITUDINAL SEC

CTION

Figure 2-23
Container Drop Heights in the WHB

ION

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SECTION D
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Figure 2-24
Cask Drop Heights in the WHB

3.0 DETERMINATION OF THE LIMITING DROP HEIGHT OF A LOADED CONTAINER

In this section, the relationship between the drop height of a loaded container and failure of that container is analyzed. Specifically, the limiting drop height - the height above which a container, when dropped, will fail or cause large deformation - is determined. The NNWSI hybrid spent fuel container was selected for analysis. The container holds three intact PWR assemblies and four intact BWR assemblies. However, in the finite-element impact analyses, the configuration and the number of fuel assemblies were modified (see Subsection 3.2.2) to take the advantage of symmetrical conditions. The container, shown in Figure 2-5, is 28 in. in outside diameter and 187.5 in. in total length; its wall thickness is 0.375 in. and its bottom plate thickness is 1.5 in.

The section consists of three parts:

- o Subsection 3.1. Assumptions
- o Subsection 3.2. Literature Search
- o Subsection 3.3. Estimate of the Limiting Drop Height

3.1 Assumptions

- o The material for the waste container is austenitic stainless steel 304L. (For other stainless steel alloys being considered for the container, the mechanical properties are not significantly different. However, for other metals in addition to the stainless steel alloys being considered for the container, the mechanical properties of those other metals may differ substantially from those of stainless steel, and the analysis results described in this report may not be valid.)
- o The specified mechanical properties of the container are based on an average temperature of 100°C. This temperature value is a reasonable assumption and is used only for

temperature-dependent material properties that are not very sensitive to the variation of temperature over its conceivable range.

- o For a uniaxial test, stainless steel 304L can sustain an elongation up to 71 percent before failure (Ref. 11). However, for the drop analysis, the container wall or bottom plate is considered failed if the effective plastic strain exceeds 15 percent.
- o If the container is dropped and suffers significant deformation, it may not be able to be handled by normal repository operations.
- o There is a 1.0 in. clearance between the top of the fuel assembly and the bottom face of the cap or inner lid of the container. If the container is shortened by this amount or more as a result of the drop, the top and the bottom of the container will compress the fuel assemblies within it and may cause these assemblies to fail. Therefore, if the container is shortened by more than 1.0 in., it is considered to have failed.

3.2 Literature Search

To determine the limiting drop height of the container, a literature search was first conducted for the purpose of collecting useful information available in the public domain.

This search covered:

- o Analytical methods and experimental results related to the effect of impact on containers, especially the spent fuel container
- o The effect of impact on the container in terms of drop height

Very little information about the above subjects is available. Only two reports on the impact testing of simulated waste glass

canisters (Refs. 12 and 13) were found. These tests were conducted between 1975 to 1983 by Pacific Northwest Laboratory for the U.S. Department of Energy.

3.2.1 Report on Impact Testing of Centrifugally Cast Canisters* of Simulated Waste Glass

In the first study (Ref. 12), four simulated high-level waste canisters were subjected to impact tests. The canister design, as shown in Figure 3-1, was similar to the canister design for the Defense Waste Processing Facility.

Table 3-1 summarizes the physical measurements of these canisters. Three of the canister bodies were fabricated out of a special cast alloy, equivalent to 304L stainless steel, by recycling slightly contaminated stainless steel. Another canister was fabricated by using wrought 304L stainless steel. The canisters were filled with a borosilicate glass.

The purpose of these tests was to evaluate the effect of impact on the canisters and to determine if slightly contaminated metal could be used for waste containers. Each canister was subjected to (1) two vertical drops from a height of 30 ft onto an unyielding surface (one of these drops causing impact on the bottom corner and the other on the fill nozzle and head) and (2) a horizontal drop from a height of 40 in. onto a solid steel vertical cylinder in a puncture test. Canister orientations during these impact tests are given in Table 3-2. No rupture of any of the canisters occurred as a result of these impacts. The maximum tensile strain experienced was 13 percent; the maximum compressive strain experienced was 16 percent. These measured strains were below the minimum strain required for failure, which is believed to be at least 30 percent. A helium leak test and a liquid dye penetrant test conducted after the impacts revealed no leaks and no significant indications of cracks.

* In the studies discussed here, the term "canister" is used to refer to an object that throughout this report is referred to as a "container."

(All Dimensions are in Inches)

Figure 3-1
Configuration of Canister Used in Drop Tests

Table 3-1

PHYSICAL MEASUREMENTS OF THE CANISTERS (REF. 12)

<u>Canister No.</u>	<u>Weight (lb)</u>	<u>Diameter (in.)</u>	<u>Length (in.)</u>	<u>Distance from Bottom to Center of Gravity (in.)</u>
18	4,335	24	118.00	44.38
19	4,328	24	118.56	46.00
20	4,280	24	118.63	46.44
21	4,600	24	117.81	46.25

Table 3-2

SUMMARY OF CANISTER ORIENTATIONS DURING IMPACT TESTS (REF. 12)

<u>Canister No.</u>	<u>Impact Area</u>	<u>Angle(a)</u>
18	Bottom	15°
	Side	90°
	Nozzle	6°
19	Bottom	15°
	Side	90°
	Nozzle	4°
20	Bottom	13°
	Side	90°
	Nozzle	9°
21	Bottom	13°
	Side	90°
	Nozzle	0°

(a) Angle as measured from the vertical axis. This angle was calculated such that the center of gravity was located over the desired impact point.

3.2.2 Report on Impact Testing of Simulated High-Level Waste Glass Canisters

In the second study (Ref. 13), three Savannah River Laboratory (SRL) reference high-level waste canisters were subjected to impact tests at the Pacific Northwest Laboratory in June 1983. The purpose of these tests was to determine the integrity of the canister, nozzle, and final closure weld, and to assess the effects of impacts on the glass (the content of the canisters). Table 3-3 gives the physical measurements of these SRL containers. Two of the canisters were fabricated from 304L stainless steel, and the third was fabricated from titanium.

The impact tests of the three SRL canisters were conducted in the same way as was described in the first report. Table 3-4 summarizes the canister orientations of these tests. The results indicate no failure and no leak during a helium test leak in the stainless steel canisters. However, a large breach in the titanium canister in the region where the fill nozzle joins the dish head occurred during the top (head) impact test. After the dropped canisters had been opened, the glass particles in the impact zone of these canisters were sampled and analyzed for particle size. The quantity of glass fines smaller than 10 microns was found to be largest in the bottom impact zone. The total amount of fines smaller than 10 microns after impact was reported to be less than 0.01 wt% of the total amount of glass in the canisters.

3.3 Estimate of the Limiting Drop Height

The criteria used to estimate the limiting drop height of a container are that the resulting impact will not cause the container to shorten by more than 1 in. and that the effective plastic strain in the container material will not exceed 15 percent. The results of the drop test of high-level waste

Table 3-3

PHYSICAL MEASUREMENTS OF SRL CANISTERS (REF. 13)

<u>Canister No.</u>	<u>Weight</u>		<u>Diameter</u>		<u>Length</u>		<u>Distance from Bottom to Center of Gravity, in.</u>	
	<u>kg (lb)</u>		<u>m (ft)</u>		<u>m (ft)</u>		<u>m (ft)</u>	
3	1,849	(4,076)	0.61	(2)	3.05	(10)	1.81	(3.88)
4	2,189	(4,825)	0.61	(2)	3.05	(10)	1.27	(4.16)
5	2,413	(5,320)	0.61	(2)	3.05	(10)	1.38	(4.52)

Table 3-4

SUMMARY OF CANISTER ORIENTATIONS DURING DROP TESTS (REF. 13)

<u>Canister No.</u>	<u>Material</u>	<u>Impact Area</u>	<u>Angle(a)</u>
3	Ti	Top Bottom	4° 13°
4	304L SS	Top	4°
5	304L SS	Bottom Side	11°

(a) Angle as measured from the vertical axis. This angle was calculated such that the center of gravity was located over the desired impact point.

canisters presented in the previous subsection provided some technical information about the effect of impact on the container. To estimate the limiting drop height of the container depicted in Figure 2-5, finite-element impact analyses for three different drop heights were conducted. The results of these analyses were then examined and interpolated to obtain the limiting drop height.

3.3.1 Description of the Computer Program

To carry out the highly nonlinear impact analysis of the container (and the fuel pin, described in Section 4.0), finite-element computer program DYNA3D was selected. Developed at Lawrence Livermore National Laboratory by John O. Hallquist (Ref. 14), DYNA3D was first released in December 1981 and has been revised several times. In 1986, a Bechtel study (Ref. 15) recommended DYNA3D for an impact analysis. DYNA3D was selected because (1) it had been implemented on the CDC CRAY-1 Supercomputer by Bechtel in the aforementioned study, and (2) it is well suited for the impact analyses of the spent fuel container and the fuel pin.

DYNA3D is a completely vectorized program that uses explicit integration to solve three-dimensional, inelastic, large-deformation structural dynamics problems. In DYNA3D, the coordinate system is strictly Lagrangian. Other features include auto-time-step control and sophisticated contact algorithms for the impact interactions.

DYNA3D has found widespread application in the defense and aerospace industries for highly nonlinear dynamic simulations, including dynamic simulations of extremely high-velocity impact. The results of DYNA3D simulations have shown very close agreement with the results of experimental tests (see Numerical Examples in Ref. 14).

3.3.2 Assumptions Used in the Impact Analyses

The following assumptions were made in the finite-element analyses of the container:

- o The container is dropped in a vertical fashion, its bottom end plate receiving the impact in a normal direction.
- o Four PWR and five BWR fuel assemblies are in a symmetrical configuration so that a quarter container can be modeled. (To obtain this configuration, the original arrangement of hybrid spent fuel container was modified. This modification lowered computer cost without changing the total weight of fuel assemblies.)
- o Fuel assemblies do not actively interact with the top end plate and the cylindrical wall of the container, and hence are not actually modeled by finite elements. However, their masses are lumped at the top surface of the bottom end plate of the container. It is believed that this lumped mass approach produces equivalent impact effects, except for the rebound of the fuel assembly, which is not considered here.

3.3.3 Finite-Element Model of Spent Fuel Container

A quarter three-dimensional model of the container was created for impact analyses. The model consists of 2,934 nodal points and 1,345 solid elements. Figures 3-2, 3-3, and 3-4 show three typical cross sections of the model. Nodal points lying on one of the two vertical symmetrical planes are constrained in the direction normal to the plane. All other degrees of freedom are unrestrained. A completely fixed target plate of 18 in. x 18 in. x 6 in. of stainless steel is assumed.

Figure 3-2

Finite-Element Model of Spent Fuel Container
(Top End Plate at Z = 183.500 in.)

Figure 3-3

Finite-Element Model of Spent Fuel Container
(Cylindrical Wall)

Figure 3-4

Finite-Element Model of Spent Fuel Container
(Bottom End Plate at Z = 1.500 in.)

3.3.4 Material Modeling for the Container

The container is made of 304L austenitic stainless steel. The mechanical properties of the stainless steel at a temperature of 100°C was considered in the model. Although the stainless steel is very ductile (total elongation in the uniaxial test is 0.71 in./in.), a maximum accumulated effective plastic strain of 0.150 is assumed as the failure strain. Beyond this point, the material is assumed to be incapable of resisting tension and deviatoric shear stress. However, it can continue to resist compression. Table 3-5 summarizes the material properties used in the impact analyses.

3.3.5 Results of the Analyses

Three finite-element analyses for drop heights of 30 ft, 7.5 ft, and 5.0 ft were conducted using the computer program DYNA3D. In the first two analyses (30 ft and 7.5 ft drop heights), the computations were carried out for a duration of 4,000 microseconds; in the third analysis (5.0 ft drop height), a shorter duration, 3,500 microseconds, was needed to determine the peak response.

Table 3-6 summarizes the results of the analysis. It was found that all of these drops produced a shortening greater than the assumed 1 in. clearance between the fuel assemblies and the top end plate of container. The 30 ft drop caused two elements in the bottom end plate to fail as a result of accumulated effective plastic strain reaching the specified failure strain of 0.15; the 7.5 ft and 5.0 ft drops did not yield any failure strain. The deformed shapes of the bottom portion of the container for the 30 ft drop are shown in Figure 3-5. It is clear that buckling takes place at the bottom of the cylindrical wall.

Figure 3-6 shows the relationship between the drop height and the shortening of the container. This relationship is derived from the three impact analyses. The graph in this figure was created

Table 3-5

MECHANICAL PROPERTIES OF AUSTENITIC STAINLESS STEEL (TYPE 304L)
AT 100° C (REF. 4)

<u>Item</u>	<u>Value</u>
Modulus of elasticity, ksi	27,900
Shear modulus of elasticity, ksi	11,100
Yield strength, ksi	28.7
Ultimate tensile strength, ksi	68.1
Modulus of strain hardening, ksi	265.0
Failure strain	0.150
Poisson's ratio	0.257
Density, lb/in ³	0.29

Table 3-6

SUMMARY OF ANALYSIS RESULTS FOR A SPENT FUEL CONTAINER
FOR DROP HEIGHTS OF 30 FT, 7.5 FT, AND 5.0 FT

<u>Types of Response</u>	<u>Locations</u>	<u>Strain/Shortening</u>		
		<u>30.0 ft</u>	<u>7.5 ft</u>	<u>5.0 ft</u>
Maximum effective plastic strain (in./in.)	Top end plate	0.0025	0.0011	0.0008
	Cylindrical wall	0.0919	0.0318	0.0239
	Bottom end plate	0.1500 (two elements failed)	0.0584	0.0387
Shortening of container (in.)		2.825 (a) (extrapolated)	1.365 (a)	1.100 (a)

(a) Since the shortening exceeded 1.0 in., the container failed.

Figure 3-5

Deformed Shapes of the Bottom Portion of the
Container (for 30 ft Drop)

Figure 3-6
Relationship Between the Shortening of the Container
and the Drop Height

by drawing a smooth curve that passed through the origin and the three data points obtained from the analyses. From this curve, it can be seen that 3.75 ft is the minimum drop height that will produce a 1.0 in. shortening of the container (and therefore cause the container to fail as defined in Section 3.1). And from Table 3-6, it can be deduced that a drop from this height will not cause a strain that exceeds 0.150 (the value of strain at which the container is considered to fail). Therefore, 3.75 ft is the limiting drop height.

Table 3-7 compares the results of the 30 ft drop analysis with the results of the drop test described previously. If the failure strain in the DYNA3D analysis had been specified at a value higher than 0.150 (for example, 0.300), it is felt that the maximum effective plastic strain from the analysis would not have increased significantly above 0.150. Therefore, the maximum strain and the container condition after impact, shown in Table 3-7 for the analysis and the drop test, are in reasonable agreement.

Table 3-7

COMPARISON OF THE DYNA3D ANALYSIS WITH THE SNL DROP TEST

<u>Container Parameter</u>	<u>DYNA3D Analysis</u>	<u>PNL Drop Test (Ref. 14)</u>
Type	Waste container	Simulated high-level waste canister
Contents	Spent fuel	Borosilicate glass
Material	304L SS	Equivalent to 304L SS
Dimensions	O.D. 28 in. Length 187.5 in.	O.D. 24 in. Length 118 in.
Total weight	11,026 lb	4,280 to 4,600 lb
Drop height	30 ft	30 ft
Drop angle	0°	13° to 15°
Max. strain	Accumulated effective plastic strain 0.150	Compressive 0.160 Tensile 0.130
Condition after impact	Bottom end plate failed with effective plastic strain greater than the prescribed failure strain of 0.150	Integrity maintained

4.0 ANALYSIS OF AN ACCIDENTAL DROP OF A TYPICAL BARE FUEL ASSEMBLY OR OF AN INDIVIDUAL FUEL PIN

In this section, the accidental drop of a bare nuclear fuel assembly is analyzed and an impact analysis of fuel pins and fuel pellets is performed. The Westinghouse 17 x 17 PWR fuel assembly was selected for the fuel assembly drop analysis. This is typical of the spent fuel assemblies to be received at the repository.

This section consists of the following subsections:

- o Subsection 4.1. Assumptions
- o Subsection 4.2. Literature Search
- o Subsection 4.3. Estimate of Energy Absorption by Various Parts of the Fuel Assembly
- o Subsection 4.4. Effect of Impact on Fuel Pins and Fuel Pellets

4.1 Assumptions

- o The ceramic spent fuel pellets are characterized by their brittle fracture behavior. The brittle fracture occurs when the strain exceeds 1.1 times the yield strain of the ceramic fuel material.*
- o The zircaloy cladding of the fuel pin is characterized by its elastic-plastic fracture behavior. The fracture failure of the zircaloy occurs when the strain exceeds 9 percent.*

4.2 Literature Search

4.2.1 Introduction

The purpose of this task is to determine, using simplified but rigorous analytical techniques, the consequences of an accidental

* See Subsection 4.4.4 for details.

drop of (1) a bare fuel assembly or (2) a fuel pin. The task was initiated by a literature search to collect recent technical information on:

- o Research literature related to the drop of fuel assemblies
- o Geometrical and mechanical properties of a typical fuel assembly
- o Mechanical properties of fuel tube cladding material in the irradiated state
- o Analytical techniques for impact analyses

Most of the technical literature defining impact loads is concerned with the target rather than the projectile, thus greatly restricting the available resources. The major fuel assembly vendors (Westinghouse, Combustion Engineering, Babcock and Wilcox) have conducted in-house impact analyses for each of their (or their clients') assemblies. Unfortunately, most of the data and the results are proprietary and could not be obtained. Because the literature data base is so limited, the search was expanded to include impact analyses of other types of equipment. A representative example is the Reactor Vessel Head Drop analysis by Westinghouse (Ref. 16), which uses a simplified method to describe the impact load (outlined by Roark in Ref. 17). The procedure and assumptions described therein are employed to a large extent in the simplified analysis of the fuel assembly.

Possible modes of failure for various components of a fuel assembly were determined after compilation and assessment of industry-wide experience with fuel assembly damage caused by abnormal conditions in handling and transporting operations. Much of this information, which is summarized in detail in Ref. 18, is found in its entirety in the U.S. NRC's Public Document Room. As of 1982, 34 fuel assemblies have been dropped during handling operations. All the drops were in water, some with nondirect impacts. Therefore, these cases have less serious consequences

than a drop through air. Typical examples of the damage sustained by BWR and PWR fuel rods and bundles include:

- o Spacer grid damaged
- o Lower tie plate damaged
- o Assembly skeleton/wrapper/can twisted, bowed, or distorted
- o Channel spacers bent or disturbed
- o Channel deformed
- o Fuel pin bent, bowed, lost, dropped, difficult to remove, or broken
- o Upper nozzle broken off assembly or damaged
- o Lower nozzle damaged
- o Nozzle springs bent or broken
- o Nut capture devices bent

Damage to fuel assemblies and fuel pins as a result of handling is generally detected by visual techniques (direct observation, binoculars, periscope, or closed-circuit television). Fuel assemblies having fuel pins with breached cladding can be detected by gas release, radiation monitoring, or leak-testing (sipping). Damage to fuel pins can also be detected by eddy-current and ultrasonic techniques.

4.2.2 Summary of Recent Fuel Damage Experience

Additional case histories of fuel assembly drops are available in Abnormal Occurrence Reports submitted to NRC by utility companies. Reports collected from several nuclear power generating stations describe a variety of fuel assembly drops on several surfaces and at different orientations. Damage to the assemblies varied widely, as indicated below.

4.2.2.1 Example 1

During transfer of fuel from the core to a fuel storage pool, one fuel assembly was inadvertently dropped 9.1 m (30 ft) onto another

fuel assembly in the core. The lower tie plate cage on the first assembly was deformed upwards toward the tie plate. The bail handle on the second was deformed almost horizontally; the channel was driven downward so that its lower edge flared over the lower tie plate shoulder. Movement of the second assembly caused a tensile force to be applied to the fuel pins, and during this movement, there was a temporary increase in airborne radioactivity, which apparently indicated that the fuel pins had been damaged to some extent. Channels on two fuel assemblies that were adjacent to the second assembly were dented on the top edge.

4.2.2.2 Example 2

During unloading of the core, a channeled fuel assembly came loose from the grapple and dropped about 3.7 m (12 ft) to the transfer pool floor. No gaseous release was noted, and there was no apparent damage to the fuel assembly.

4.2.2.3 Example 3

During transfer, an irradiated fuel assembly became detached from the grapple and fell about 6 m (20 ft) into the spent fuel pool. The grapple hook apparently had not been completely latched under the handle of the fuel assembly. There was no measurable release of radioactivity. The nose piece and the nose piece end of the fuel channel were crushed, but there was no indication of broken fuel pins.

4.2.2.4 Example 4

Because of improper grappling, an irradiated fuel assembly dropped about 1.8 m (6 ft) to the spent fuel pool floor and then tipped over into the corner of the pool in the 3 m (10 ft) deep spent fuel cask pit. When the fuel assembly was lifted to a vertical position, the channel fell off and fuel pins came out of the

assembly. Apparently, the fuel assembly separated because the tie rods and/or tie rod keepers had been sheared when the assembly hit the pool floor.

4.2.2.5 Example 5

One fuel assembly fell from the fuel preparation machine from a vertical to a horizontal position. Only three other fuel assemblies were struck or could have been struck by the falling assembly. The fuel assembly that fell was not visibly damaged; however, the bail of another fuel assembly was bent. Preliminary visual inspection of the two other assemblies indicated localized scratches or crud removal on the bails. Inspection of the fuel preparation machine indicated that the upper roller guide had separated from the carriage.

4.2.2.6 Example 6

During transfer of an unchanneled spent fuel assembly from a fuel preparation machine to a spent fuel rack in the fuel pool, the assembly fell about 1.5 m (5 ft) from the main grapple to the pool floor because of a grapple design deficiency. No release of radioactivity was measured even though the assembly was damaged. (Visual inspection of the assembly revealed it to be considerably bowed over its whole length.)

4.2.2.7 Conclusion

This summary of recent fuel damage experience in underwater environments from abnormal handling and transporting operations shows that in most cases involving damage, minor degradation of fuel assembly components did not cause a breaching of the fuel pin cladding or a release of radioactive gases or solids. This was true even in those cases where the fuel assemblies fell as far as 30 ft through water and impacted other fuel assemblies or the bottom of the spent fuel storage pool.

4.2.3 Geometrical and Mechanical Properties of Fuel Assemblies

Technical descriptions of the geometrical and mechanical properties of a variety of fuel assemblies were compiled to facilitate selection of a reference configuration for analytical purposes. Information was gathered for Westinghouse 14 x 14, 15 x 15, 16 x 16, and 17 x 17 PWR fuel assemblies, G.E. 7 x 7 and 8 x 8 BWR fuel assemblies, the Babcock and Wilcox 15 x 15 PWR fuel assembly, and the Combustion Engineering 15 x 15 PWR fuel assembly. All pertinent mechanical design parameters and properties are tabulated in the literature (Refs. 19, 20, 21, and 22).

It was necessary to select one of the above assemblies as the reference assembly because there is no standard design for any vendor and in-house designs are continually being modified. Many design details are considered proprietary by the fuel vendors. Some consider only the mechanical design proprietary; others consider the materials used for specific components proprietary. This further restricts the selection of a representative assembly, and makes it impossible to define the same level of detail for all the fuel bundle types. On the basis of the available information, the Westinghouse 17 x 17 design was selected.

4.2.4 The Effect of Irradiation on Zirconium Alloy Cladding

The effect of fast-neutron irradiation on zirconium alloys used for the fuel tube cladding material has been documented by numerous investigators. These changes include an increase in tensile strength, a reduction in impact strength, and a decrease in ductility. The pertinent mechanical properties of irradiated zircaloy were extracted from the technical literature for use in the nonlinear fuel pin impact analysis. These properties are discussed in detail in Subsection 4.4. Most researchers agree on the principal effects of irradiation on most mechanical properties. However, there are many differences of detail, and it is clear that materials supplied by different manufacturers or fabricated differently can vary significantly in mechanical properties.

4.3 Estimate of Energy Absorption by Various Parts of the Fuel Assembly

In the present design configuration, the bare fuel assemblies are handled in the fuel unloading hot cells. The floor level of the cask transfer tunnel, the fuel racks and other isolated areas are 25 ft below the floor elevation of the fuel unloading hot cells. Allowing 5 ft clearance for handling in the fuel unloading hot cell, the maximum potential drop height during waste-handling operations is approximately 30 ft. Hence, this analysis was conducted to estimate the amount of energy absorbed by a typical fuel assembly after an accidental drop from a height of 30 ft.

Energy balance methods were used to determine the percentage of impact energy absorbed by various parts of the fuel assembly. The analytical model used for impact analysis is an adaptation of the seismic model created by Westinghouse (Ref. 23). Since the mass, stiffness, and damping properties of this model are proprietary information, it was necessary to revise the model and recalculate the properties.

4.3.1 Fuel Assembly Description

The fuel assembly selected for this study is the Westinghouse Standard 17 x 17 PWR fuel assembly, shown in Figure 4-1. The 17 x 17 design incorporates an array of 289 positions, of which 264 are occupied by fuel pins. The remaining 25 positions are occupied by 24 guide tubes and one instrument tube in which a variety of other components are inserted. Also included are upper and lower end fittings (nozzles), which are made of cast type-304 stainless steel. Eight fuel rod spacers (grid assemblies) maintain rod-to-rod configuration along the length of the assembly. These grids, as well as the rods and tubes, are made of zircaloy-4. The 24 guide tubes and the instrument tube are externally larger than the fuel pins, but replace only one fuel pin each. The physical properties of all elements in the assembly are given in Table 4-1.

Figure 4-1
Fuel Assembly Outline 17 x 17

Table 4-1

MECHANICAL DESIGN PARAMETERS FOR THE WESTINGHOUSE 17 x 17
STANDARD PWR FUEL ASSEMBLY

<u>Item</u>	<u>Value</u>
Assembly	
Transverse dimension, in.	8.426
Assembly weight, lb	1,467
UO ₂ /assembly, lb	1,154
Overall length, in.	159.8
Fuel pins	
Number per assembly	264
Length, in.	151.635
Fuel length, in.	144
OD, in.	0.374
Diametral gap, in.	0.0065
Clad thickness, in.	0.0225
Clad material	Zr-4
Fuel pellets	
Type	UO ₂
Total weight/pin, lb	4.37
Guide tubes	
Number/assembly	24
OD, in.	0.474
Wall thickness, in.	0.016
Material	Zr-4
Instrument tube	
Number/assembly	1
OD, in.	0.48
Material	Zr-4
Bottom nozzle	
Material	SS 304

4.3.2 Analytical Model of Fuel Assembly

The fuel assembly is idealized by an assembly of masses, springs, and a gap, as shown in Figure 4-2. This model is a simplified version of the computer model used for the Westinghouse seismic study (Ref. 23). The fuel pins and fuel pellets are lumped together as a single mass which is supported (before impact) by the friction between the fuel pins and grid assemblies. This friction force is assumed to be 100 lb/tube as a reasonable average value, giving a total friction force of 26.4 kips.

The grid assemblies are supported by the guide thimbles and the instrument tube. The fuel pins are mounted on the grids so that there is a 0.75 in. gap between the fuel pins and the bottom nozzle assembly. Upon impact, the kinetic energy is initially absorbed by friction between the grid assembly and fuel pins and compression of the guide thimbles.

The spring constants for the fuel pins and guide tubes were determined from the equation:

$$k = \frac{nAE}{L}$$

where

- E = modulus of elasticity at temperature of 300°C
- L = one half of the length of fuel pin or guide tube
- n = number of tubes
- A = cross-sectional area of tube

Stiffness values obtained in this way are slightly higher than those computed considering the actual cross-sectional geometry. Consequently, the force required to initiate yielding of the guide tubes, computed as the product of the cross-sectional area and yield stress of the tubes, is approximately 30.9 kips.

M_{fp} = Mass of fuel pins

F_{fr} = Friction force between fuel pins and grid assembly

M_{th} = Mass of thimbles

K_{th} = Stiffness of thimbles

M_n = Mass of bottom nozzle

K_n = Stiffness of bottom nozzle

Figure 4-2
Analytical Model of a Fuel Assembly

Once fuel pins have impacted the bottom nozzle, the kinetic energy is absorbed by compression of both the guide thimbles and the fuel pins as well as the friction resistance. In addition, the bottom nozzle absorbs kinetic energy through flexural deformation of the bottom plate and compression of the nozzle legs.

4.3.3 Loading Condition

A conservative estimate of the load is made by assuming that the impact occurs vertically on a rigid surface and that the fuel assembly does not rebound. Consequently, the total energy imparted to the model is equal to the kinetic energy of the fuel assembly after it has fallen 30 ft. The velocity, v , upon impact is

$$\begin{aligned} v &= (2 gh)^{1/2} \\ &= 44 \text{ fps} \end{aligned}$$

The total mass is 45.6 lb-sec²/ft. Thus, the total impact energy, KE, for the fuel assembly is

$$\begin{aligned} KE &= 1/2 mv^2 \\ &= 44,100 \text{ ft-lb, or } 530 \text{ k-in.} \end{aligned}$$

4.3.4 Analytical Results

Energy dissipation by several modes of failure of fuel assembly components were examined. These include friction between the grid assembly and fuel rod, compression of the guide tubes, compression of the fuel rods, bending of the bottom nozzle base plate, and compression of the bottom nozzle legs.

The amount of energy dissipated as strain energy in each component of the fuel assembly is computed from the force-displacement curves for each. The friction mechanism and the spring representing the guide tube stiffness in the model act in series.

Since the maximum friction force is lower than the yield force of the guide tubes, the frictional resistance is overcome first. The energy required to close the 0.75 in. gap between the bottom nozzle and the fuel pin is 14 k-in. This is the sum of the energy dissipated by the friction between the fuel pins and the thimbles and the elastic strain energy resulting from the compression of the thimbles and instrument tubes. This 14 k-in. energy is about 3 percent of the total energy imparted to the fuel pins. At the moment when the fuel pins have just impacted the bottom nozzle, the guide tubes have not yet been stressed to yield, and the kinetic energy of fuel pins is 516 k-in. This energy is absorbed in the deformation of the fuel pins.

In the above calculation, it is assumed that the bottom nozzle is infinitely rigid. This nozzle, however, could be included in the model with a stiffness equal to the flexural stiffness of a 6.75 in. x 6.75 in. square plate, simply supported at the four nozzle legs, subjected to a uniform load. Since the information about the nozzle leg was not completely available, the actual stiffness and the yield force of the bottom nozzle could not be readily calculated. Judging from the pictorial representation of the nozzle, it was believed that this force is much larger than the friction force between the fuel pins and the grid assembly, in which case the previous rigid nozzle assumption would still be valid. The key question concerns the pin-nozzle interaction, namely, How much kinetic energy is absorbed by the fuel pins and how much by the bottom nozzle after the fuel pins have impacted the bottom nozzle? The effect of the bottom nozzle on the maximum stress and strain of the fuel pins can be calculated only when more information about the bottom nozzle becomes available.

4.3.5 Conclusion and Recommendations

Based on the rigid bottom nozzle assumption, when a standard Westinghouse 17 x 17 fuel assembly is dropped from a height of 30 ft, 483 k-in. of kinetic energy is retained in the fuel pins after they have impacted the bottom nozzle. This constitutes 97 percent of the initial energy imparted to the fuel pins. Further refinements of the model and finite-element techniques are needed to account for the effect of the bottom nozzle on the dynamic response of fuel pins during the pin-nozzle interaction.

4.4 Effect of Impact on Fuel Pins and Fuel Pellets

4.4.1 Assumptions Used in the Impact Analysis

The typical fuel pin structure of a standard Westinghouse 17 x 17 fuel assembly is shown in Figure 4-3. An impact analysis of the fuel pin was performed using the finite-element computer program DYNA3D. Only axisymmetrical deformation was considered; no lateral buckling deformation was investigated. The following assumptions were made:

- o A separated individual fuel pin is dropped 30 ft in a vertical position and strikes a rigid target surface in a perpendicular direction.
- o Fuel pellets are rigidly connected as a continuous piece of cylinder.

4.4.2 Finite-Element Model of a Fuel Pin

As assumed previously, the deformation of fuel pins after impact would be axisymmetrical. A three-dimensional model for a quarter fuel pin was created. The model consists of 5,202 solid elements and 12,424 nodal points. Among these elements, 2,160 elements were employed to model fuel pellets, and 3,000 to model zircaloy cladding. Top and bottom end plugs were also modeled.

Figure 4-3
Fuel Pin Structure

The spring inside the fuel pin was not considered in the model because the initial spring force on fuel pellets would be reduced rather than increased before the fuel pellets started to rebound.

Every nodal point in this model is completely free, except that those lying in the symmetrical planes are constrained in the direction normal to the plane. Figures 4-4, 4-5, 4-6, and 4-7 show a typical section for each component in this model; Table 4-2 summarizes the nodal point and element ranges for these components.

In this model, three sliding interface surfaces are defined. The first interface surface defines the contact between the bottom surface of the bottom end plug and the rigid target plate; the second interface describes the interaction between the bottom surface of fuel pellets and the top surface of the bottom end plug; and the third interface defines the interaction between the inner cylindrical surface of zircaloy cladding and fuel pellets. All of these three interfaces allow contact surfaces to slide against one another with gaps.

Figure 4-4

Finite-Element Model of a Fuel Pin
(Cross Section of Bottom End Plug at $Z = 0.00$ in.)

Figure 4-5

Finite-Element Model of a Fuel Pin
(Cross Section of Fuel Pellet at $Z = 143.7880$ in.)

Figure 4-6
Finite-Element Model of a Fuel Pin
(Cross Section of Zircaloy Cladding at $Z = 150.9880$ in.)

Figure 4-7

Finite-Element Model of a Fuel Pin
(Cross Section of Top End Plug at Z = 151.6760 in.)

Table 4-2

SUMMARY OF THE FINITE-ELEMENT MODEL OF THE FUEL PIN

<u>Component</u>	<u>Nodal Points</u>	<u>Elements</u>	
Bottom end plug	1 to 48	1 to 21	(21)
Fuel pellets	49 to 4,376	22 to 2,181	(2,160)
Zircaloy clad	4,367 to 12,384	2,182 to 5,181	(3,000)
Top end plug	12,377 to 12,424	5,182 to 5,202	(21)
Target plate	12,425 to 12,432	5,203	(1)

Note: Numbers in parentheses indicate the total number of elements in the component.

4.4.3 The Effect of Irradiation on the Mechanical Properties of Zircaloy-4

Like many other metals, zirconium is strongly influenced by the lattice defects created by fast neutron bombardment.

Consequently, the behavior of zircaloy-4 cladding tubing subjected to impact loading cannot be adequately described without taking into account its mechanical properties in the irradiated state. The properties of particular interest in this analysis are yield stresses, ultimate tensile stress, total elongation, modulus of elasticity, and Poisson's ratio.

The effect of irradiation on these properties must be reviewed and assessed for a given clad temperature, neutron dose, and metallurgical condition. For this study, mechanical properties are evaluated at a temperature of 280°C and a fluence (time integral of the particle flux density) of 2.7×10^{20} neutrons/cm² (Ref. 24). The more common methods of tube manufacture involve hot extrusion of a hollow billet to a hollow tube, followed by cold reduction with interstage annealing treatments, and final stress relief or recrystallization anneal. The properties of the tube vary according to the amount of residual cold work. Since the 13.1 percent cold work is the most common case, the mechanical properties of zircaloy at this amount of cold work is selected for the present study.

The mechanical properties of irradiated and unirradiated zircaloy are presented in Table 4-3. Because of the scarcity of published data on irradiated zircaloy-4, some of the values (as indicated) are given for zircaloy-2 instead of zircaloy-4. In addition, few researchers have tested irradiated zircaloy-4 fuel cladding under conditions that represent the stressing systems operative in a fuel pin, and few results have been published. Since the difference between the known values for the two alloys is less than 10 percent, and no significant differences have emerged from the recent development work on the two alloys, the use of zircaloy-2 properties for the unknown values is considered to be adequate for this initial analysis.

Investigations have shown that, in general, exposure to neutrons increases ultimate tensile strength and yield strength, and decreases ductility. Furthermore, these effects become more pronounced as the neutron dose increases. In addition, these same characteristic changes occur at all temperatures of interest in this study - room temperature to about 400°C.

The fabrication history, however, has a large effect on the irradiated properties. Irradiating a material is comparable to cold-working it. Both processes increase the strength and

Table 4-3

MECHANICAL PROPERTIES OF ZIRCALOY AT 280°C
AND 13.1% COLD WORKING

<u>Property</u>	<u>Alloy</u>	<u>Irradiated</u>	<u>Unirradiated</u>	<u>Ref.</u>
Proportional limit, ksi	2	57.7	41.0	24
2% offset yield stress, ksi	2	61.0	47.8	24
Ultimate tensile stress, ksi	2	62.1	48.8	24
Total elongation, %	2	9.0	13.0	24
Density, lb/in. ³	4	0.237	0.237	25
Modulus of elasticity, ksi	4	14,000	14,000	25
Poisson's ratio	4	0.35	0.35	26,27

decrease the ductility. Specifically, materials that have more than 20 percent cold working prior to irradiation show much smaller increases in their ultimate tensile strength and yield strengths. Kemper and Kelly (Ref. 28) also found that these changes are recoverable and approach the values for the unirradiated materials by annealing for 200 hours at 250°C. However, irradiated materials do not recrystallize during post-irradiation annealing, whereas cold-worked materials will recrystallize if a sufficiently high annealing temperature is used.

4.4.4 Material Modeling for the Fuel Pin

Material properties at a temperature of approximately 300°C for UO_2 and zircaloy cladding were input into this model. At this temperature, UO_2 is nearly brittle, which means that the fracture of UO_2 will take place with a very small or no plastic strain. However, an effective plastic strain equal to 10 percent of yield strain was assumed as the failure strain for UO_2 . This assumption is necessary in order to use the elastic-plastic

failure material model in the computer code employed, and it does not cause a significant deviation from the brittle behavior of UO_2 . At the same temperature (300°C), zircaloy cladding is relatively ductile even after being irradiated. It has a failure (effective plastic) strain of 0.0864, or a total strain of 0.09. In this analysis, after an element fails, it no longer takes tension and the deviatoric stresses, but can still be subjected to compression.

Although zircaloy cladding has a strain-softening characteristic after the initial yielding (Ref. 24), an equivalent bilinear strain hardening relationship was employed to avoid possible numerical instability in the computer analysis. This equivalent strain hardening material was based on the equivalence of energy absorption capacity. Table 4-4 summarizes the material properties used in this model.

Table 4-4

MATERIAL PROPERTIES OF THE FUEL PIN MODEL

<u>Property at 300°C</u>	<u>UO₂</u>	<u>Zircaloy Cladding</u>
Density, lb/in. ³	0.372	0.237
Modulus of elasticity, ksi	30,400	14,000
Shear modulus of elasticity, ksi	11,220	5,185
Yield stress, ksi	18.85	50.00
Modulus of strain hardening, ksi	304	140
Yield strain	0.00062	0.00357
Effective plastic strain at failure	0.000062	0.086430
Bulk modulus, ksi	34,940	15,560
Poisson's ratio	0.355	0.350
Ultimate tensile stress, ksi	18.87	62.10

4.4.5 Results of the Analyses

A fuel pin free-falling 30 ft to the target surface reaches a maximum velocity of 527 in./sec. at the point of impact, which was prescribed as the initial condition for the analysis. The analysis was carried out for a duration of 1,000 microseconds.

The deformations of the fuel pellets and zircaloy cladding are shown in Figure 4-8. At 50 microseconds, the fracture of the bottom pellet (height, 0.53 in.) was found. After the failure of the bottom pellet, interaction between the failed pellet and the zircaloy cladding started. At 100 microseconds, the next bottom pellet failed. The interaction between the failed fuel pellet and zircaloy cladding caused the bottom zircaloy clad to expand outward continuously. At 350 microseconds, the first failure of zircaloy occurred at approximately 0.30 to 0.45 in. from the bottom surface of fuel pellet. As time passed, this failure extended downward. At a time 550 microseconds from the beginning of impact, the failure of the zircaloy clad stopped at approximately 0.15 in. from the bottom surface of the fuel pellet. At 800 microseconds, when the impact wave reached the top of the fuel pin, three fuel pellets fractured. When the computation was terminated at 1,000 microseconds, no additional fuel pellet fractured, although the deformation of the fuel pellet and zircaloy cladding continued to increase. The fractured portion of the fuel pellets amounted to about 1.325 in., or less than 1 percent of the total height of the fuel pellets. Table 4-5 summarizes the accumulated effective plastic strains at critical locations.

Figure 4-8

Deformation of a Fuel Pellet and
Zircaloy Cladding Due to Impact

Table 4-5

ACCUMULATED EFFECTIVE PLASTIC STRAINS

<u>Component</u>	<u>Location</u> (from the bottom of fuel pin)	<u>Accumulated Effective Plastic Strain</u>
Bottom end plug	Middle thickness	Ductile failure
Fuel pellet	0.69-2.01 in.	Brittle failure
Zircaloy cladding	0.69-0.84	0.0701
	0.84-1.14	Ductile failure
	1.14-1.29	0.0845
	1.29-1.44	0.0785
	1.44-1.59	0.0605

5.0 FUEL PELLET PULVERIZATION

5.1 Introduction

Brittle materials are those that fracture without plastic deformation when subjected to tensile strain above the elastic limit. Common glasses, ceramics, and UO_2 are brittle materials by this definition, but common metals are not. The impact-fracture behavior of selected brittle materials was examined in a study conducted at Argonne National Laboratory (ANL) in 1979-1981 (Refs. 29 and 30). Although a variety of materials and a range of impact configurations and conditions were used, the generalized results found cannot be said to have received sufficient empirical support to establish their generality as theory. Nevertheless, the basic principles of physical mechanics, the theory of elasticity, material science, and small-particle statistics have been combined to provide a useful analytical tool for research in a very difficult area, namely impact fracture with its noncontinuum, nonequilibrium mechanics and thermodynamically irreversible rate processes.

The ANL analysis were based on the well-established theory of elasticity (Ref. 31), on the state-of-the-art of glass science (Ref. 32), and on energy-surface area correlations established experimentally for small specimens of glass and quartz (Ref. 33). The application of the lognormal probability function to describe the size distribution of fracture particulates followed the state-of-the-art of small-particle statistics (Ref. 29). Details and conclusions of the ANL experimental tests on selected materials have been reported previously by Mecham et al. (Ref. 29) and Jardine et al. (Ref. 30).

5.2 Impact Fracture of Brittle Materials

In the ANL studies, a literature review was conducted as a preliminary phase of a study of the impact fracture of brittle

materials (Ref. 29). The principal conclusions of this review were the following:

- o If sufficiently high levels of elastic strain energy per unit volume of materials (energy density) can be developed within brittle material by the application of an external force, the material disintegrates into particles of a range of sizes, including submicron particles. This happens for both slowly and rapidly applied forces and for tensile and compressive forces.
- o This fracture behavior is consistent with current knowledge of fracture mechanics and with observed rates of crack propagation, as well as with correlations of fracture surface area with energy dissipated in the brittle material.
- o Lognormal statistics have been developed for describing fracture particulates, and the empirical lognormal size distributions provide a general model of the impact-fracture process (Refs. 34 and 35).

A preliminary series of drop-weight impact tests of representative brittle materials was made (Ref. 29). Cylindrical specimens (approximately 25 mm x 25 mm) were impacted diametrically in a bellows-sealed impact chamber by a falling 10 kg steel bar, and the resulting particle size distributions were measured by sieving the Coulter counter analysis (down to about a 5-micron size). The materials tested included: Pyrex glass, Macor glass ceramic, sintered UO_2 ceramic, and fused quartz (vitreous silica). Three natural materials were also tested: crystalline quartz, nepheline syenite, and sandstone. All results showed that the fracture particulate proper, which included all particles of respirable size (i.e., diameters less than 10 microns), and which contained more than about 90 percent of the total surface area, had a straight-line size distribution when plotted on lognormal graphical coordinates as shown in Figure 5-1 (Ref. 30).

Figure 5-1

Computer Regression Analysis Plots of $P(\%)$, the Cumulative Lognormal Mass Distributions (in mass percent of initial specimen mass) of Fragments vs $D(m)$, the Measured Fragment Diameters from 10 J/cm^3 Impact Tests of (1) Glasses (Upper Plot) and (2) Crystalline Ceramic and Concrete Simulated Waste Forms (Lower Plot). The shaded areas correspond to potentially respirable particles (i.e., $< 10 \mu m$).

5. Empirical Descriptions of Fracture Particulates

Empirical characterization of the size distributions of particles produced from brittle material by various crushing processes has led small-particle statisticians to extensive application of the lognormal probability function, e.g., Herdan (Ref. 34), although this lead has not been much followed by experimenters. The applicability of the lognormal mathematics to characterization of particulates is very extensive. Of course, the utility of using a lognormal analysis rests not on theoretical, but on empirical grounds. Size-distribution measurements give data points that plot as an approximately straight line on lognormal graphical coordinates.

5.4 Correlation of Impact Energy and Fracture Surface Area

The thermodynamic (reversible) free energy of surface formation in a typical brittle material is the order of 1 J/m^2 (Ref. 33). In practical impacts, the energy consumption is much higher per unit of surface formed. In a systematic study of the energy-surface correlation conducted at the University of Minnesota in 1962, an impact calorimeter was used to make an energy balance for the fracture of small Pyrex and quartz (vitreous and crystalline) specimens over a wide range of energy input. The particle sizes were not measured, but the total particulate surface area was measured by the BET gas-adsorption method. The principal equation investigation was

$$\epsilon W_o = \gamma_f S_n \quad (1)$$

where W_o was the energy input, ϵ was the fraction of input kinetic energy actually dissipated in the brittle material (measured with the calorimeter), S_n was the measured total fracture surface area, and γ_f was the material fracture strength calculated from the equation. The input energy density

(energy per unit volume of material) varied over a factor of 20 in these tests, but the value of the impact-strength property γ_f was constant (within about 5 percent) at a value of 77 J/m^2 . The value of ϵ was measured in the range of 0.5 to 0.95 in these tests (Ref. 33). In the ANL impact tests, different values of ϵ could have occurred, but the basic energy-surface correlation was corroborated in the ANL work.

5.5 Surface Areas and Shape Factors

Although the particles produced by impact fracture are very irregular, the irregularity (as observed with the microscope and electron microscope) is definitely limited by physical conditions. There are, for instance, no extremely long needle-shaped particles nor any very thin plate-shaped particles. A statistical mean surface/volume ratio can be used to describe the actual particles. For a given particle diameter D (however measured), there is both a mean volume and a mean surface, each of which can be expressed mathematically as a shape factor. From available empirical data, it appears that these shape factors are uniform over the range of size of the fracture particulate, although different materials may have somewhat different shape factors. The shape factor of practical interest is α : the surface area/volume ratio for the lognormal fracture particulate as a whole.

One of the mathematical properties of the lognormal particle statistics is that, once the mean diameter, D_g , and the standard deviation, σ_g for the volume distribution is known, the surface-area distribution can be calculated.

For an ideal (complete) lognormal distribution ($0 \leq D \leq \infty$), there is a mathematical relation for the ratio of the total surface area, S_n , and the total volume, V_n of the particles

$$\frac{S_n}{V_n} = \frac{\alpha \sigma_g^{0.15 \ln \sigma_g}}{D_g} \quad (2)$$

where α is the overall surface/volume shape factor. If Equations (1) and (2) are combined

$$\frac{\epsilon}{\gamma_f} \frac{W_o}{V_n} = \frac{S_n}{V_n} = \frac{\alpha \sigma_g^{0.15 \ln \sigma_g}}{D_g} \quad (3)$$

Now, if the input energy, W_o , specimen volume, V_n , particulate surface area (by BET method) S_n , and D_g and α (by sieving) are measured both the shape factor, α , and the combined strength parameter (γ_f/ϵ) can be calculated. This gives a complete characterization of the results of fracture, since the size fractions and surface areas of the particulate are determined for the full range of particle diameters.

5.6 Correlation of Fracture Parameters with ANL Input Energy Density

In Equation (3) above, the fracture surface/volume ratio, S_n/V_n , is proportional to the impact energy density, W_o/V_n ; the proportionality constants are the lognormal fracture parameters previously identified. The utility of the impact-characterization method described here depends on being able to correlate the fracture parameters with impact conditions and material properties. Preliminary correlations were presented in Table 5-1, which summarizes the results of five diametrical impact tests of Pyrex specimens (38 mm dia. x 68 mm long cylinder, Ref. 36). Impact energy densities varied 20-fold. In addition, the correlation of the respirable sizes (less than 10 microns) versus the energy density was compiled in this study. These results are shown in Figure 5-2 and Table 5-2. Of the parameters listed, the mean diameter, D_g , was inversely proportional to energy density; the others, σ_g , α , α_f/ϵ , etc., were approximately independent of energy density. From the percentage range indicated, the accuracy of these correlations was within about a factor of 2. A similar accuracy was observed for the respirable fraction, the volume fraction of particles with diameters less than 10 microns, which was directly proportional to

Table 5-1

PRELIMINARY CORRELATIONS OF LOGNORMAL PARAMETERS
WITH ENERGY DENSITY FOR FIVE DIAMETRICAL IMPACT TESTS
OF PYREX CYLINDRICAL SPECIMENS^(a)
(FROM REF. 36)

<u>Parameter</u>	<u>Symbol, Units</u>	<u>Mean Value, % Range</u>	
Geometric standard deviation	σ_g , dimensionless	5.9	(+25%, -27%)
Correlation of geometric mean	$D_g (W_o/V_n), J/m^2$	1.6×10^4	(+25%, -38%)
Correlation of respirable fraction ^(b)	$V(10 \mu m)/W_1, m^3/J$	2.0×10^{-10}	(+35%, -60%)
Surface/volume shape factor	α , dimensionless	24	(+13%, -21%)
Combination strength parameter ^(c)	$\alpha \gamma_f / \epsilon, J/m^2$	3.3×10^3	(+70%, -40%)
Energy efficiency ^(d)	$\epsilon, \%$	56	(+40%, -29%)

(a) Range of energy density: $2.4 J/cm^3 \leq (W_o/V_n) \leq 50 J/cm^3$.

(b) Equal to $[V(10 \mu m)/V_n][W_o/V_n]$.

(c) Calculated as $[W_o/V_n] D_g \sigma_g^{-0.5} \ln \sigma_g$ from test data.

(d) Assuming $\gamma_f = 77 J/m^2$ (Ref. 34).

Table 5-2

IMPACT TEST DATA FOR PYREX CYLINDERS

Energy	> Respirable	> Mean	> Standard	>	>	>	>
Density	> Fraction	> Diameter	> Deviation	>	>	>	Specimen
J/cm ³	> wt % (<10cm)	> D _g ,mm	> σ _g	>Reference>	>Page>	>Table>	Size
	>	>	>	>	>	>	>
0.41	0.003 ± 0.001	21 ± 5.0	7.1 ± 0.2	ANL 81-27	44	4	38mm OD
0.41	0.003 ± 0.001	17 ± 7.0	6.8 ± 0.7	ANL 81-27	44	4	38mm OD
0.41	0.002 ± 0.001	15 ± 5.0	6.2 ± 0.4	ANL 81-27	44	4	38mm OD
1.2	0.067 ± 0.010	11.0 ± 3.0	8.7 ± 0.5	ANL 82-39	29	7	25mm OD x 25mm
1.2	0.011 ± 0.003	18 ± 5.0	7.6 ± 0.5	ANL 81-27	43	3	38mm OD
1.2	0.012 ± 0.001	13 ± 2.0	7.1 ± 0.2	ANL 81-27	43	3	38mm OD
1.2	0.0045 ± 0.0014	9.6 ± 3.0	5.8 ± 0.4	ANL 81-27	43	3	38mm OD
2.4	0.052 ± 0.007	6.9 ± 1.4	7.3 ± 0.5	ANL 82-39	29	7	25mm OD x 25mm
2.4	0.0034 ± 0.0005	4.6 ± 0.7	4.7 ± 0.1	ANL 81-27	43	3	38mm OD
2.4	0.0016 ± 0.0004	5.4 ± 0.2	4.6 ± 0.2	ANL 81-27	43	3	38mm OD
2.4	0.0047 ± 0.0009	6.6 ± 1.5	5.3 ± 0.2	ANL 81-27	43	3	38mm OD
2.4	0.0022 ± 0.0004	6.1 ± 0.9	4.8 ± 0.1	ANL 82-27	43	3	38mm OD
5	0.11 ± 0.02	3.4 ± 0.7	6.7 ± 0.4	ANL 82-39	29	7	25mm OD x 25mm
10	0.27 ± 0.03	1.4 ± 0.2	6.0 ± 0.2	ANL 82-39	24	6	25.0mm OD x 25.8mm
10	0.27 ± 0.04	1.7 ± 0.5	6.3 ± 0.4	ANL 82-39	29	7	25mm OD x 25mm
10	0.28 ± 0.03	2.1 ± 0.3	6.9 ± 0.2	ANL 82-39	41	12	25mm OD x 25mm
10	0.29 ± 0.09	1.9 ± 0.8	6.7 ± 0.5	ANL 82-39	43	13	N/A
10	0.29 ± 0.02	1.6 ± 0.2	6.3 ± 0.1	ANL 82-39	41	12	25mm OD x 25mm
10	0.30 ± 0.08	1.1 ± 0.4	5.6 ± 0.3	ANL 82-39	43	13	N/A
10	0.30 ± 0.08	1.1 ± 0.4	5.6 ± 0.3	ANL 82-39	41	12	25mm OD x 25mm
10	0.09(a)	1.1(a)	3.3(a)	ANL 82-39	82	34	13mm OD x 25mm
50	1.1(a)	0.38(a)	4.9(a)	ANL 82-39	82	34	13mm OD x 25mm
100	0.31(a)	0.31(a)	3.4(a)	ANL 82-39	82	34	13mm OD x 25mm
140	3.1 ± 0.2	0.18	4.7	ANL 82-39	35	10	12.5mm OD x 12.5mm

(a) These data were taken from graphs in references cited. More accurate data could be obtained from ANL experimental logbooks or monthly reports.

Respirable Size Fraction
wt% < 10 μ m

input energy density. For many practical purposes, these approximate characterizations are adequate to describe the results of impact fracture. Fracture behavior depends on mechanical properties and not on chemical properties. The range of behavior for a variety of different brittle materials (vitreous and crystalline) has been reported in detail by Mecham et al. (Ref. 30) and Jardine et al. (Ref. 35). Lognormal analysis was found applicable for all cases investigated, and no significant difference between axial and diametrical impact was observed.

5.7 Application of Laboratory-Scale Experimental Data to the Results of Finite-Element Analysis

Future studies need to examine and develop the relationships and possible correlations between the laboratory-scale results for small specimens and the finite-element analysis results for a single full-scale spent fuel rod. The schedule and resources did not allow this to be done in this initial study. With further study, it may be possible to determine the scaleup factors and correlations that exist between the laboratory-scale and full-scale spent fuel assemblies. Such a future study should also contain recommendations for critical confirmatory-type experimental tests that could verify the analytical modeling approaches. The overall goal of such future studies should be to work out a modeling approach using small-scale laboratory test results that could be used to predict the performance of full-scale spent fuel assemblies in impact scenarios, especially estimating the amount of radioactive airborne source terms while minimizing the need for more expensive full-scale testing. The same types of studies could be used to predict the performance of full-scale canisters of vitrified DHIW.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Load Envelopes and Potential Drop Heights for Casks and Containers

From the load cases evaluated in Subsection 2.3, load envelopes have been developed for casks and containers (Tables 2-1, 2-2, and 2-3). These load envelopes are preliminary estimates of the maximum stresses imposed upon parts of a typical cask or container. The load envelopes for the casks indicate that the maximum stresses occur when the truck cask or rail cask rolls off a transfer car and strikes the floor. The stress levels determined for these two cases are less than the yield strength of the stainless steel. The actual impact forces are expected to be lower, since part of the impact energy will be either dissipated in the crushing of the concrete surface or absorbed by the flexibility of the concrete floor (or wall).

The load envelopes for the containers indicate that the maximum stresses occur when the (loaded) container impacts the hot-cell walls or a 2 in. dia. stationary object. For these impacts, the stress level at the point of contact exceeds the yield strength, but is much lower than the critical fracture stress of the stainless steel. This indicates that the container shell may yield, but will not fracture. For the impact on a sharp object due to a 2 ft free fall, the shear stress level exceeds the shear yield stress if the object is assumed to be perfectly rigid. This stress level is substantially reduced if the object is assumed to be elastic.

Because of the preliminary nature of this study, assumptions have to be made for the layout of the facility and the design of equipment. In the course of the stress analysis, simplified methods of analysis are used and conservative assumptions made.

* This is the most probable drop height. Drops from greater heights should be investigated.

To deal with the complex impact loading phenomenon, more sophisticated analyses utilizing the finite-element method are recommended as the design effort progresses. The load envelopes from this study should be considered as a guideline for preliminary design, and should not be treated as conditions to simplify the complexity of the impact phenomenon.

6.1.2 Potential Drop Heights During Normal Operations

Drop heights for both casks and containers are summarized in Table 2-4. For both cask and containers, the most likely drop height during the normal operation is 2 ft above the operating floor. The maximum drop height for the cask is approximately 10 ft from the operating floor; for the container, it is approximately 34 ft. However, the total area where the drop height is greater than 2 ft represents a very small part of the total operation area. Nevertheless, drops from such heights should be investigated.

6.1.3 Recommendations for the Mitigation of Impact Effects

As discussed in Subsection 4.1.1, the preliminary layouts do not provide sufficient information to specifically identify the areas or items of equipment that are vulnerable to potential impacts. Therefore, only a general discussion of mitigation processes is given in this report. For details and general recommendations, refer to Subsection 2.4.

6.2 Limiting Drop Height of the Container

6.2.1 Conclusions

Finite-element analyses for three different container drop heights revealed that for a limiting drop height of 3.8 ft the container

retains its integrity. It should be noted that this conclusion was based on analyses that were conducted using very limited resources. Further studies are recommended to learn more about the dynamic response of the container to the potential various impacts. These recommendations are given in Subsection 6.2.2.

6.2.2 Recommendations

In future studies of the limiting drop height of the container, the following should be investigated:

- o The effect of impact orientation, especially the impact on the pintle of the container
- o The effect of total container weight on the limiting drop height
- o The effect of interactions between the fuel assemblies and interactions between fuel assemblies and the container on the limiting drop height.
- o The effects of container impact on sharp objects and various target conditions
- o Confirmatory laboratory or full-scale testing.

6.3 Drop of Fuel Assembly and Spent Fuel Pulverization

6.3.1 Conclusions

A 30 ft drop analysis of a typical Westinghouse 17 x 17 PWR fuel assembly was performed using hand calculations to estimate the energy absorption by various parts of the fuel assembly. A finite-element impact analysis by DYNA3D was performed for a separated individual fuel pin with a 30 ft drop height. As a result of this analysis, the following conclusions were drawn:

- o The friction between fuel pins and the grid spacers dissipates only a small amount of the impact energy, approximately equal to 3 percent of the total kinetic energy imparted to the fuel pins.
- o The bottom 1.3 in. of fuel pellets (which is less than 1 percent of the total volume) fractures.
- o The zircaloy cladding fails in the region (0.15 to 0.45 in from the bottom of fuel pellet) where the fractured fuel pellet expanded radially.
- o There is no failure in the bottom end-plug of the fuel pin.

6.3.2 Recommendations

Further studies on the effect of impact on fuel assemblies and fuel pins are recommended. These studies should investigate the effect of lateral buckling on the failure of fuel pellets and the zircaloy cladding. Correlations of the initial small-scale ANL impact tests with the individual fuel pin finite-element modeling results should be attempted, and recommendations for future confirmation laboratory and fuel-scale testing should be made on the basis of this modeling. A simplified finite-element model can be created for the fuel assembly. A finite-element impact analysis, instead of the (oversimplified) hand calculations by the energy balance method, may be carried out to determine the energy absorption of the bottom nozzle so that the effect of the bottom nozzle on the dynamic response of fuel pins can be accounted for more realistically. The effects of nonperpendicular impact and impacts on various target conditions should also be investigated.

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- 1 NRC Document Control Desk
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U.S. Nuclear Regulatory Commission
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NRC Site Representative
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Las Vegas, NV 89101
- 1 E. P. Binnall
Field Systems Group Leader
Building 50B/4235
Lawrence Berkeley Laboratory
Berkeley, CA 94720
- 1 Center for Nuclear Waste
Regulatory Analyses
6220 Culebra Road
Drawer 28510
San Antonio, TX 78284

- 3 L. J. Jardine
Technical Project Officer for YMP
Mail Stop L-204
Lawrence Livermore National
Laboratory
P.O. Box 808
Livermore, CA 94550
- 4 R. J. Herbst
Technical Project Officer for YMP
N-5, Mail Stop J521
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
- 1 H. N. Kalia
Exploratory Shaft Test Manager
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr.
Suite 820
Las Vegas, NV 89109
- 1 J. F. Divine
Assistant Director for
Engineering Geology
U.S. Geological Survey
106 National Center
12201 Sunrise Valley Dr.
Reston, VA 22092
- 6 L. R. Hayes
Technical Project Officer
Yucca Mountain Project Branch--MS 425
U.S. Geological Survey
P.O. Box 25046
Denver, CO 80225
- 1 V. R. Schneider
Asst. Chief Hydrologist--MS 414
Office of Program Coordination
& Technical Support
U.S. Geological Survey
12201 Sunrise Valley Drive
Reston, VA 22092
- 1 R. B. Raup, Jr.
Geological Division Coordinator
MS 913
Yucca Mountain Project
U.S. Geological Survey
P.O. Box 25046
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- 1 D. H. Appel, Chief
Hydrologic Investigations Program
MS 421
U.S. Geological Survey
P.O. Box 25046
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- 1 E. J. Helley
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Nevada Operations Office
U.S. Geological Survey
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U.S. Geological Survey
101 Convention Center Dr.
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Project Planning and Management
U.S. Geological Survey
P.O. Box 25046
421 Federal Center
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- 1 A. L. Flint
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MS 408
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Las Vegas, NV 89193-8521
- 1 B. W. Colston
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