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Shipping Container Response to Severe Highway and Railway Accident Conditions

Main Report

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THE MODAL STUDY: THE RESPONSE OF SPENT FUEL PACKAGES TO SEVERE TRANSPORTATION ACCIDENTS

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ABSTRACT

The Modal Study was initiated by the U.S. Nuclear Regulatory Commission (NRC) to further evaluate the Safety of spent fuel shipments. The Study involves an investigation of the relationship between NRC's spent fuel package performance standards and real transportation accident conditions. The probable response of representative spent fuel packages to the forces generated in actual accidents was determined. The Modal Study results are used to provide several perspectives on the level of safety provided under real accident conditions by spent fuel packages designed to current standards and practices.

BACKGROUND

The transportation of radioactive materials is regulated principally by the Nuclear Regulatory Commission (NRC) and the Department of Transportation. A Memorandum of Understanding (MOU) defines the respective roles of the two agencies. Under the MOU, NRC develops package safety standards for fissile and larger quantities of radioactive materials, while the Department of Transportation (DOT) develops transport safety regulations for all packages and standards for packages of quantities of radioactive materials not covered by NRC. NRC's packaging regulations are found in 10 CFR Part 71.

In the mid-1970's, the NRC conducted a reevaluation of its transportation regulations to assess the adequacy of its regulations to protect public health and safety. In the course of the reevaluation, the NRC published a Final Environmental Statement, designated NUREG-0170. which included an examination of the transportation of radioactive material by all modes of transport. After considering the information developed, the public comments received, and the safety record associated with the transportation of radioactive materials, the NRC determined that its regulations are adequate to protect against unreasonable risk from transport of radioactive materials and that no immediate changes were needed to improve safety. Nevertheless, the NRC continues to study safety aspects of transportation of radioactive materials to determine where improvements might be made.

The accident resistance of packages was identified as a subject for further study in NUREG-0170. It was recognized that for certain types of shipments, such as spent fuel, the nature and quantity of material being transported was such that the consequences of release in an accident could be serious. Packages used for these types of shipments are required to be designed so that there is essentially no increase in radiological hazard when the package is subjected to the Hypothetical Accident Condition tests specified in 10 CFR Part 71. The tests are adequate to assure high integrity packaging and are generally recognized to be rigorous. The extent to which the tests simulate real accidents, however, had not been fully developed. The adequacy of the tests, particularly with respect to spent fuel packages, had also become a subject of public concern. To address these concerns the NRC initiated a study to evaluate the safety of spent fuel shipments in terms of severe accidents which actually occurred in non-nuclear shipments in surface transport modes. This study became known within NRC as the Modal Study.

The final phase of the Modal Study has recently been completed by the Lawrence Livermore National Laboratory (LLNL), and LLNL has recently presented their findings in a report entitled "Shipping Container Response to Severe Highway and Railway Accident Conditions" (NUREG/CR-4829). Prior to publication, the report was subjected to a peer review by the Denver Research Institute. The descriptions presented in this paper are based on the LLNL final report and its analysis by the NRC staff.

PACKAGE STANDARDS

Safety in transporting radioactive materials is regulated through a combination of packaging requirements and operational and administrative controls. The requirements and controls are based on the radiological hazard posed by the materials to be shipped. For shipments of small quantities of radioactive materials, primary reliance for safety is placed on an administrative control. That is, the regulations limit the package content of radionuclides to an amount which, if released under accident conditions, would not pose a substantial radiological hazard. For shipments of larger quantities of radioactive material, such as spent fuel, primary reliance for safety is placed on the packaging.

To provide safety in transport, a spent fuel package must provide three functions: containment of the spent fuel; shielding from radiation emitted by the spent fuel; and control of the spent fuel configuration so as to prevent a chain-reaction (i.e., maintain nuclear subcriticality). NRC's packaging standards have been developed to assure that spent fuel casks provide these functions under both normal and accident conditions in transport. The standards are performance oriented, that is, the standards basically state how the packaging must perform under normal and accident test conditions. The performance standard approach for spent fuel packagings was developed and accepted internationally, with the requirements expressed in terms that may be reproduced and satisfied by test or analysis.

NRC's performance standards for casks are comprised of two components: (a) package tests, to represent transport conditions; and (b) acceptance criteria, to gauge the package's performance after being subjected to the tests. The tests for hypothetical accident conditions, upon which we will focus, specify a sequential series of severe impact, puncture, fire, and immersion environments as follows (paraphrased):

(1) **Free Drop** - Thirty-foot drop of the cask onto a flat, horizontal, unyielding surface with the cask positioned so that its weakest point is struck.

(2) **Puncture** - Forty-inch free drop of the cask onto a 6-inch diameter steel bar at least 8-inches long; the cask must strike the bar at the cask's most vulnerable point.

(3) **Thermal** - Totally engulf cask in a fire or furnace at 1475°F for 30 minutes. (Other thermal conditions must be met.)

(4) **Submersion** - Immerse all packaging surfaces under 3 feet of water for 8 hours. An additional test requires immersion of a separate undamaged package in 50 feet of water for 8 hours.

The acceptance criteria used with the tests are expressed in terms related to the three safety functions described earlier: the package may not release more than a small amount of its contents, or exhibit more than a small increase in the external radiation levels and the package must maintain subcriticality.

[illegible] the NRC's package design certification process, an applicant must demonstrate that a package design meets the acceptance criteria after being subjected to the test conditions. The demonstration may be accomplished by actual tests, but demonstration by analysis is more commmon. The package design is reviewed by the NRC engineering staff to verify its accident resistance. A certificate is issued by the NRC before a package fabricated from the design can be used to transport material. In addition to other requirements, both manufacturers and users of the packages must follow NRC approved quality assurance programs.

A difficulty with the expression of performance standards is that the severity of the hypothetical accident conditions is not readily understood. This is particularly true for the 30-foot drop test and the half-hour fire test. For example, in the free-drop test, attention is often focused on the 30-foot height of the drop, while the requirement that the package strike an unyielding surface is disregarded. If the drop height alone is (mistakenly) considered to indicate the severity of the test, the test may not appear rigorous when compared to real accidents. There are many instances of trucks falling off highway bridges from heights exceeding 30 feet. But, the height comparison alone is inappropriate because it disregards the hardness of the surfaces being struck. The unyielding surface requirement in the test basically means the package must absorb almost all of the energy of the impact, and therefore, poses a very rigorous test of package integrity. Surfaces under bridges, such as river beds, railroad tracks, etc., and the vehicle itself, all yield under impact, thereby absorbing energy and posing a less severe impact shock to the package. Thus, the impact test is more rigorous than it may appear on first impression.

What has proved a more serious difficulty is illustrating how packages designed in accordance with the standards would perform in severe, real-world transportation accidents. Limited information about this relationship has hampered efforts to explain the level of safety provided by the existing standards. Addressing this issue was the central objective for the Modal Study: investigate the relationship between the package performance standards and real accident conditions, and explain clearly the level of safety provided by packages meeting the standards. The investigation was designed to constitute a generic, systematic evaluation of the standards. In addition to explaining safety, the results of the investigation were also intended to provide a basis for reaffirming the adequacy of the existing standards or indicating where changes are needed.

THE STUDY

A conceptual description of the Modal Study approach and methodology follows. For a precise description of the Modal Study's structure, please consult NUREG/CR-4829.

The approach used in the Modal Study is analytical. Basically, the Study first involves an examination of actual highway and railway accident experiences to determine the conditions encountered in real accidents. Computer models were then used to evaluate how a package designed to NRC standards would respond to the types of forces generated in those accidents.

The Modal Study is not empirical in nature. An empirical approach was not considered feasible since such an approach would rely necessarily on either spent fuel package accident experience or new accident experiments. With respect to accident experience, the scarcity of cask accidents provides an inadequate basis for the evaluation of cask response to severe accidents. During the last 30 years, only a few cask shipments have been involved in vehicle damaging accidents. There was no release of radioactive material in any of the accidents. Also, none of the accidents were considered to be particularly severe from an impact or fire standpoint. Regarding new experiments, the number of full- or semi-scale demonstration (crash) tests required for this study would be large and therefore prohibitively expensive. Further, such an approach would have required the definition of some sort of "reference accident" for the demonstration tests. The approach followed was to determine the response of large packages designed to current standards upon exposure to real accidents. Thus, the Modal Study did not include any specific crash tests.

One of the initial steps in the Modal Study was to determine a generic reference package design. The package design used is important because it serves as a surrogate in evaluating transport safety standards. The contractor developed a representative design for a road and a rail cask which would satisfy the standards. These representative cask designs were not as detailed as those for actual casks, but did include those features judged necessary to evaluate the safety functions described earlier. The representative designs for both road and rail casks employed concentric stainless-steel shells (inner shell providing containment) with lead placed between the shells to provide shielding. This basic design type was selected because it is in common use and because the lead shielding material melts at a lower temperature than does other shielding materials.

The next step included determining how the representative designs would respond to the range of forces encountered in real accidents. The contractor determined that strain on the inner steel shell was the best measure of package response to mechanical forces (impact, crush, puncture, etc.) and that temperature at the mid-line of the lead shielding was the best measure of package response to thermal input. Using computer models, the contractor then determined the degree of package response, i.e., determined the amount of damage caused as mechanical forces or thermal input on the package was increased. This analysis defined "package response states" for the various combinations of strain and temperature. The analyses were performed for both the road and rail packages.

The radiological hazard-of each package response state was then estimated, based on the assumption that the packages contained a full load of spent fuel that had been cooled 5 years. That is, the contractor estimated the amount of radioactive material release or increase in external radiation level, if any, for each response state. The contractor could then determine the radiological hazard arising from a given strain or temperature on the representative casks.

The other major steps concerned determining the forces which are experienced in real accidents, and the accident probabilities for various levels of severity. This involved a review of the historical record for road and rail accidents, including the severe accidents. This review yielded distributions of accident scenarios showing the occurrence rates for collisions over a widerange of target hardness, from soft objects, such as traffic cones, signs, etc., to hard objects, such as large concrete columns or abutments. An estimate of the forces involved in severe accidents were derived from reported accident conditions, vehicle speed in particular.

In the final steps of the evaluation, the contractor combined the package response and accident force analyses to estimate, given an accident has occurred, the probability of a representative cask reaching the various response states. Since the cask reflects the package standards and the cask response states can be related to radiological hazard, it is possible to determine the relationship between the standards and radiological safety provided under real accident conditions in transport.

THE RESULTS

The Modal Study approach, assumptions, and analyses have been reviewed by an independent peer review group, the Denver Research Institute. The Institute received analytical assistance from the Los Alamos National Laboratory. The group examined the appropriateness of the Study approach, the conservativeness of assumptions, and the accuracy of calculations. The peer review group did not identify any technical issues that would substantially alter the Study's results. For further detailed information, including a discussion of the impact of uncertainty in determining parameter values, refer to NUREG/CR-4829.

The Modal Study's objective was to investigate the performance of spent fuel packages under transport accident conditions and explain the level of safety provided by spent fuel package standards. The results, as summarized here, provide three perspectives on spent fuel transport safety: (1) the probability of an accident in which the package acceptance criteria are exceeded; (2) the total annual risk to the public from a large number of shipments; and (3) the probable response of the representative package to specific, severe accidents on record.

With respect to severe accident probabilities, results from the Study indicate that if the representative truck casks were involved in 1,000 accidents, the forces involved in 994 would not exceed either the strain or thermal responses corresponding to the Hypothetical Accident Conditions. For this 99.4 percent of accidents involving casks, damage would be superficial, and any release of radioactive material or increase in radiation exposure levels would be 3 well within NRC acceptance criteria.

Some release allowed

Of the six remaining accidents, four would cause minor functional damage to cask; however, the analyses indicates that the radiological hazard of these accidents would be small, still well within NRC's acceptance criteria.

In 2 of the 1.000 accidents, cask structural damage could be significant, althouqh rupture of the cask's containment-shield would not-be expected. Thermal damage could include some lead shield melting. The analysis predicts that the radiological hazard of those accidents would only slightly exceed the regulatory acceptance values.

Finally, if the number of cask accidents were to approach 10,000, 1 of these accidents might be expected to lead to cask damage in the higher response states. The associated radiological hazard is estimated to be 10 times that of the acceptance criteria. It should be noted, however, that the contractor could not identify a historical accident of sufficient severity that would cause this degree of cask damage. Results for the representative rail cask are similar to those for the truck cask.

The preceding discussion summarizes the likelihood of real accidents resulting in various levels of cask damage and how the associated radiological hazard compares with the acceptance criteria for releases of radioactive material and increases in radiation exposure. With regard to the acceptance criterion for criticality. the results indicated that the probability of a cask reaching conditions necessary for a criticality event, i.e., significant package damage and package immersion. is less than 0.000001 percent, given an accident has occurred.

Another way to view the level of safety is to evaluate the risk to the public if packages designed to NRC standards were used over time in a large series of shipments. This type of risk evaluation for spent fuel shipments was included in NUREG-0170.

The NUREG-0170 evaluation assumed an annual shipment scenario of 1,530 truck spent fuel shipments of 1,570 miles each and 650 rail shipments of 750 miles each. The annual radiological risk from accidents, which was based on conservatively assumed package releases in NUREG-0170, was estimated to be 0.0004 latent cancer fatalities per year. In the Modal Study risk evaluation, the assumed shipment scenario from NUREG-0170 was left essentially the same. The Modal Study, which is based on analysis of package releases, indicates the annual risk from accidents to be less than one third of the NUREG-0170 values. It may be recalled that NRC's finding that transport risk is small and transport regulations are adequate was based, in part, on the NUREG-0170 values.

In addition to the level of safety and risk summaries the Modal Study provides a third perspective on cask performance. Since the Modal Study analysis is based on subjecting the representative package designs to real accident conditions, it is possible to evaluate how the representative package would have performed had it been involved in specific, historically severe accidents. Part of the Modal Study analysis included a review of the 400 most severe accidents on record at the Department of Transportation. From these, the contractor selected several particularly severe accidents to illustrate the probable cask response. Two of these evaluations are described below:

In March 1981, a tractor-trailer was struck by a pickup while on an overpass on Interstate-80 near San Francisco, California. The tractor-trailer broke through the bridge railing and fell 64 feet to the soil surface below. The probable response of the representative truck cask was estimated, assuming the truck struck the ground at an impact angle between 20 and 70 degrees. From the height of the fall, the cask impact velocity would be approximately 44 mph, which would cause 0.2 percent strain on the cask. The accident would fall between the superficial and minor cask structural damage response regions, still within NRC acceptance criteria.

On September 28, 1982, 43 railroad cars derailed near Livingston, Louisiana. Following derailment, a fire started to burn various cargoes, including plastic pellets, vinyl chloride, and petroleum products. The fire was allowed to burn for several days because of the toxic chemicals involved. A rail tankcar carrying motor fuel anti-knock compound exploded about 19 hours after the derailment. On October 1, 82 hours after the derailment, a car carrying vinyl chloride exploded, rocketing 400 feet north of the derailment. The fire cooled down sufficiently on the fifth day to permit fire fighting operations.

The contractor estimated the probable response of the representative rail cask to the Livingston train accident. Assuming that the vinyl chloride fire continued until the fifth day and that the cask was located adjacent to the fire, the accident would fall in the significant thermal damage region. The radiological hazard, however, was estimated to only slightly exceed those permitted in the standards.

By relating NRC's package tests and acceptance criteria to real accident conditions, the Modal Study provides new insight to the protection provided by the standards against severe accident conditions. One of the key objectives of the Modal Study was to explain this relationship in an easily comprehendible manner. The Modal Study report, however, is of necessity a very technical document of analyses with appendices numbering several hundred pages. NRC staff is preparing a 40-page brochure which summarizes the Modal Study's approach and results. It is hoped this brochure will make the information contained in the Modal Study more understandable to the public at large.

In this discussion of package performance and accident conditions, attention has been focused on the role of hypothetical accident conditions and large packages in protecting public safety. It should be noted that many other requirements and guides apply to the package certification process, including guidance on suitable and well-known material properties, quality assurance programs in fabrication and use, etc., all of which embody a quality product principle. The results of the Modal Study should not be applied to packagings with significant differences in overall quality.

In conclusion, the Modal Study clarifies the level of safety provided under real accident conditions by spent fuel packages designed to current standards and practices.

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Main Report

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ABSTRACT

This report describes a study performed by the Lawrence Livermore National Laboratory to evaluate the level of safety provided under severe accident conditions during the shipment of spent fuel from nuclear power reactors. The evaluation is performed using data from real accident histories and using representative truck and rail cask models that likely meet 10 CFR 71 regulations. The responses of the representative casks are calculated for structural and thermal loads generated by severe highway and railway accident conditions. The cask responses are compared with those responses calculated for the 10 CFR 71 hypothetical accident conditions. By comparing the responses it is determined that most highway and railway accident conditions fall within the 10 CFR 71 hypothetical accident conditions. For those accidents that have higher responses, the probabilities and potential radiation exposures of the accidents are compared with those identified by the assessments made in the "Final Environmental Statement on the Transportation of Radioactive Material by Air and other Modes," NUREG-0170. Based on this comparison, it is concluded that the radiological risks from spent fuel under severe highway and railway accident conditions as derived in this study are less than risks previously estimated in the NUREG-0170 document.

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PREFACE

This report describes a study conducted to estimate the responses of spent fuel casks to severe highway and railway accident conditions and to assess the level of safety provided to the public during the shipment of spent fuel. The study was performed by the Lawrence Livermore National Laboratory for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research.

This report is divided into two volumes: Volume I, the main report, describes the study, the technical approach, the study results, and conclusions; and Volume II, the Appendixes, provide supporting accident data and engineering calculations. This report has been reviewed by the Denver Research Institute at the University of Denver under a separate contract to the NRC as the peer review. A companion summary report entitled "Transporting Spent Fuel-Protection Provided Against Severe Highway and Railway Accidents" (NUREG/BR-0111) has been prepared by the NRC for wide distribution to federal agencies, local governments, and interested citizens.

Commercial spent fuel shipments are regulated by both the Department of Transportation (DOT) and the NRC. The NRC evaluates and certifies the design, manufacture, operation, and maintenance of spent fuel casks, whereas the DOT regulates the vehicles and drivers which transport the spent fuel.

Current NRC regulations require spent fuel casks to meet certain performance standards. The performance standards include normal and hypothetical accident conditions which a cask must be capable of withstanding without exceeding established acceptance criteria that

(1) limit the release of radioactive material from the cask,
(2) limit the radiation levels external to the cask, and
(3) assure that the spent fuel remains subcritical,

This study evaluates the possible mechanical and thermal loads generated by actual and potential truck and railroad transportation accidents. The magnitudes of the loads from accidents are compared with the loads implied from the hypothetical accident conditions. The frequency of the accidents that can produce defined levels of mechanical and thermal loads are developed from the accident data base. Using this information, it is determined that for certain broad classes of accidents, spent fuel casks provide essentially complete protection against radiological hazards. For extremely severe accidents--those which could impose loads on the cask greater than those implied by the hypothetical accident conditions--the likelihood and magnitude of any radiological hazards are conservatively estimated. The radiological risk is then estimated and compared with risk estimates previously used by the NRC in judging the adequacy of its regulations.

The results of this study depend primarily on the quality of the cask response models, the radiation release models, and the probability models and distributions used in the analysis. Models for cask responses, radioactive releases, and distributions for the accident parameters are new developments based on current computer codes, limited test data on radioactive releases, and limited historical accident data, The results are derived using representative spent fuel casks which use design principles and materials that have been used in casks currently licensed by the NRC. The representative casks are assumed to have been designed, manufactured, operated, and maintained in accordance with national codes and standards (or equivalent) which have adequate margins of safety embedded in them. The results of this study are limited to spent fuel casks designed and fabricated under current technologies and operated under current regulations. New designs using alternative design principles and materials, or changes to regulations such as the imposition of a 75 mph national speed limit, could affect the results and conclusions of this study.

This study does not consider the effects which human factors can have on the cask design, manufacture, operation, and maintenance. If further study is conducted, human factors should be considered because they can contribute to the overall risk in each phase of transporting spent fuel.

L. E. Fischer

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1.0 INTRODUCTION

This report addresses the level of safety provided during the shipment of spent fuel from nuclear power reactors. The number of shipments will increase in the near future because of the need to transfer this fuel from the nuclear power reactors to a waste repository. During the shipments the shipping containers (casks) carrying the spent fuel could be exposed to severe highway and railway accident conditions. At the request of the U.S. Nuclear Regulatory Commission (NRC) the Lawrence Livermore National Laboratory (LLNL) has performed studies to evaluate and document the response of spent fuel casks exposed to severe highway and railway accident conditions.

1.1 Background

Nuclear fuel, contained in fuel rods, is used in nuclear power reactors to generate useful heat for electric power generation. The fuel rods used in most nuclear power reactors in the United States are made up of approximately one-half-inch-diameter ceramic pellets of uranium oxide encased within a cylindrical cladding. The fuel rods are approximately 15 feet in length. The cladding is made from metallic materials such as zirconium. After being capped, the cladding provides a contained environment for the uranium oxide fuel pellets. Depending on the type of nuclear power reactor, square arrays of the fuel rods numbering from about 50 to 300 are structurally assembled to form a single fuel bundle.

When nuclear fuel burns or fissions, it not only generates useful heat, but also creates radioactive fission products. Spent fuel is nuclear fuel that has been burned to its specified limits and has served its useful purpose. Spent fuel is highly radioactive when initially removed from a nuclear power reactor. Before being transported to a waste repository, spent fuel is usually stored, five or more years in the spent fuel pool at the reactor site to allow the fuel to cool or decay to lower radiation levels.

Because of its radioactive nature, spent fuel is shipped in specially designed shipping containers called casks. These casks are massive, cylindrically shaped objects weighing from 25 to more than 100 tons. The designs of several currently used casks consist of steel shells enclosing a dense metallic material (lead or depleted uranium) that is used to provide radiation shielding. In the United States, these casks must be certified by the U.S. NRC as being in compliance with the regulations contained in Title 10 of the Code of Federal Regulations, Part 71 (10 CFR 71).[1] These regulations, which are almost identical in substance to internationally accepted standards, have been in effect for nearly 20 years. The regulations are intended to assure that the public will be protected both during normal transportation or in the event that a spent fuel shipment is involved in a transportation accident.

Basically, the regulations state that each spent fuel cask must meet certain containment, radiation control, and criticality control requirements when it is subjected to specified normal transport conditions and also hypothetical accident conditions. The hypothetical accident conditions are of most interest to this discussion. They are specified in terms of regulation defined test conditions that include a free drop (30 feet onto a flat unyielding surface), a puncture (40-inch drop onto a vertical 6-inch-diameter mild steel bar), thermal exposure (30 minutes to a defined 1475°F environment), and immersion under specified depths of water. The test conditions must be sequentially imposed on all casks in a manner that would cause maximum damage. The resulting cask response must then be determined by test or analysis.

The regulations do not define the allowable structural or thermal damage a cask may sustain, but instead use radiological criteria, i.e., radioactivity release (leakage) and radiation levels external to the cask as a measure of the acceptability of the design. The cask response must be such that the cask can (1) meet containment requirements (any radioactive material release must be restricted within extremely small limits), (2) keep radiation levels external to the cask within stated limits, and (3) ensure that a criticality event cannot occur. In more practical terms, these compliance criteria require the cask structural integrity to be effectively unimpaired.

Historically, the few shipments of spent fuel that have been involved in transportation accidents have never created any significant radiological hazard, However, the number of these events has been limited. To quantify the radiological risk to the public from all shipments of radioactive material, including spent fuel, the NRC published, NUREG-0170, in 1977 entitled, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes."' The study was primarily performed using conservative engineering judgments. The analysis performed in that document *presumed* that, in certain classes of accidents, transportation accident loads could exceed those implied by the hypothetical accident conditions specified in the regulations. The analysis further *presumed* that for these classes of accident, releases of radioactive material could occur. Even under these presumptions, the analysis indicated that the potential radiological hazards from real transportation accident loadings on a spent fuel cask were most often very small (i.e., limited to minor property contamination which required only cleanup actions). Since no release of spent fuel material has ever occurred, this assessment is consistent with historical events. Even though NUREG-0170 *presumed* the release of radioactive material under certain severe accident circumstances, the overall resulting radiological risk from transporting spent fuel under current regulations was calculated to be acceptable.

Nevertheless, because of the lack of actual data on the real effects of severe accidents on spent fuel casks, studies were initiated by the NRC prior to this work to define more precisely (1) the variability of mechanical and thermal loads which could be experienced by a cask in recorded severe railway and highway accidents, and (2) the degree to which these loads might exceed those implied by the hypothetical accident conditions.' In order to better understand the effectiveness of current regulations, this recorded severe accident information supplemented with other accident data has been used by the LLNL, working under contract to the NRC, to evaluate the responses of spent fuel casks exposed to severe highway and railway accident conditions. This report documents the work performed under this contract.

1.2 Regulations and Past Assessments

1.2.1 Title 10, Code of Federal Regulations, Part 71

To protect the public health and safety, commercial shipments of spent fuel are required to be made in spent fuel casks which are designed, fabricated, and operated in accordance with provisions of 10 CFR 71. The three basic safety requirements addressed by the regulations and which must be met when transporting spent fuel are:

1. Adequate containment of radioactive material
2. Adequate shielding of the radiation emitted by the radioactive contents
3. Prevention of nuclear criticality.

The containment requirements, as they apply to spent fuel shipments, impose a limit on radioactive material releases following the application of certain mechanical and thermal loadings on a spent fuel cask. The loadings are imposed by a series of test conditions called hypothetical accident conditions. The radioactive material release limits include a value for the relatively innocuous inert gas, ^{85}Kr, ($\leq$ 10,000 curies in one week) and a separate limit on other releases over a l-week period (called an A_2 quantity). These limits on specific radioactive material releases are such that the doses to members of the public can be expected to be less than the allowable annual dose to individuals whose occupation involves potential exposure to radiation.

The shielding requirement following the application of the hypothetical accident condition is stated in terms of an external radiation dose rate at 1 meter from the external surface of the cask, This radiation level must not exceed one rem per hour.

The prevention of criticality under accident conditions is achieved by cask design features which assure subcriticality. This subcriticality must be achieved assuming (1) optimum (most reactive) configurations of the spent fuel consistent with the cask damage imposed by the hypothetical accident conditions and (2) most reactive conditions associated with the presence of water. (Water or other materials which act as neutron moderators or reflectors enhance criticality possibilities when in close contact with spent fuel.)

The safety requirements of 10 CFR 71 play an important role in this study because they provide a benchmark for relating a specific magnitude of mechanical or thermal loading (implied by the hypothetical accident conditions) to a specified level of cask response. For example, in practice, the containment limits are usually met by demonstrating that the cask containment experiences essentially no permanent deformations and the closure seals and penetration remain essentially leak tight (Fig. 1-1). The external dose rate limit is met by demonstrating that essentially no loss of the gamma shield occurs under accident conditions. Finally, the prevention of criticality requirement is typically met by demonstrating that essentially no deformation occurs to the basket, the structure within the cask which holds the spent fuel. These limits serve as benchmarks against which cask responses in real accident conditions can be compared,

One particular cask design feature is especially significant in ensuring that a spent fuel cask will meet the containment, shielding, and subcriticality requirements when the cask is subjected to the 30-foot drop onto the unyielding surface called for by 10 CFR 71. This feature is called an impact limiter (Fig. 1-1). Impact limiters reduce the mechanical loads to the main cask body under accident conditions.

Impact limiters are typically made of crushable material surrounding the extremities of a cask, but designs can also include the use of crushable exterior metal fins. In either case, the impact limiters are designed to absorb most of the energy generated in the regulatory-defined 30-foot drop onto the unyielding surface without causing any significant permanent damage to the cask containment or closure features.

The significant point is that, through the response of this design feature, a load level is defined which translates into no cask containment damage and, therefore, essentially no radiological hazard. For those real accidents which result in mechanical loads less than this limit, the radiological hazard is insignificant.

Similarly, protection against the regulatory-defined thermal loading conditions is typically provided by the use of thermal barriers. Thermal

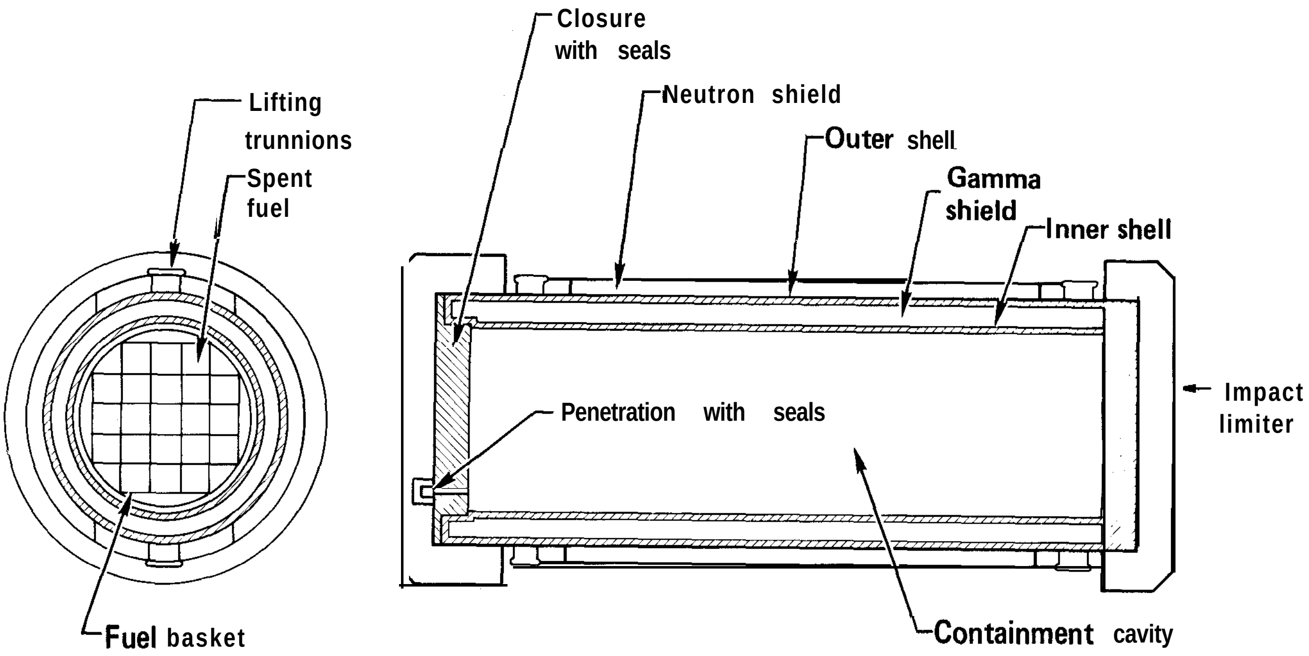


Figure 1-1 Schematic of a typical spent fuel cask.

barriers limit the heat transfer from a fire or thermal source external to the cask, to the cask containment structure, and to the contained spent fuel. Again, real world accidents involving fire can be compared with this defined thermal loading. These types of comparisons form the essence of the first-stage of a screening process used in this study.

1.2.2 Transportation of Radioactive Material - Environmental Statement (NUREG-0170)

In December 1977, the NRC published NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes".' The report included an assessment of the likelihood and magnitude of the radiological consequences associated with potential transportation accidents for all shipments of radioactive material. Most shipments consisted of medical and industrial isotopes, but spent fuel shipments were specifically addressed. The assessment indicated that the radiological risk involved in all shipments was small. This conclusion provided the technical basis for the Commission's decision that the existing 10 CFR 71 regulations are adequate and not in need of immediate change.

The NUREG-0170 analysis provides an additional benchmark for this study. Specifically, the radiological risk from spent fuel shipments reported in NUREG-0170 can be compared with the risk estimated in this study. In NUREG-0170, accident severities were divided into eight categories. For each category, the radiological hazards were assigned based on conservative engineering judgments. These hazards were measured in terms of the fraction of radioactive material released from the spent fuel and an equivalent fraction caused by shine from any unshielded fuel. For truck and rail accidents, the estimates in NUREG-0170 indicated that 91% of truck accidents and 80% of train accidents would result in no significant radiological hazard. In the remaining accidents, the radiological hazards increased as the accident severity increased. The increase is indicated in Table 1.1. As a point of reference, NUREG-0170 indicated that 0.4% of truck accidents and 0.2% of train accidents could involve a complete release from the cask of certain gaseous and volatile materials. These materials represent the radioactivity

Table 1.1
Correlation of NUREG-0170 Accident Fractional Occurrence and Radiological Hazards as a Function of Accident Severity

Accident Severity Category	Truck Fractional Occurrences	Train Fractional Occurrences	Radiological Hazards: Fraction of Radioactive Material Released[a/]	Radiological Hazards: Fraction of Equivalent Unshielded Fuel[b/]
I	0.55	0.50	0	0
II	0.36	0.30		0
III	0.07	0.18	0.01	0
IV	0.016	0.018		0
V	0.0028	0.0018	0.10	0
VI	0.0011	1.3x10-4	1	$3.18x10^{-7}$
VII	$8.5x10^{-5}$	$6.0x10^{-5}$		$3.18x10^{-5}$
VIII	1.5x10-5	1.0x10-5	1	$3.12x10^{-3}$

a/ Radioactive gases and vapors

b/ Approximates the reduction in radiation shielding which typically migrates from the fuel pellets to the fuel rod gap, the void space between the fuel pellets and the surrounding fuel rod. In this small percentage of accidents, all the fuel rods in the shipment were assumed to fail and to release their radioactivity.

Also, for accidents in Category VI and greater, a reduction of shielding was assumed. To provide a consistent measure of the radiological effects with cask damage, the radiological hazard due to the reduction in shielding was presented in terms of an equivalent fraction of unshielded fuel. The equivalent fraction of unshielded fuel is the ratio of that portion of the total spent fuel inventory that, if unshielded, would produce radiation levels equivalent to those being emitted from a damaged cask with reduced shielding.

The results of NUREG-0170 rely in part on the presumption that spent fuel casks have sufficient margins designed into them that major radioactive hazards will not occur even at loading conditions which exceed those specified in regulations. These margins of safety are included in all licensed cask designs through the use of established codes and standards which have margins of safety embedded in them.

The evaluation conducted in this study analyzes the response of representative shipping casks in severe accident environments. This evaluation uses representative cask designs that are likely to be licensed and have margins of safety included in their designs. The responses of the representative casks to all possible accident conditions are analyzed and categorized into cask response regions. For each cask response region, assessments are made of the potential for release of radioactive material and the potential for reducing the radiation shielding capabilities of the cask. This evaluation is the basis for a comparison with NUREG-0170; that is, what accident classes result in radiological hazards and how do those hazards and their likelihoods compare in terms of radiological risk to the public.

1.3 Objective and Approach

The objective of this study, the Shipping Container Response to Severe Highway and Railway Accident Conditions, is to estimate the adequacy of radiological protection offered the public by the current NRC regulations when highway or railway accidents occur involving spent fuel shipments. The estimates are performed using data from real accident histories of similar types of vehicles and using models of cask designs that have a likelihood of meeting requirements for spent fuel shipments.

A two-stage screening process is used. The screening process is illustrated in Fig. 1-2. The first stage compares cask responses to accident loading conditions with those associated with the accident test conditions specified in 10 CFR 71. As an example of such a comparison, cask loadings from a class of accidents involving impacts exceeding 30 mph (the velocity reached in the 30-foot drop) are examined.

An example of such an accident class is the accident scenario involving a 60-mph collision with a highway sign pole. The cask loading ih this scenario is such that no damage occurs to the containment, radiation shielding, or subcriticality assurance features of the cask, even though the accident velocity exceeds the regulatory-implied impact velocity. The reason is that although the accident velocity is twice the regulatory defined velocity, the loading imposed on the cask in the 30-foot drop test far exceeds the loading achieved on impact with the sign pole. The pole failure essentially limits the load to which the cask is exposed.

There are classes of accidents in which the loading can be conceived to approach or exceed the values imposed by the accident test conditions. Examples of these classes are high-speed impacts with massive bridge abutments and falls from great heights onto hard rocks. Sophisticated analysis can be used in many cases to demonstrate that the loadings on a cask are still less than those imposed by the regulation-defined hypothetical accident conditions. However, questions arise involving the specifics of a particular cask design and the orientation of impact (i.e., does the orientation assumed cause maximum damage). On the analysis side, the validity of analytical methods used to predict the cask response can be questioned. A major part of this report is directed toward demonstrating what broad classes of real-world accidents and their associated loadings are enveloped by the loadings implied

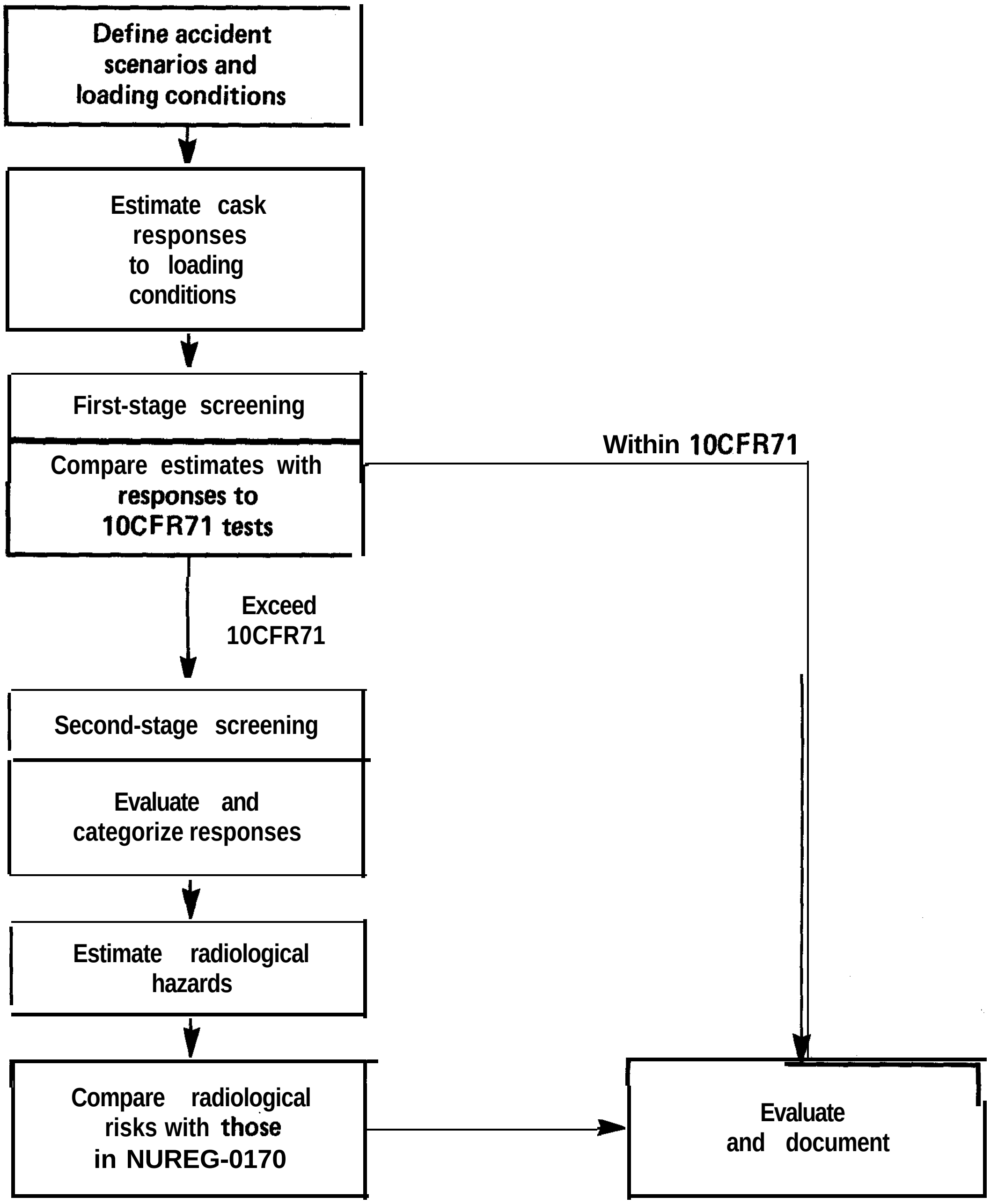


Figure 1-2 Two-stage screening process used in evaluating the regulations.

in the current regulatory standards. The first-stage screening envelopes accident loading conditions whose magnitudes do not exceed those defined by the accident test conditions and, therefore, the potential radiological hazards are less than those implied by regulations.

For those accident scenarios with loads and cask responses greater than those implied by the accident test conditions, a second-stage screening is performed. This screening evaluates the likelihood of the cask responses.

The potential radiological hazards associated with the cask responses are then determined. By summing all accident scenarios, the probability and magnitude of the radiological hazards is estimated and then compared with the risk evaluated in NUREG-0170.

Because of the numerous variables involved in defining cask loading and response, and because of the broad range of possibilities and interrelationships for each of the variables, a systematic scheme is developed to accomplish the two-stage screening process and to assess the effectiveness of 10 CFR 71 in assuring adequate radiological protection to the public. To describe this systematic process, this report is arranged into several sections. Many tasks are performed: model developments, data sources, data development, analysis of models, classification, and comparison of results. Although the tasks are described in the report by sections, the separate tasks are not developed independently, and they cannot be described without considering the interrelationship involved.

Figure 1-3 shows the interrelationship of the various tasks and how they influence the performance of the analysis. The initial tasks in this study involve developing models for casks and accident environments. Methods are also developed for evaluating how the cask models respond to accidents and for classifying their responses into response regions. The screening analyses are performed by subjecting the casks to the accident events identified in the accident scenarios, determining the predicted responses of the casks to these events, and classifying these predicted responses into the response regions. The cask physical responses are then related to any resulting radiological hazards. Because the likelihood or probability associated with an accident

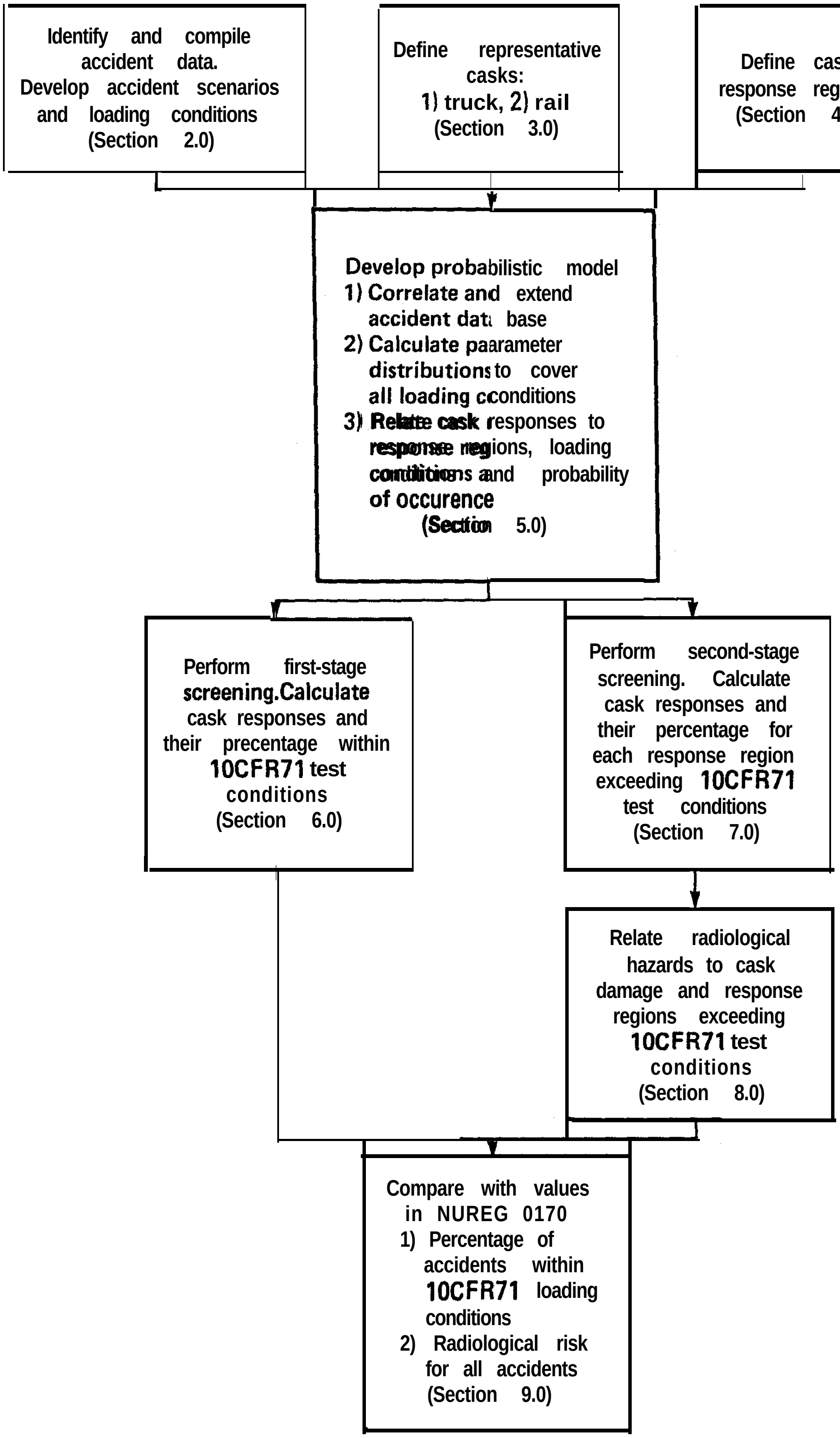


Figure 1-3 Schematic representation of the report.

event can be derived from accident data, the probability associated with the response and radiological hazard can be estimated.

In Section 2.0, the mechanical and thermal loads associated with real accidents are discussed. Also, accidents are classified into accident scenarios to systematize the analysis. Statistical accident data have been used and enhanced where necessary to establish likelihood estimates for the occurrence of those mechanical and thermal accident loads determined to be important to cask response. The mechanical loads are described in terms of parameters such as velocity of the cask, the hardness of the object that the cask hits, and whether the crash is head-on, glancing, or at some intermediate direction. The thermal loads are described in terms of location, temperature, and duration of a fire.

In Section 3.0, two casks are defined as representative of those used for ground transportation of spent fuel, one for highway and one for railway. The details and justification for selecting the representative cask designs are explained. The margins of safety included in their designs are discussed.

Cask response regions are specified in terms of the physical response of the cask to accident events. The response regions are described in Section 4.0; they are represented as strain for mechanical loads, and as temperature for thermal loads. The strains from mechanical loads and temperatures created by thermal loads which define the response regions are related to deformations and degradation of the cask's containment and shielding system. Deformation and degradation of the cask's containment and shielding systems can result in specific radiological hazards for each of the response regions. Details for relating radiological hazards to the response regions are found in Section 8.0.

In Section 5.0, the probabilistic model used in the analysis is described. The formulations used to relate cask responses to loading conditions, response regions, and the probability of occurrence are described. Techniques also are developed for calculating the probability for combined loading conditions for each accident scenario.

In Section 6.0, the first-stage screening process is described. The first step in this process is to subject the casks to each accident scenario identified in Section 2.0 and to estimate the responses. The responses are sorted into the response regions. The appropriate response region for the first-stage screening is the lowest response region since it is defined to encompass 10 CFR 71 accident test conditions. Since the accident rates are known, the fraction of accidents falling into each response region can be determined.

In Section 7.0, the second-stage screening process is described. The accidents not falling into the lowest response region are analyzed and the responses calculated. These responses are then categorized into the other response regions.

In Section 8.0, the radiological hazards associated with each cask response region are estimated. The radioactive material releases are estimated from laboratory test data. The radiation increases caused by lead slump are estimated from structural, thermal, and shielding calculations.

Finally, in Section 9.0, the results of the two-stage screening process are presented with respect to NUREG-0170. The conclusion reached is that at least 99.4% of truck and train accidents involving a spent fuel shipment will result in negligible radiological hazards which are less than those implied by the current 10 CFR 71 regulations. Of the remaining spent fuel shipment accidents, the overall radiological risk is less than the risk estimated in NUREG-0170.

2.0 ACCIDENT RATES, ACCIDENT SCENARIOS, AND LOADING PARAMETER DISTRIBUTIONS

2.1 Introduction

Severe accidents are typically characterized and reported by fatalities, injuries, property damage, transportation equipment damage, or a combination of these consequences. In this study, however, the characterization is in terms of the magnitude and frequency of loads that could be experienced by a spent fuel cask under accident conditions. Normally the higher the load on a cask, the higher the cask response and the greater the potential for radioactive release.

Both mechanical and thermal loads generate response states for a cask which could result in damage to the cask. High mechanical loads caused by impact can cause damage to the cask shielding or cause the cask containment to leak. High thermal loads caused by fires can cause the cask containment seals to deteriorate and leak or the lead shield to melt. In performing the two-stage screening process of accidents discussed in Sections 6.0 and 7.0, all possible accidents have to be included, especially those that could cause high mechanical and thermal loads on a cask.

Mechanical and thermal loads depend on the magnitudes of the accident loading parameters. Two examples of accident loading parameters and their magnitudes are a velocity of 50 mph and a fire duration of one hour. The same accident-caused load on a cask can occur for various combinations of loading parameters and loading magnitudes. For example, the same impact force on the cask can be generated by a low-velocity impact on a hard object or a high-velocity impact on a soft object. Also, the same heat load on a cask can occur for a short duration high-temperature fire or a long duration low-temperature fire. Consequently, specific mechanical and thermal loading conditions on the cask can occur under a variety of accident conditions.

Accident loading conditions must take into account many loading parameters and must include a wide range of values for each loading parameter. Accident scenarios can be derived from historical records. An accident scenario describes a sequence of events as they occur, allowing the identification of possible loading conditions. For example, an accident scenario can involve a truck running off the highway, going over an embankment, and crashing into a rock. The loading conditions for this scenario primarily depend on the hardness of the rock, the velocity of the truck when it hits the rock, the direction of the truck velocity, and the orientation of the truck with respect to the rock. By varying these four parameters, thousands of loading conditions are possible for one accident scenario.

In order to evaluate all possible accident loading conditions on a cask, the following accident information is derived in this section:

(1) Accident rates for spent fuel shipments are estimated from historical accident records for truck and train accidents for similar vehicles.

(2) 'Accident loads that dominate the accident loading conditions and the structural and thermal responses of spent fuel casks are identified. The significant loading parameters for the dominant accident loads are identified.

(3) Accident scenarios, to include all possible accident loading conditions for truck and train transport, are identified. Accident data, survey results, and engineering judgment are used to establish accident loading parameter distributions.

The accident information derived in this section is used with the probabilistic computer code called TASP (Transportation Accident Scenario Probabilities) described in Section 5.0 to calculate and screen the expected magnitude and frequency of cask responses to accident conditions.

In Sections 2.2 and 2.3, the expected accident rates for spent fuel shipments by highway and railway are estimated. In Section 2.4, the accident data required to estimate the accident loads on a cask are identified. In Sections 2.5 and 2.6, the accident scenarios and loading parameter distributions are discussed.

2.2 Highway Accident Rates

Highway accident rates depend on many elements including road type, vehicle type, regulations, and driving practices. The accident rate for all vehicles on California highways during 1981 through 1983 ranged from $1x10^{-6}$ accidents/vehicle-mile for freeways with limited access to $5x10^{-6}$ accidents/ vehicle-mile for conventional four-lane highways.[1] Studies by the U.S. Department of Transportation (DOT) have indicated that accident rates are significantly lower for interstate federal highways (usually freeways) than for other road types. Routes for transport of spent fuel are selected in accordance with the DOT regulations to minimize the radiological risk. In general, the routes follow interstate federal highways.[2]

As discussed in Appendix B, two sources are used for estimating a typical accident rate for spent fuel transportation. An average' accident rate of $2.5x10^{-6}$ accidents/vehicle-mile is derived from the data published by the Bureau of Motor Carrier Safety (BMCS) for all roadways.[3-5] Their data covered all truck and carrier type accidents from 1960 through 1972. The second data source is the American Petroleum Institute (API) for the period of 1968 through 1981 for all roadways.[6-10] The average accident rate is $6.4x10^{-6}$ accidents/vehicle-mile or approximately 2.5 times higher than that based on the BMCS data. For this study the API accident rate is used as the estimate for spent fuel truck accident rates because the data is judged to be more reliable, and trucks which transport hazardous petroleum materials are similar in size and weight to trucks that transport spent fuel casks. The use of the more conservative API value is not critical to the results of this study.

2.3 Railway Accident Rates

Train accident rates depend on many elements including the type of train, the type of track, and the reporting requirements. Freight trains are used to transport spent fuel over all track types and are subject to Federal Railroad Administration (FRA) reporting requirements. Because over 90% of all train mileage is attributed to freight trains, there is no significant difference in applying data based on all trains to freight trains in order to estimate accident rates, accident velocities, fire frequencies, etc.

Appendix C discusses the train accident rate selected for spent fuel shipments by train. Based on the FRA data for all train and track types, an accident rate of 1.2×10^{-5} accidents/train-mile is assumed for spent fuel rail shipments.[11-17]

2.4 Accident Loading Data Requirements

Historical data bases on transportation accidents exist at all government levels. These data bases range from local accident records to state and national accident statistics. Typically, these records include many accident conditions and consequences that are not pertinent to this study, including weather conditions, fatalities, injuries, and property damage. However, some of the data are pertinent to this study; namely, data pertaining to accident loading conditions which could cause cask damage. Typical of such data are estimations of accident velocities, descriptions of objects impacted, and duration of fires. Most of these data bases are compiled to aid general transportation safety with the main focus on reducing injuries, fatalities, and property damage. They do not always include all the information necessary to define the loading a cask might experience. Therefore, specific data necessary to estimate accident loads on a cask are not always available.

Table 2.1 presents mechanical and thermal loads that can occur in an accident. The accident loading parameters that cause the loads and affect the response of the cask for various load types are also listed.

Mechanical loads include forces on the cask caused by impact with a surface or hard object, puncture by strong objects, and crushing by heavy objects. Based on the evaluation in Appendix E, it is concluded that impact loads are the dominant mechanical loads and have the greatest potential for causing significant structural damage to a spent fuel cask. Therefore, only impact loads and their associated loading parameters are used to perform the two-stage screening of accidents generating mechanical loads.

Mechanical loads from impacts can be analyzed using three loading parameters that affect the cask response and potential damage: impact velocity, orientation of the cask, and the hardness of the object impacted.

Table 2.1
Accident Loads and Loading Parameters

Loading Parameter	Accident Loads					
	Mechanical Load Type			Thermal Load Type		
	Impact	Punch	Crush	Fire	Torch	Decay Heat[a]
Object Hardness	X	X	X			
Impact Velocity	X	X				
Cask Orientation	X	X	X			
Object Weight	X	X	X			
Object Impact Area		X				
Flame Temperature				X	X	
Fire Duration				X	X	
fire Location				X	X	
Flame Emissivity				X	X	
Convection Coefficient				X	X	
Surrounding Material						X

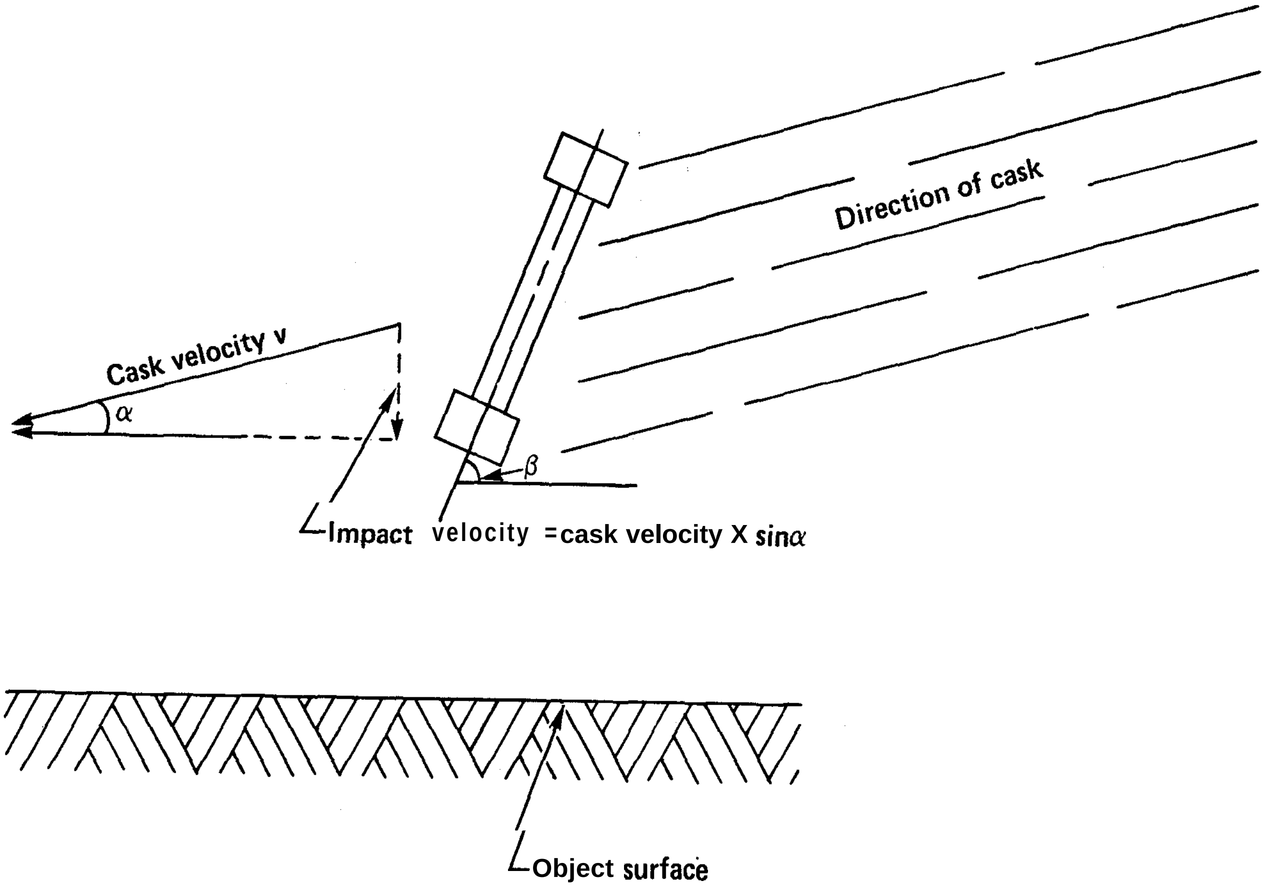
a/ Decay heat from spent fuel cargo.

Figure 2-1 defines these three loading parameters. The impact velocity is the cask velocity perpendicular to the surface impacted. The angle of impact, a, represents the angle between the cask velocity vector and the object's surface. When an accident occurs, the cask velocity vector can take any direction. However, it can always be decomposed into two components: one perpendicular to the impacted object surface and one parallel to it. The accident velocity is a function of reported vehicle velocity, braking effects, and fall heights from bridges or embankments. In the cask response calculations, only the velocity component perpendicular to the object surface is considered. The velocity component parallel to the object surface introduces a sliding-friction effect to the cask structure. The sliding-friction effect will not induce any significant structural deformation in the cask. In this study, the angle of impact is combined with the cask velocity to produce the cask impact velocity, i.e., impact velocity equals cask velocity times sine a where a is the angle of impact and the impact velocity is treated as a single loading parameter.

The angle defining the cask orientation, β, is the angle between the cask longitudinal axis and the object's surface. The cask orientation affects the cask response, particularly for endwise impacts ($\beta = 90^{o}$) where lead slump can occur at high impact velocities.

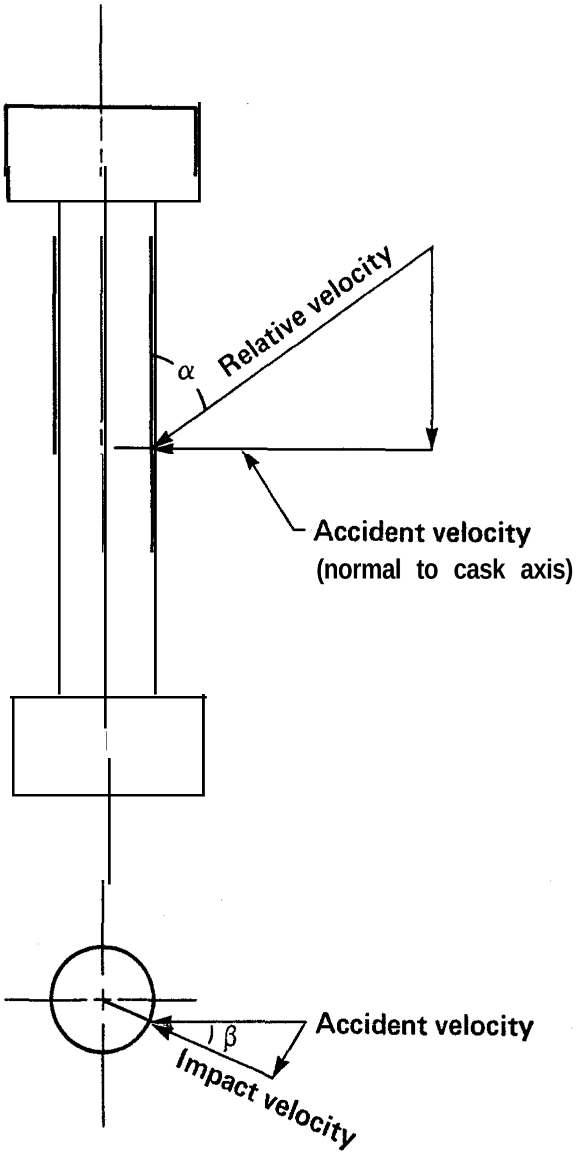
Object hardness needs to be considered because casks can strike objects such as concrete abutments, roadbeds, hard rock, soft rock, hard soil, and water. The hardness of the objects and the associated impact responses vary greatly. The weight of the object impacted can also affect the response of the cask. However, only massive objects can cause significant mechanical loads on a cask, hence the object hardness is the dominant parameter that is considered for objects impacted.

In some accidents, such as rail grade-crossing accidents, the impact limiters on the cask can be bypassed and the side of the cask can be struck directly. Once again the mechanical loads depend on the impact velocity, the orientation of the cask, and the hardness of the object struck. Figure 2-2 defines these three loading parameters for this type of accident. The impact



- Object surface hardness
- Impact velocity: Cask velocity component perpendicular to the object surface
- Cask orientation is defined bv angle β, the angle between the cask longitudinal axis and the object"'s surface

Figure 2-1 Three impact loading parameters considered in the response analysis for impacts on surfaces.



- Object hardness
- Impact velocity: Relative velocity component perpendicular to cask surface.
- Cask orientation angle, β: the angle between the accident velocity and impact velocity.

Figure 2-2 Three impact loading parameters considered in the response analysis for impacts with objects such as train sills.

velocity is the component of the relative velocity of the cask and object that is perpendicular to the cask surface. The angle of impact, a, represents the angle between the relative velocity direction and the cask axis. For the purpose of this study, the impact angle is conservatively assumed to be 90°, that is, perpendicular to the cask axis in all cases. Also, it is assumed that the impact occurs at the mid-plane of the cask to cause the most damage. The cask orientation angle, β, is the angle at which the impact occurs on the cask surface as shown in Fig. 2-2. In the worst case the cask is hit at 0° or head-on. For orientation angles near 90°, the cask is essentially not struck. The object hardness depends on the object hitting the cask, such as a train sill or a small bridge column.

The thermal loads identified in Table 2.1 include the heating of a spent fuel cask by large fires, both engulfing and non-engulfing; torch fires; and decay heat from the spent fuel, particularly when the cask is accidentally buried in debris. Based on the evaluation in Appendix F, it is concluded that heat loads from large fires, both engulfing and non-engulfing, have the greatest potential for causing significant damage to a spent fuel cask. Therefore, only heat loads from large fires and their associated loading parameters are used in the screening of accidents generating thermal loads.

Thermal loads from large fires depend on three loading parameters that affect the cask response and potential damage: fire duration, flame temperature, and fire location. The fire duration affects the amount of heat that is transferred into the cask--the longer the fire burns the greater the amount of heat that is absorbed by the cask. Higher flame temperatures cause greater amounts of heat to be transferred to the cask. As discussed in Appendix F, the flame temperature, assuming a flame emissivity of 0.9, is the single parameter used to characterize both radiation and convection heat transfer over a wide range of conditions. The location of the fire with respect to the cask affects the amount of heat that can be transferred to the cask. An engulfing fire would transfer the most heat to the cask, given the same flame temperature and fire durations, whereas less heat would be transferred from non-engulfing fires.

Accident records typically classify accidents into broad categories or types that describe, in general, the causes of the accidents. Examples are ran-off-the-road, overturn, and derailment. Accident scenarios describe a sequence of events and involve individual accidents that occur at specific velocities, impact specific objects at specific angles, and perhaps include a fire. For the purpose of this study, accident scenarios are specified and typically identified by the object impacted. By interpreting accident data bases in the context of these scenarios, the analysis is made manageable.

2.5 Highway Accident Loading Parameters

2.5.1 Mechanical Loading Parameters

Three mechanical loading parameters have been identified which can affect the structural response of a cask in a severe accident: object hardness, impact velocity, and cask orientation. The distribution functions for these parameters can differ with each specific accident scenario. The object hardness distribution is derived from the truck accident data base, For accident scenarios that could cause high mechanical loads on a cask, impact velocity distributions are estimated from truck and train accident velocity data, bridge height data, and engineering models. No specific data is available to estimate cask orientation on impacts; therefore, distributions are estimated from engineering models.

2.5.1.1 Accident Scenarios and Object Hardness

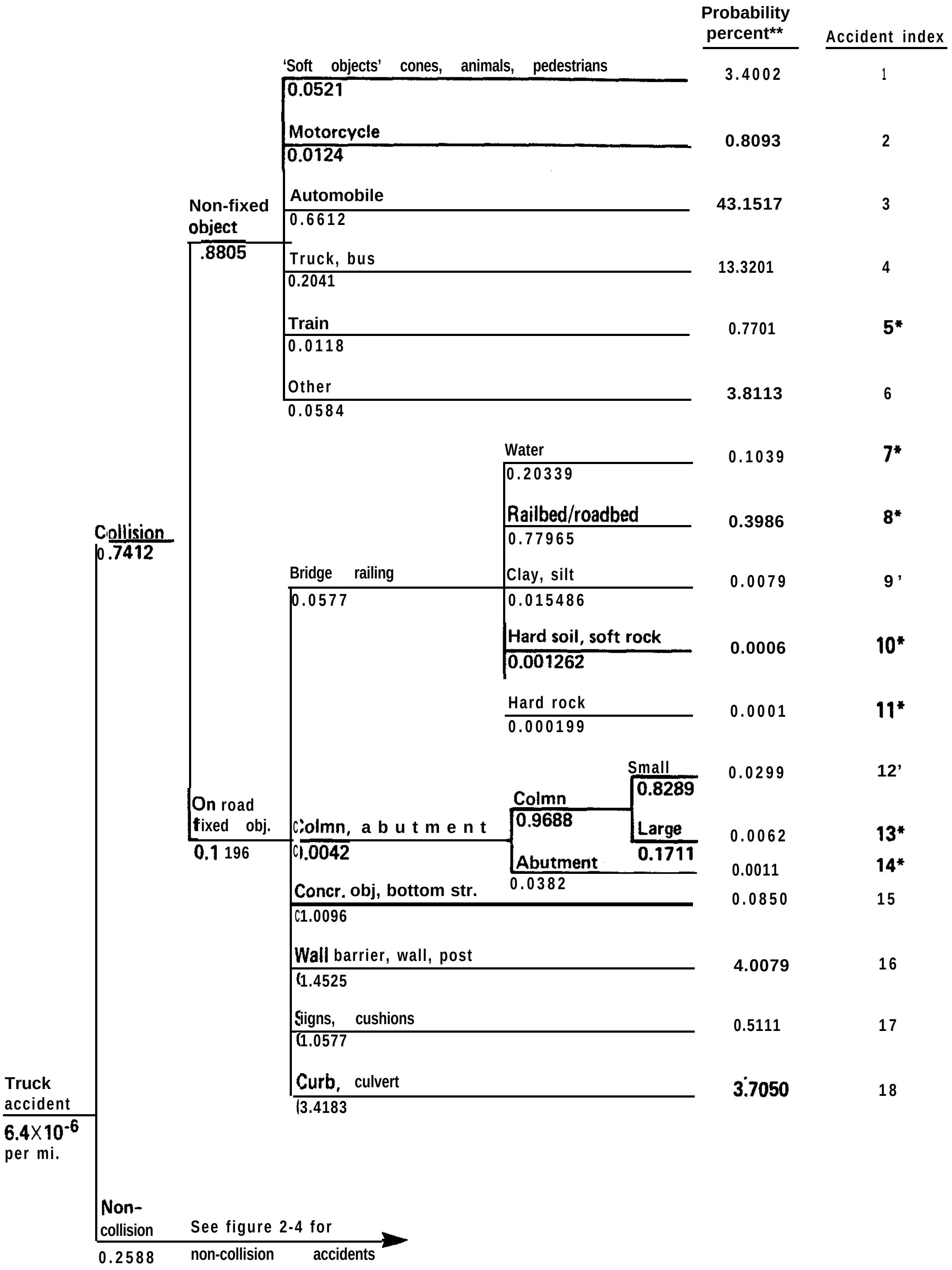
Data from several sources are collected and combined in Appendix B to estimate the frequency of specific accident scenarios and potential impacts on specific objects of varying hardness. The accident scenarios are primarily based on truck accident data documented in the BMCS annual reports for the years 1973 through 1983.[18-27] The BMCS accident data are for all truck sizes and all roadways including city streets, county roads, state and interstate highways.

Figures 2-3 and 2-4 list the truck collision and non-collision accident scenarios used to categorize the response of spent fuel casks to accident loads. Thirty-one scenarios, each identified with an accident index number, are presented. By combining historical accident records with a survey of highway roadside structures, the probability associated with each accident scenario is estimated in percent. For example, a truck can be involved in a collision accident, hit a bridge railing, run over the bridge, and drop into water below (accident index 7 in Fig. 2-3). This scenario describes a sequence of events involving many different accident features such as collision objects, bridge railings, and water.

An example will be used to illustrate how this probability estimate is made. Figure 2-3 shows that 74.12% of truck accidents are collisions. Of these collision accidents, 11.95% involve hitting a roadside fixed object. The probability that the roadside object is a bridge railing is 5.77%. The probability that the truck, after hitting the bridge railing, breaks through the bridge railing and lands in the water is 20.34%. Therefore, the fractional occurrence for the example scenario is 0.104% given that a truck accident occurs. Multiplying this fractional occurrence by the assumed truck accident rate of 6.4×10^{-6} accidents/vehicle-mile gives the chance of this kind of accident occurring per mile traveled as 6.7×10^{-9}.

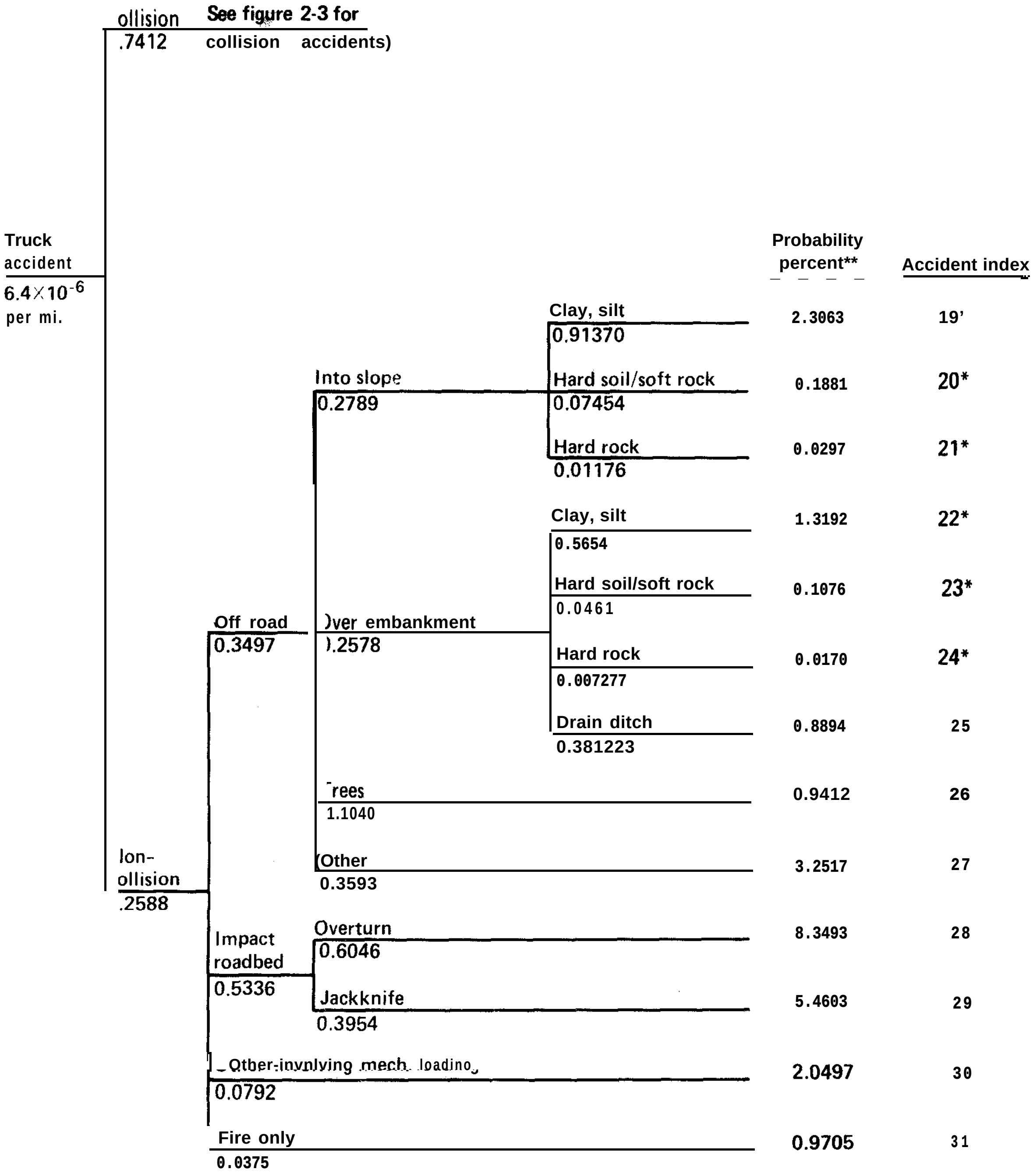
2.5.1.1.1 Collision Accident Hardness Data

Figure 2-3 summarizes collision accident scenarios and the frequencies of collisions with moving objects such as trucks, autos, and trains as compiled from the BMCS data. Over 56% of the truck accidents involve collisions with another truck or auto. The BMCS accident data did not classify collisions with fixed objects, even though they ranged from stop signs to bridge columns. To classify fixed objects, highway accident data are obtained from the California Department of Transportation (CALTRANS) reports of stationary objects struck along state and interstate highways for the years 1975 through 1983[28-36] Those objects in the CALTRANS survey are tabulated and a fraction calculated for each type of fixed object. These fractions are then applied to the fixed object collision accidents in the BMCS data to estimate the number of accidents involving each type of object, such as a bridge rail or column.



- Potentially significant accident scenarios
- * Conditional probability which assumes an accident occurs

Figure 2-3 Truck collision accident scenarios and their percent probabilities.



* Potentially significant accident scenarios

** Conditional probability which assumes as accident occurs

Figure 2-4 Truck non-collision accident scenarios and their percent probabilities.

Based on the quasi-static screening analysis in Section 6.0 for mechanical loads and responses of the representative truck cask, only three significant accident scenarios can cause mechanical loads high enough to damage a spent fuel cask: collisions with trains and columns, trucks running off bridges and over embankments, and trucks running into slopes. Therefore, detailed accident loading information is compiled only for these significant scenarios.

Since collision accidents involving piers, columns, and abutments may lead to significant damage to a spent fuel cask, a survey is performed to differentiate among the various sizes of piers, columns, and abutments along state and interstate highways.[37] From the survey data, the fractional occurrence is determined for each pier, column, and abutment size and is used to estimate the probability of collision accidents involving piers, columns, and abutments. For example, the expected probability of collisions with large concrete abutments is estimated to be 0.0011% as given in Fig. 2-3.

In the event a truck runs off a bridge, the magnitude of the resulting impact load depends not only on the bridge height, but also on the surface being impacted below the bridge. A survey along Interstate 80 in California is performed to identify the types and frequency distributions of surfaces that could be impacted below the bridge.[38] These surfaces are classified into four categories: roadbeds, railbeds, water, and earth. The earth category is then subdivided into three sub-categories: soil, soft rock, and hard rock. The earth sub-category distributions are determined by the survey performed for "ran-off-the-road." Table 2.2 is a summary of the impact surface distribution under bridges.

2.5.1.1.2 Non-Collision Accident Hardness Data

Non-collision accident scenarios include rollover, jackknifing, and running off the road. The accident scenarios judged to have greatest damage potential for a spent fuel cask are the ran-off-the-road scenarios. In these accidents, the truck could impact a slope or go over an embankment, with the possibility of hitting a hard rock such as granite.

Table 2.2
Fractional Occurrence of Surface Types below Bridges on Interstate 80 from Davis, California to Nevada Border

Surface Type	Fractional Occurrence
Water	0.2034
Roads/Railways	0.7797
Earth	
Soil	0.0154
Soft Rock	0.0013
Hard Rock	0.0002

The hardness of earth surfaces adjacent to highways can vary over a wide range. This variability can have a significant effect on the loadings that could be imposed on a cask or any other impacting object. The water and land (hard rock, soft rock/hard soil, and tillable soil) distribution along proposed spent fuel shipment routes between the east coast and west coast is initially estimated using agricultural soil survey data and geological highway maps for the United States.[39,40] The initial distributions estimated from these sources are considered to be indicative of the types of surfaces which could be impacted along highways in the various regions of the United States. However, since highway construction and landscaping can greatly affect the adjacent surroundings, the initial distributions are used to select representative portions of Interstates 5 and 80 in California to perform detailed highway surveys and to establish final distributions along highways.

The types of earth adjacent to 133 miles of Interstate 5 through Orange and Los Angeles Counties in California are classified into three groups: tillable soil, non-tillable soil, and hard rock (Appendix D, Table D.2). Only tillable soil (92.8% fractional occurrence) and untillable soil, classified as soft rock (7.2% fractional occurrence), are identified on a total mileage basis. Although this survey included portions of the Santa Susana Mountain, no hard rock is identified in the survey.

A highway survey of soil types adjacent to the roadway is then performed on a section of Interstate 80 from Davis, California, to the Nevada border.[38] This 122 mile section of Interstate 80 crosses the Sierra where numerous outcroppings of granite rock occur. This survey (Appendix D, Table D.3) indicates the following earth distribution : tillable 90.2%, non-tillable 7.3%, hard rock 2.5%.

Based on the results of both highway surveys and the reviews of the agricultural soil surveys, the geological highway maps, and proposed spent fuel shipping routes, the representative earth distribution used in this study is tillable soil 91.4%, soft rock/hard soil 7.4%, hard rock 1.2%.

2.5.1.2 Impact Velocity

The impact velocity depends on the relative velocity of the cask and the angle of impact with respect to the object impacted. The distributions of these two variables are estimated from truck accident records, train accident records, highway surveys, and engineering judgments for the significant accident scenarios.

2.5.1.2.1 Cask Velocity

The distribution of potential cask velocities can vary depending on the specifics of the accident scenario. Each accident scenario may have a different historically based velocity distribution. For example, the distribution of accident velocities experienced in truck-truck collisions differs from the distribution associated with accidents involving falls from bridges. In the truck-truck accidents, the distribution depends on the individual velocities of the trucks at collision. For accidents involving falls from bridges, the accident velocity is determined by the fall height. The accident velocity distribution for accident scenarios involving trucks running over or off embankments could, at worst, be represented by the vector sum of the vehicle velocity and the velocity attained in the resulting fall.

One of the following distributions of cask velocities at impact is considered applicable to a particular truck accident scenario:

V1: A distribution based on truck accident velocities with braking effects included,

V2: A distribution based on fall heights from bridges,

V3: A distribution based on truck accident velocities with braking effects and fall heights from bridges, or

V4: A distribution based on train accident velocities at grade crossings.

Reports record accident velocity data in many different forms. Most reports give the vehicle velocity prior to the accident. Therefore, it is difficult to estimate the actual velocity of impact which a cask can realistically experience.

Distribution V1 is determined by consideration of accident reports involving trucks/semitrailers. Table 2.3 gives the fraction of accidents occurring in the State of California for 1958 through 1967 for trucks/ semitrailers as a function of truck velocity prior to the accident.[41-51] This accident data is derived from the California Highway Patrol's (CHP) annual report on fatal and injury motor vehicle traffic accidents. This data represents a sample of truck/semitrailer drivers involved in fatal and injury accidents and their estimated accident velocity without braking effects included. Approximately half of truck accidents occur at velocities greater than 30 mph. This velocity data is conservative because it does not include non-injury accidents, which typically occur at lower velocities.

Accident velocities for the State of California are compared with those in the states of Alabama, Texas, Virginia, and North Carolina.[52-56] The comparison is made for all vehicles because not all of the states had information on trucks. The comparison shows that the California accident velocities are comparable for the same conditions. Therefore, it is concluded that the accident velocities from California are representative of those in the nation and that the truck/semitrailer accident velocities for California provide a reasonable estimate of future accident velocities for spent fuel transport trucks. Accident data from North Carolina is used to estimate the effects of braking on the reduction of impact velocity. The method used to estimate the velocity reduction is described in Subsection 5.2.1.2.

Distribution V2, the velocity attained in falls from bridges is developed directly from a survey of bridge height data presented in Table 2.4.[37] This bridge height data is collected along Interstate 5 during the survey of bridge column sizes and types of soil along the highway. The bridge height distribution is reasonable for representing travel on interstate and state highways.

Table 2.3
Distribution of Velocities for Trucks/Semitrailers Involved in Fatal and Injury Accidents in California, 1958-1967[a/]

Velocity (mph)	Number of Accidents	Fractional Percent (%)	Cumulative Percent (%)
0	1,774	**6.41**	6.41
1 - 10	4,143	14.96	21.37
11 - 20	4,122	14.89	36.25
21 - 30	4,248	15.34	51.59
31 - 40	4,733	17.09	68.69
41 - 50	7,264	26.23	94.92
51 - 60	lj173	4.24	99.15
61 - 70	171	0.62	99.77
>70	63	0.23	100.00
Subtotal	27,691	100.00	
Not stated	2,834	-	-
Total	30,525	-	-

[a/]. **Data derived from the** 1958 **to 1967 annual reports on fatal and injury motor vehicle traffic accidents, California Highway Patrol**

Table 2.4
Distribution of Bridge Heights along Interstate 5 through Orange and Los Angeles Counties, California

Bridge Height (ft)	Number of Bridges	Fractional Percent (%)	Cumulative Percent (%)
0 - 10	5	4.13	4.13
11 - 20	22	18.18	22.31
21 30	74	61.16	83.47
31 I 40	14	11.57	95.04
41 - 50	3	2.48	97.57
51	1	0.83	98.34
61 - 60 70	1	0.83	99.17
71 - 80			
81 - 90	1	0.83	100.00
Total	121	100.00	

Distribution V3 is developed for those accident scenarios in which the velocity is considered to be the vector sum of the accident velocity V1 and the fall velocity V2. This distribution is used for accidents that involve running off of embankments and into slopes.

Distribution V4 is used for accident scenarios involving train-truck collisions at grade crossings. The magnitude and frequency of the cask velocity is estimated from rail-highway grade-crossing accident velocity data. This accident data is derived from the FRA annual report on rail-highway grade-crossing accident/incident and inventory for the years 1975 through 1982.[57-64] Table 2.5 gives the fraction of rail-highway grade-crossing accidents as a function of train velocity. Fewer than 30% of the accidents occur at velocities greater than 30 mph.

2.5.1.2.2 Impact Angle

The impact angle is the angle between the cask velocity and the plane of the surface struck. The damage caused in a transportation accident is not controlled solely by the vehicle(s) velocity at impact. A head-on impact is more severe than a sideswiping event, even though both accidents could involve similar accident velocities. The reason is that accident severity is most directly related to the vector component of the accident velocity perpendicular to the object being struck. The orientation of the vehicle, or in this case, cask motion relative to the plane or surface of the object impacted, is established by a parameter called the impact angle, depicted earlier as angle α in Fig. Z-l. A 90°-impact angle defines the accident as head-on; that is, the impact velocity and accident velocity at impact are the same. An impact angle close to 0° defines the accident as a sideswiping impact; that is, the impact velocity is only a small fraction of the accident velocity. In mathematical terms the impact velocity is the accident velocity multiplied by the sine of the impact angle.

The distribution of impact angles can be expected to be a function of the accident scenario being considered. For example, if an accident involves a collision with another vehicle on the road, any impact angle is equally

Table 2.5
Train Velocity Distribution for Rail-Highway Grade-Crossing Accident/Incidents Involving Motor Vehicles, 1975-1982[a]

Velocity (mph)	Number of Accidents	Fractional Percent (%)	Cumulative Percent (%)
0 - 9	27,553	33.79	33.79
10 - 19	16,765	20.56	54.35
20 - 29	14,611	17.92	72.47
30 - 39	10,788	13.23	85.50
40 - 49	7,617	9.34	94.84
50 - 59	2,879	3.53	98.37
60 - 69	824	1.01	99.38
70 - 79	461	0.57	99.94
80 - 89	29	0.04	99.98
>90	17	0.02	100.00
Subtotal	81,544	100.00	
Unknown	573		
Total	82,117		

[a] Data derived from the 1975 to 1982 annual inventory on rail-highway grade-crossing accidents/incidents, Federal Railroad Administration

likely. Information on impact angle distributions is not readily available; however, three distributions are defined. The distributions include:

VV1: A uniform distribution in which any impact angle is equally likely,

VV2: A distribution which considers all impacts as 90° occurrences, and

VV3: A triangular distribution in which 90° impacts are most likely with other orientations decreasing in likelihood as the impact angle decreases.

2.5.1.3 Cask Orientation-

Historical records do not contain significant information on the orientation of the cask with respect to the object impacted. For impacts on a surface 0° cask orientation defines a sidewise impact while a 90° cask orientation defines an endwise impact of the cask. Alternatively for impacts by train sills, a 0° cask orientation defines a head-on impact to the cask side while a 90° cask orientation indicates a near miss. Again, since the cask orientation distribution can be dependent on the accident scenario being considered, three cask orientation distributions are defined. The distributions include:

CT1: A uniform distribution in which all cask impact orientations are equally likely,

CT2: A triangular distribution in which end-on impacts on surfaces or head-on impacts to the side of the cask by train sills are most likely, with other orientations decreasing linearly in likelihood as the orientation angle approaches 0°, and

CT3: A triangular distribution in which impacts at 45° are most likely, with other orientations decreasing linearly in likelihood as the orientation angle approaches either 0° or 90°.

2.5.2 Thermal Loading Parameters

The thermal response of a cask, specifically the temperature reached within the gamma shield, is determined by three major thermal loading parameters: fire duration, flame temperature, and fire location with respect to the cask. The distribution functions for these parameters can be a function of the specific accident scenario being evaluated and can also vary from accident to accident within the same accident scenario (e.g., variations of fire locations with respect to the cask).

The BMCS reports and other sources provide information such as the accident type, the cause of fire property damage, and method of extinguishment.[65] This information is useful for defining actions to improve public safety. The sources, however, do not provide data on thermal loading parameters such as flame temperature and fire duration. Limited data on thermal loading parameters are sometimes included in the National Transportation Safety Board severe accident reports, but the data is not sufficient to adequately define thermal loads and their fractional occurrence.

A truck-fire accident has many variables that affect the fire and thermal loads. The variables include the involvement of the truck's fuel tank and its contents; the possibilities of a collision with an auto, another truck or a tanker truck; and the availability of fire fighting equipment. The many variables and the lack of specific data lead to the use of the Monte Carlo technique[66] and engineering models to determine the distribution functions for the thermal loading parameters.

2.5.2.1 Accident Scenarios and Fire Frequency

The accident scenario in which a truck is involved can affect the thermal loads on the truck and its cargo. Table 2.6 presents the accident type and the frequency of fires.[66] In Subsection 5.3 these accident fire frequencies are correlated with the accident scenarios in Figs. 2-3 and 2-4 to determine the probabilities of fire for each of the scenarios.

Table 2.6
Frequency of Fire for Truck Accident Types

Accident Type	Fire Involved in Accident (%)	No Fire in Accident (%)
Collision with Auto	0.3	99.7
Collision with Truck	0.8	99.2
Collision with Fixed Object	0.4	99.6
Other Collision	0.9	99.1
Ran off Road	1.1	98.9
Overturns	1.2	98.8
Other Noncollision	13.0	87.0

2.5.2.2 Fire Duration

Since the available fire-accident data do not provide specific information on fire duration, the Monte Carlo method is used to derive the fire duration distribution for each accident scenario.[66] This method combines data on accident types, cause of the fire, availability of combustibles, and fire-fighting efforts with statistical engineering models on the burning of combustibles for various types of accidents. A Monte Carlo computer code is used as recommended[66] to analyze the interaction and probabilistic involvement of fuel tanks, tires, cargo, brakes, and electrical systems, as well as the effects of fire fighting efforts.

The Monte Carlo code is also used to predict fire duration distributions for each accident scenario in Figs. 2-3 and 2-4. As might be expected, there is a large variation in the fire duration distributions for the scenarios. In general, the fire durations following high impact loads on hard surfaces are shorter compared to those involving lower impact loads or collisions with other trucks, particularly tanker trucks.

2.5.2.3 Flame Temperature

Flame temperature depends on the burning materials and the amount of oxygen present in the flame. This study uses the flame temperature probability distribution from Sandia.[66] The fire distribution is primarily based on the open burning of hydrocarbon fuels such as diesel and gasoline in the temperature range of 1400 to 2400°F, but also includes other materials which tend to burn at lower temperatures.

The size of a fire affects both the radiation heat transfer capabilities and the duration of the fire. Fires with a flame that is at least four feet high radiate essentially as a blackbody with flame emissivity in the range of 0.9 to 1.0. Smaller fires have much lower emissivities and are usually of short duration, and would have little effect on a cask.

The convection heat transfer from a fire to a truck and its cargo is usually less than 10% of the radiation heat transfer. As discussed in Appendix F, an equivalent flame temperature for specific cask configurations can be used to estimate the thermal loads for various combinations of flame temperatures, flame emissivities, and convection coefficients. In this study, it is conservatively assumed that all fires will have an emissivity of 0.9.

2.5.2.4 Fire Location

The heat load to a cask varies with the location of the fire with respect to the cask. The heat load to the cask can decrease by a factor of 4 for a fire 20 feet from the cask compared with the heat load for an engulfing fire. As with other fire parameters, insufficient historical accident data exists to develop fire location distributions with respect to the cask. A uniform distribution for cask-to-fire location is assumed for all fire accident scenarios defined by:

L1: A uniform distribution in which any fire location relative to the cask is equally likely, in the interval between 0 and 31.5 feet. The cask is sidewise to the fire in all cases to maximize the heat load to the cask.

2.6 Railway Accident Loading Parameters

2.6.1 Mechanical Loading Parameters

Types of train accidents are identified from FRA data, and supplemented by other sources to define accident scenarios used in this study. For some of the accident scenarios, loading parameter magnitudes and frequencies are estimated from highway data. In other cases, loading parameter data is derived from severe accident reports. In all cases, the selection of the data is justified as being suitably conservative. As with highway accident scenarios, the primary effort in obtaining railway accident data is placed on collecting information on those accident scenarios that could result in high loads to a cask. In this subsection the distribution functions are determined for three mechanical loading parameters: object hardness, impact velocity, and cask orientation.

2.6.1.1 Accident Scenarios and Object Hardness

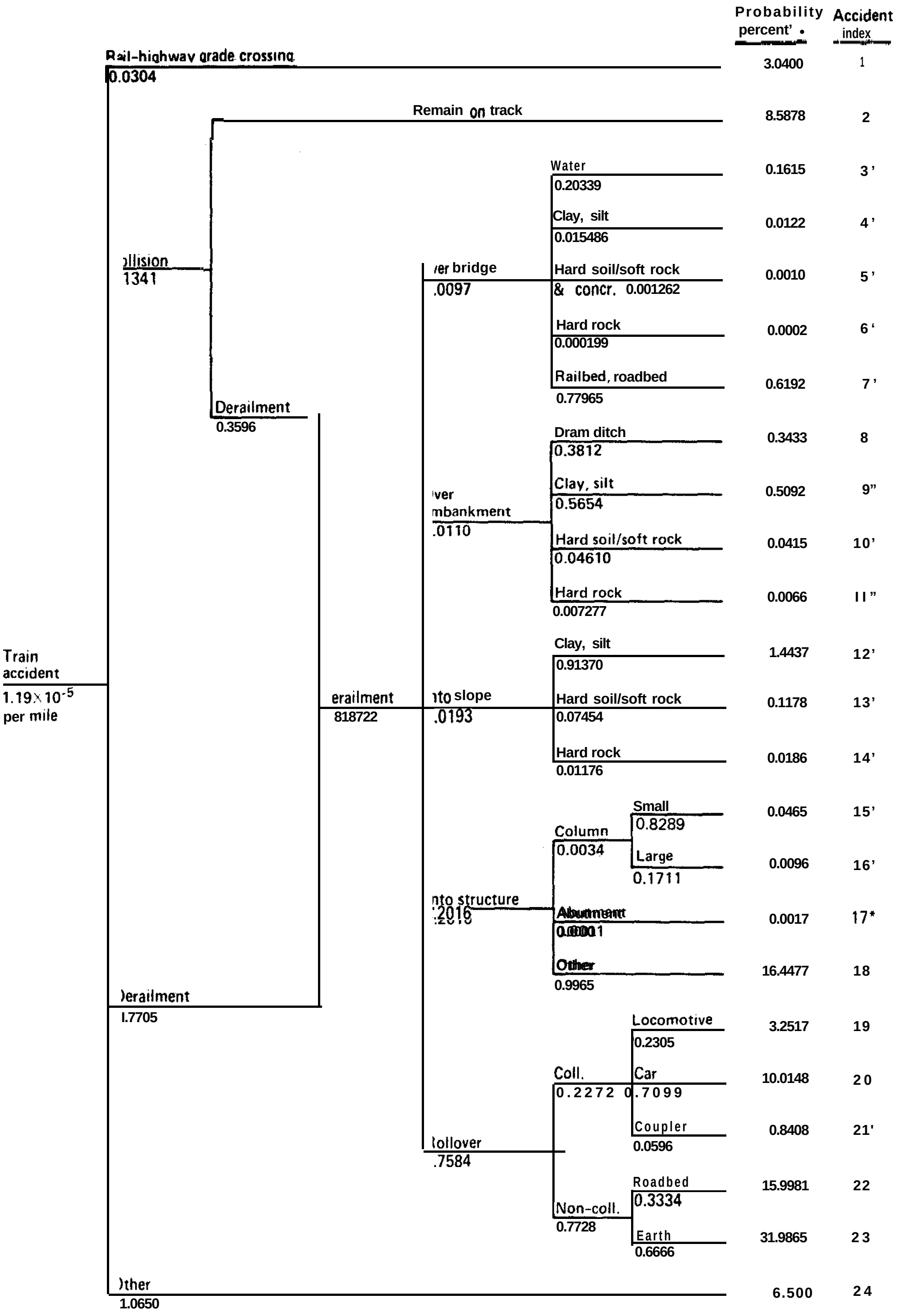
Data is collated from several sources to derive accident scenarios and to estimate the cask impact frequency with a particular object. The combined data are presented in Fig. 2-4 for derailment, collision, and other accident types. The fraction of train accidents due to each type is estimated from the FRA data in Appendix C.[11-17] Derailment is the most common railway accident, accounting for 77.1%. Derailment involves a section or all of the train leaving the track. The section leaving the track separates from the preceding car as it leaves the track, causing the braking system to activate for all cars in the train. The lead car leaves the track at the highest speed, and the other cars follow at successively slower speeds. The average derailment involves approximately 10% of the cars in the train.

Collision accidents account for 13.4% of train accidents. The damage during a collision is usually limited to the cars near the impact point and involves less than 10% of the cars. For head-on collisions, damage is usually limited to the locomotive and the few cars that follow. For rear-end collisions, only the caboose and the few cars ahead of it are damaged.

Other accidents, including grade-crossing accidents, account for the remaining 9.5% of the accidents. These accidents usually do not cause serious impact forces to the train.

As shown in Fig. 2-5, collision accidents can result in derailments. In 64% of the collisions, the train remains on the tracks. In this case the cars may impact each other, but the forces would be relatively low or else the cars would have left the tracks. In 36% of the collisions, a derailment results and the cars leave the tracks. When considering the percentage of derailments occurring with collisions, the total percentage of train accidents that involve derailment is 82%.

The severe accident data in Appendix A is used in conjunction with the highway data to identify the objects and to estimate impact frequencies for the derailment accidents.[67] Owing to the limited amount of severe accident data and the nature of the reports, there is a high uncertainty in applying the data to the continuous spectrum of accidents.



'Potentially significant accident scenarios
*'Conditional probability which assumes an accident occurs

Figure 2-5 Train accident scenarios.

If a derailment accident occurs, the train can go off a bridge or an embankment, strike a slope, or rollover onto the adjacent ground. In this study, the percentage of accidents that go off a bridge or an embankment or onto a slope is estimated to be the same as those for highway accidents. For these types of accidents, the frequencies of impacting different soils, roadways, and water are also assumed to be the same as those used for highway accidents. These estimates and assumptions are made because of the lack of data on railway accidents and the fact that railways cross similar terrain as highways for similar routings. The remaining derailment accidents are assumed to be rollover-type accidents.

When a train derails in a rollover type of accident, it can (1) slide along the adjacent railbed or earth with relatively low damage occurring; (2) hit the superstructure of adjacent cars or locomotives; (3) strike couplers from adjacent cars; or (4) impact structures adjacent to the track. The severe accident data from Eggers[67] is used to estimate the frequencies for impact on railbed, earth, car superstructure, locomotive superstructures, car couplers, and adjacent structures. As shown in Fig. 2-5, it is estimated from the Eggers database that 0.8% of the train derailment accidents involve train couplers. The frequency for impacting large structures, such as columns and abutments, is estimated to be the same as the frequencies obtained from the CALTRANS highway data.

2.6.1.2 Impact Velocity

The impact velocity of a cask involved in a train accident depends on the cask velocity and the impact angle. The cask velocity depends on the train velocity prior to collision or derailment and the height of any fall that might occur. The impact velocity distributions for a cask involved in train accidents are estimated from train accident records, surveys, and engineering judgments.

2.6.1.2.1 Cask Velocity

For potential accidents in which the rail cask impacts an object, the magnitude and frequency of the impact velocity are estimated from the train accident velocity provided in Appendix C. This estimate conservatively disregards the fact that a reduction in impact velocity occurs because of energy absorption by the transporting car or the rest of the train. Tables 2.7 and 2.8 give the average frequencies of train collisions and derailments as functions of accident velocities, respectively, for the years 1979 through 1982. This accident data is derived from the FRA reports on train accidents.[13-17] The velocities for other accidents include grade-crossing incidents which are included in the truck data.

In the absence of a statistical data base on distance fallen by trains going off bridges and embankments in actual accidents, the highway survey bridge distribution in Table 2.4 is used to estimate distances fallen in this type of accident. Since specific train and truck routes for transporting spent fuel traverse similar terrain, the use of the highway bridge data for this study is reasonable.

In summary, the cask velocity distributions for each of the potentially significant train accident scenarios are:

TV1: A distribution based on train collision accident velocities without braking,

TV2: A distribution based on train derailment accident velocities without braking,

TV3: A distribution based on fall heights from bridges, and

TV4: A distribution based on the vector sum of train derailment velocities and fall heights from bridges.

Table 2.7

Railroad Accident Velocity Distribution, Collisions, Main Line, 1979-1982[a]

Velocity (mph)	Number of Accidents	Fractional Percent (%)	Cumulative Percent (%)
1 - 10	392	46.12	46.12
11 - 20	182	21.41	67.53
21 - 30	117	13.76	81.29
31 - 40	92	10.82	92.12
41 - 50	47	5.53	96.65
61 - 60	14	1.65	99.29
71 - 8070	3	0.35	99.65
	2	0.24	99.88
81 - 90	0	0.00	99.88
>91	1	0.12	100.00
Subtotal	850	100.00	
Unknown	8	-	-
Total	858	-	-

[a] Data derived from Federal Railroad Administration reports on train accidents, 1979 - 1982.

Table 2.8
Railroad Accident Velocity Distribution, Derailments, Main Line, 1979-1982[a/]

Velocity (mph)	Number of Accidents	Fractional Percent (%)	Cumulative Percent (%)
1 - 10	4,394	40.42	40.42
11 - 20	2,250	20.70	61.12
21 30	2,183	20.08	81.21
31 I 40	1,091	10.04	91.24
41 - 50	659	6.02	97.30
51 - 60	239	2.20	99.50
61 - 70	41	0.38	99.88
71 - 80	10	0.09	99.97
81 - 90	3	0.03	100.00
>91	0	0.00	
Subtotal	10,870	100.00	-
Unknown	76	-	-
Total	10,946	-	-

[a/] Data derived from Federal Railroad Administration reports on train accidents, 1979 - 1982.

2.6.1.2.2 Impact Angle

As for highway accidents, there is insufficient historical accident data available to define distribution functions for the impact angle of a spent fuel cask onto an object. Three distribution functions for spent fuel cask impacts are assumed for train accidents, namely: (1) uniform distribution, (2) all impacts at 90°, and (3) triangular distribution in which 90° impacts are most likely.

2.6.1.3 Cask Orientation

Since there is insufficient historical railway accident data available to define distribution functions for the cask orientation at the time of impact, three distribution functions are assumed for train accidents. The distribution functions are (1) uniform distribution, (2) all impacts endwise or head-on to the cask, and (3) triangular distributions in which 45° impacts are most likely.

2.6.2 Thermal Loading Parameters

As with truck accidents, every train accident does not necessarily result in a fire. As indicated in Appendix C, approximately 1% of train collision and derailment accidents involves a fire. As for truck accidents, the train accidents have data on type of accident, frequency of fire, cause of fire, and property damage estimates. However, the accident records do not provide data on thermal loading parameters such as flame temperature and fire duration.

A train-fire accident has a large number of variables that affect the thermal loads. Such variables are (1) type of accident (collision, derailment, grade crossing, etc.), (2) type and amount of cargo (flammable or nonflammable), (3) involvement of locomotive fuel, (4) types of cars involved (box car, tanker, etc.), and (5) the availability of fire fighting equipment.

The same methods used in Subsection 2.5.2 to estimate the truck fire duration distribution are used here to estimate the distribution functions for the three thermal loading parameters: fire duration, flame temperature, and fire location.

2.6.2.1 Accident Scenarios and Fire Frequency

The type of railway accident can affect the thermal load on a train and its cargo. Table 2.9 presents the accident type and the frequency of fires, modified to include grade-crossing accidents which were separately identified beginning in 1978 (see Appendix C).[66] The fire frequency for "other" accidents is judged to be too high, but owing to the lack of consistent data, this conservative estimate is used.[66]

2.6.2.2 Fire Duration

Since the available fire-accident data do not provide specific information on fire duration for each of the railway accidents, the same method used in Subsection 2.5.2.2 to estimate truck fire duration distribution is used to estimate the fire duration distribution for trains. A Monte Carlo scheme is used in analyzing a large number of variables and their interactions.[66] The code can evaluate the interaction and involvement of locomotive fuel tanks, different types of rail cars and their flammability, and different types and amounts of flammable cargo, as well as the effects of fire fighting efforts. The code is used to predict the fire distributions for each of the accident types in Table 2.9 and the accident scenarios in Fig. 2-5.

2.6.2.3 Flame Temperature

The thermal loads on a train and its cargo are affected by the flame temperature of the fire. They are primarily determined by the type of material involved in the fire, the oxygen supply, and geometric configuration. Train fires often include diesel fuel, flammable cargo, and flammable parts of the cars. The flame temperature for train fires are the same as those evaluated for truck fires in Subsection 2.5.2.3. For the purpose of this study, it is assumed that all train fires will have an emissivity of 0.9.

Table 2.9
Train-Fire Accident Types

Accident Type	Fire Involved in Accident (%)	No Fire in Accident (%)
Collision	1	99
Derailment	1	99
Grade Crossing	1	99
Other	90	10

2.6.2.4 Fire Location

As with other fire parameters, insufficient historical accident data exists to develop fire location distributions with respect to a spent fuel cask. As is done for the truck cask accident scenarios, uniform distributions (L1) are assumed for each of the fire accident scenarios for fire locations 0 to 43.0 feet from the cask.

Blank

3.0 SELECTION OF REPRESENTATIVE SPENT FUEL CASKS FOR EVALUATION

3.1 Introduction

Casks currently certified for shipment of spent fuel from nuclear power reactors in the United States vary distinctly in design.[1-4] The most obvious difference between these casks is that they are designed to carry differing amounts of spent fuel. Casks weighing under 25 tons carry one or two fuel assemblies and can be transported by truck. Other casks can carry three to seven fuel assemblies and can also be carried by truck if appropriate highway overweight permits are secured. Finally, because railroads can carry greater loads, currently licensed rail casks can carry between 7 and 24 assemblies.

All of these casks must be designed to accomplish certain basic safety functions which are defined by a set of performance-oriented regulatory requirements.[5] In this regulatory approach, the cask design features which accomplish a specific safety function can vary, but the functional result must meet minimum specified requirements. In order to study the adequacy of the regulations to provide radiological protection, representative casks are defined which have design features likely to meet the regulations. Sufficient features must be defined to evaluate the protection provided by spent fuel casks involved in transportation accidents.

In addition, casks designed to meet regulatory requirements are usually designed and manufactured to code and standards which have margins of safety embedded in them. These margins of safety ensure that the spent fuel cask not only will meet the regulatory accident test conditions and radiation hazard limits but will survive loading conditions beyond the regulatory conditions.

The purpose of this section is to define the representative casks which are used in the accident response calculations described in later sections of this report. These representative casks are developed from current cask designs and technology. These representative casks include the necessary design features and safety margins for evaluating their response to accident conditions.

In Section 3.2, general safety functions for the cask are defined. The cask features needed to meet these functions are identified. Specific characteristics are determined for the various design features.

In Section 3.3, each design feature is evaluated from two standpoints: (1) the feature's susceptibility to damage under transportation accident conditions, and (2) the feature's ability to mitigate damage to other important cask features. Some features, e.g., impact limiters, are characteristically sacrificial and highly susceptible to damage, but are effective in mitigating further damage to the rest of the system. At the other extreme are features that are characteristically highly resistant to damage, but transmit damaging forces into other parts of the system with little mitigation.

In Section 3.4, six preliminary cask designs are evaluated on a comparative basis. From this comparison the gamma shielding material for the representative truck and rail cask designs is selected. The six designs include three truck casks and three rail casks which use the candidate shield materials: lead, depleted uranium, and steel.

Section 3.5 describes the two representative cask designs selected--one for truck shipments and the other for rail shipments. The physical and material specifications for the two designs are established. Those design features which are necessary to perform the evaluations in this study are identified, The rationale and the sensitivity studies used to define the required design features are also described.

Section 3.6 describes the typical safety margins that are included in licensed cask designs and the representative cask. These safety margins are embedded in the codes and standards used in designing and manufacturing casks.

3.2 Cask Functions and Design Features

Casks currently certified for shipment of spent fuel are relatively complex engineering structures designed to meet certain functional needs.[1-4] Many of these functional needs are dictated by the characteristics of the spent fuel being shipped. The spent fuel is a source of radioactivity and heat, both originating within the fuel pellets which are contained within the rods of a fuel assembly. The primary cask functions include (1) containment of radioactive material, (2) shielding against the radiation emanating from the spent fuel, and (3) the assurance that subcriticality is maintained.

Containment is the retention of radioactive material within a closed vessel. Containment is provided to preclude any contact between people and radioactive material. Typically, containment is provided by the integrity of the spent fuel and by a cylindrical steel vessel (Fig. 3-l). The vessel is provided with a bolted end closure to accommodate spent fuel loading and unloading operations. The closure contains a seal to inhibit leakage between the cask containment and the environment. Piping penetrations of this containment are needed for operating purposes, and the associated closure valves are considered a part of the containment system. These penetrations are in the containment vessel for draining, filling, testing, etc. The containment cavity is filled with a non-oxidizing gas for shipments.

A radiation shield is a barrier which absorbs ionizing radiation or subatomic particles emanating from a radioactive source. Two types of radiation shielding are typically included in spent fuel cask design, gamma and neutron. The most important shielding provides protection against the highly penetrating gamma radiation. This protection is achieved through the use of dense materials such as lead, depleted uranium, or steel, These materials surround the containment vessel (Fig. 3-l) and are, in turn, enclosed within an outer steel shell, If steel is the shield material, this shield can be an integral part of the containment vessel. The second type of shielding is used to mitigate radiation caused by spent fuel emission of neutrons. This source of radiation is typically less significant than gamma radiation. Hydrogenous materials provide shielding against neutrons. The neutron shield, usually a water jacket, surrounds the cask on its exterior surfaces. The hazard associated with neutron radiation is such that loss of neutron shielding does not result in radiation levels that exceed regulations for accident situations. The regulations allow for higher external radiation levels following an accident than during normal transport.

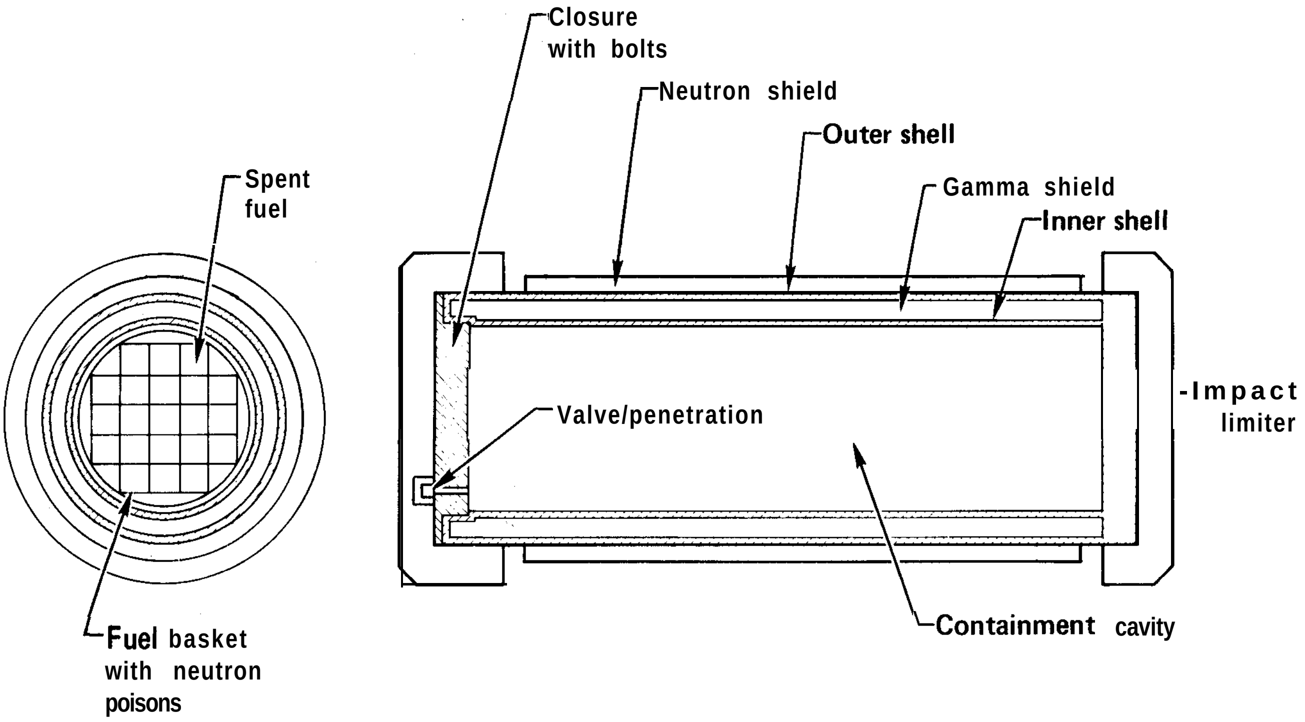


Figure 3-l Spent fuel cask features important to safety.

Criticality is a self-sustained nuclear chain reaction which might result in high energy production and a radiation burst before self-termination. Spent fuel casks are designed to maintain a condition of subcriticality. The subcriticality assurance function, if not achieved by the physical limitation on the amount of spent fuel being shipped, is assured by maintaining geometric control of the spent fuel during shipment and by including neutron poisons in appropriate cask structural materials. Neutron fission interactions with spent fuel must attain a prescribed level before criticality can occur. The neutron poisons, which are typically included in the basket holding the fuel assemblies, absorb emitted neutrons to a sufficient degree to limit neutron fission interaction and thus assure subcriticality.

As the above discussions of containment, shielding, and subcriticality assurance indicate, two fundamentally different concepts are applied in the regulations: containment and shielding are limiting in nature while subcriticality is absolute.

In all casks, the design features used to meet each of the specific functional needs have many mutual dependencies. The containment shell, for example, must be designed to structurally support the heavy surrounding gamma shielding material. Also the geometry control achieved by internal cask features is dependent on the protection against deformations provided by the overall cask structure,, These dependencies between specific design features are further described in Section 3.3 which discusses the performance requirements for the design features important to safety.

3.3 Cask Design Features Important to Safety

3.3.1 Containment

This subsection describes several design features which basically compose the typical cask containment system: (1) the cylindrical steel containment shell, (2) the bolted end-closure, (3) the closure seal, and (4) the piping and valves associated with any containment system penetrations. The containment system must be designed so that when subjected to the hypothetical accident conditions specified in existing regulations, the regulatory limits for radioactive material releases are met. In practice, the required function of the containment vessel is achieved by a combination of three factors: (1) the structural integrity of the individual containment system features, (2) the provision of external features such as energy-absorbing structures designed to protect the cask and its containment system against external forces, and (3) the integration of the containment features into an overall cask design which maximizes the protection provided against these external forces,

The steel containment is designed as a system and must support itself and the weight of the spent fuel and other internal structure under regulatory-defined normal and accident transport conditions. The steel containment shell provides a substantial resistance to any externally applied forces. To provide ensurance that this shell maintains its integrity under potential transportation accident conditions, casks are designed with impact limiters. Impact limiting devices can take the shape of large end-caps made of a crushable material such as balsa wood or rigid foam, or they can be in the form of bendable metal fins or tubes which protrude from the outer cask body. In all cases, impact limiters are designed to limit, or reduce, the mechanical loads imposed on the cask containment shell. The impact limiters do this by deforming and sacrificially absorbing the energy of the accident. The containment shell is designed for the impact-limited loads which arise from the accident test conditions.

The bolted containment end closure and the closure seal are located within the envelope of protection provided by the impact limiting devices (Fig. 3-Z). The bolted closure is typically recessed within the outer cask shell, and the closure seal is located between the end closure and the containment shell wall. These cask features are designed so that if the cask is subjected to accident conditions, the containment function is not compromised.

Piping and valves associated with subsystems that penetrate the containment are also located in protected recessed areas within the outer cask

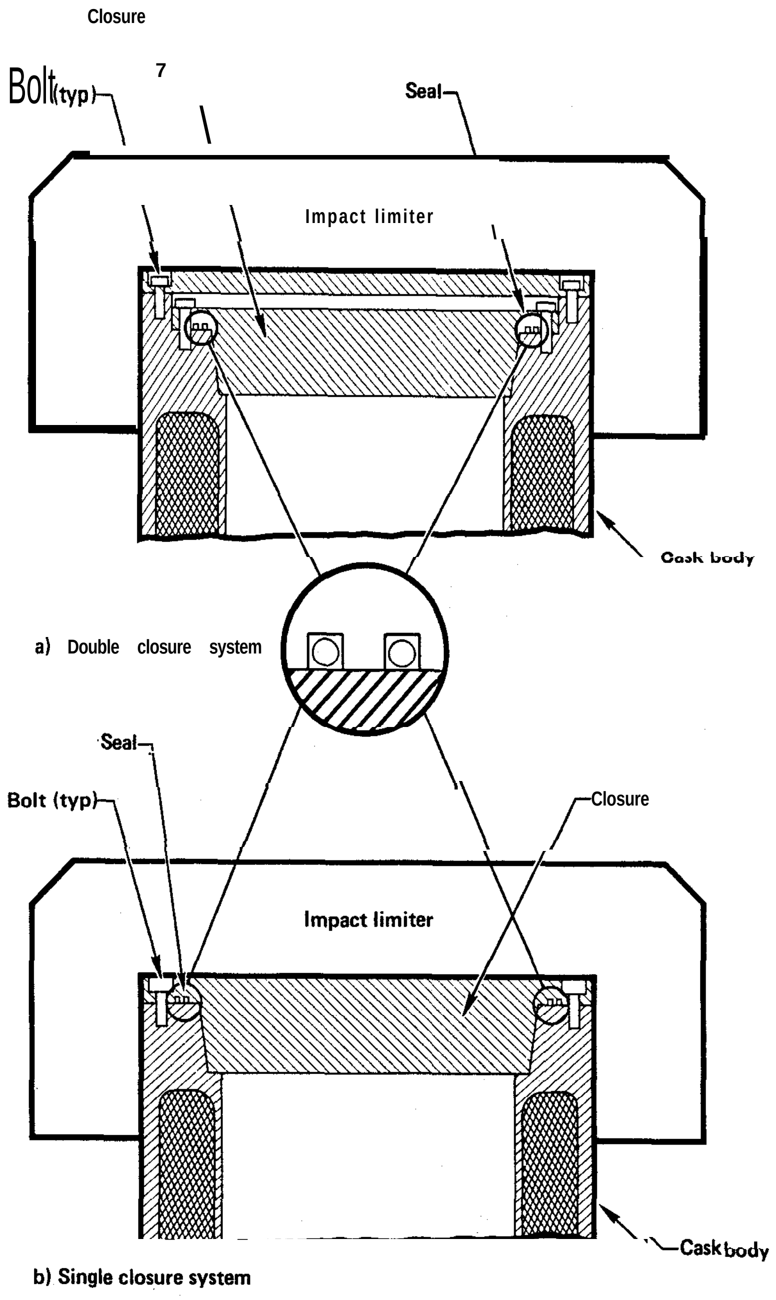


Figure 3-2 Typical closure designs for spent fuel casks.

structure (Fig. 3-3). As a result, this piping system and its related valves are also protected by the impact limiting devices. Again, this system is designed to withstand the accident conditions without compromising containment integrity.

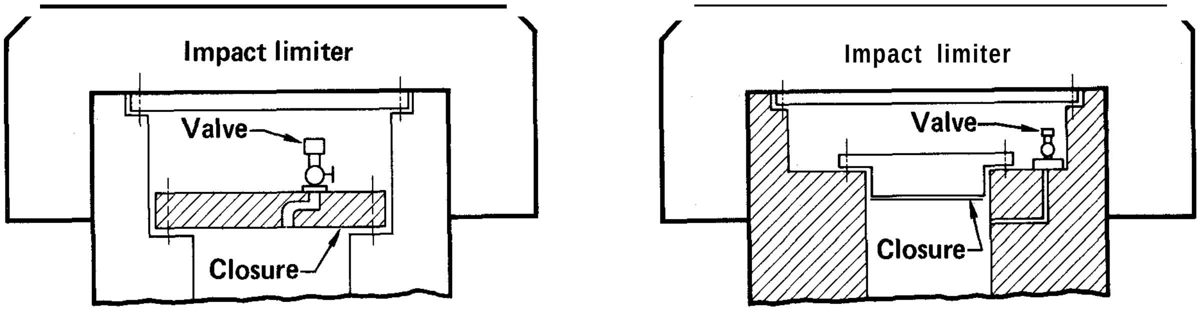
3.3.2 Radiation Shielding

Shielding is provided in all cask designs to limit the gamma and neutron radiation which emanates from the spent fuel. The gamma shield is typically a dense metal, such as lead, depleted uranium, or steel. These materials surround the cask containment vessel and, in the case of lead and depleted uranium, are enclosed within an outer steel shell. The neutron radiation shield typically consists of hydrogenous compounds such as water. The neutron shield is generally located beyond the outer steel shell which encases the gamma shield. When water is used for neutron shielding, it is contained within a water jacket. The thicknesses of these shields are determined to ensure that the radiation levels external to the cask are within regulatory values which are specified for both normal transport and transportation accident conditions, (i.e., ≤200 mrem/hr on the external surface and 61 rem/hr at 1 meter from the external surface, respectively).

In practice, the dose rate of 61 rem/hr at 1 meter from the external surface can be achieved by maintaining the integrity of the gamma shield. The magnitude of neutron radiation is intrinsically limited to levels that allow the loss of neutron shielding to be presumed in the event of a transportation accident. The gamma shielding is protected by both the outer steel shell of the cask and the cask's impact limiters. If the cask is subjected to the accident test conditions, the cask gamma shield is designed to assure that external radiation levels remain within regulatory limits.

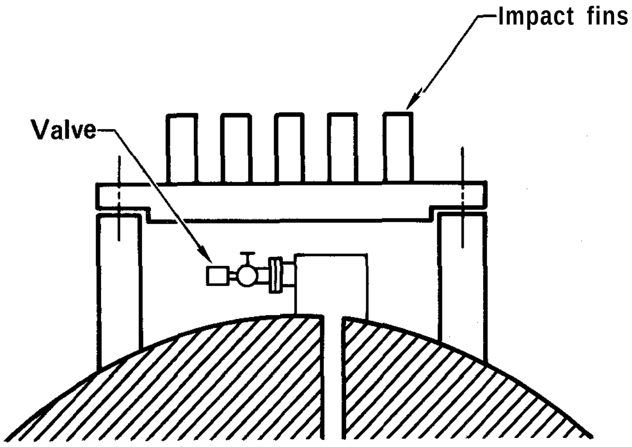
3.3.3 Subcriticality Assurance

Subcriticality for one pressurized water reactor (PWR) assembly or two boiling water reactor (BWR) assembly shipments (typically made by truck) is assured because the amount of fissile material available in the UO_2 fuel form



a) Valve through closure

b) Valve through flange



c) Exterior reinforced valve box

Figure 3-3 Typical cask penetration subsystems.

is insufficient to achieve criticality under any credible circumstances. Larger shipments, however, which are generally made by rail, do contain enough fissile material to make criticality a theoretical possibility if: (1) the material can be optimally rearranged geometrically, (2) a neutron reflecting material surrounds the fuel, and (3) a neutron moderating media such as water can be interspersed between fuel rods and assemblies. For these shipments, subcriticality assurance is achieved by geometry control features and the use of neutron poisons, materials which preclude a self-sustaining fission process.

A cask's capability to assure spent fuel subcriticality for these larger shipments is evaluated in an extremely conservative manner. The effectiveness of the geometry control provisions and the neutron poisons must be demonstrated not only under the specified accident test conditions but also under defined conditions which optimize the possibility for criticality. Among these other conditions, the larger shipments must be demonstrated to be subcritical when: (1) two similar casks are assumed to be stacked together in an arrangement which optimizes criticality potential, (2) the stacked casks are closely reflected on all sides by water, and (3) the fuel within each cask is subjected to optimum, interspersed hydrogenous moderation.

The assumed presence of the reflecting and moderating materials increases the possibility of achieving a critical configuration. The use of this conservative approach to assure subcriticality highlights the importance of cask features other than the spent fuel geometry control features and neutron poisons previously described. For example, if containment integrity is maintained, water or other hydrogenous material could not enter the cask containment vessel and the possibility of criticality would be precluded. Similarly, if the overall cask structure prevents gross internal distortions, then spent fuel geometry control and neutron poisons would be sufficient to assure subcriticality even if water or other hydrogenous material entered the cask containment vessel.

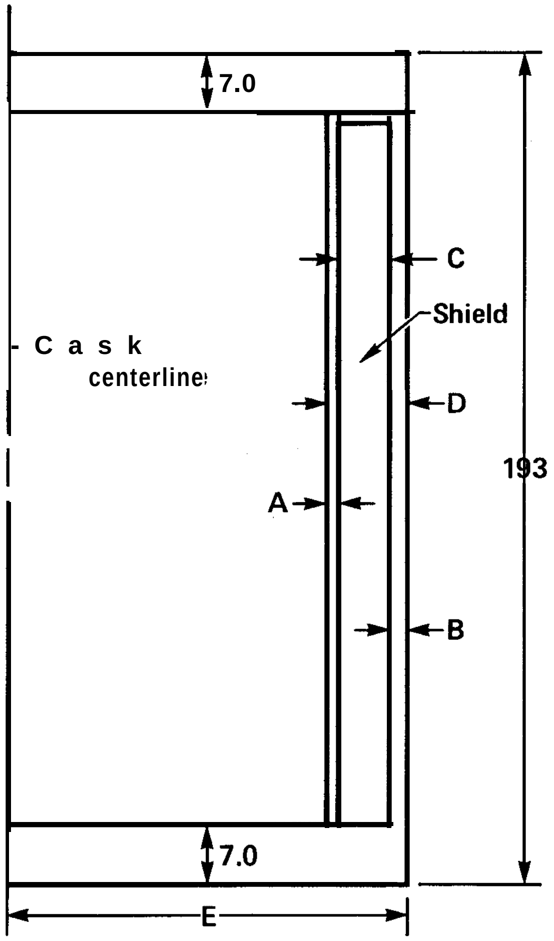
3.4 Selection of Cask Shielding Material

Shielding provides protection from both the neutron and gamma radiation emanating from spent fuel. The gamma shielding can be provided by several different materials, each with a distinct capability to withstand the mechanical and thermal loads associated with potential transportation accidents. The selection of the gamma shield material for a representative cask is based on an evaluation of the comparative performance of different preliminary cask designs: three each for truck and rail. The six preliminary designs shown schematically in Figs. 3-4 and 3-5 include consideration of sizing differences typical to truck and rail casks and the use of each of the three candidate gamma shield materials: lead, depleted uranium, and steel.

These six designs are evaluated against two quasi-static mechanical loading conditions, i.e., end-on and side loads. Then the magnitude of loads necessary to initiate yielding of the containment shell is determined. Static loads are applied to the end and side of the casks for this evaluation. The details of these evaluations are described in Appendix E. The results indicate that the lead shielded casks--both the railway and highway configurations --will begin to yield when subjected to a lower external force than the casks with steel or depleted uranium shields. From a structural standpoint, lead is the worst of the three candidate gamma shield materials and is, therefore, the material of choice.

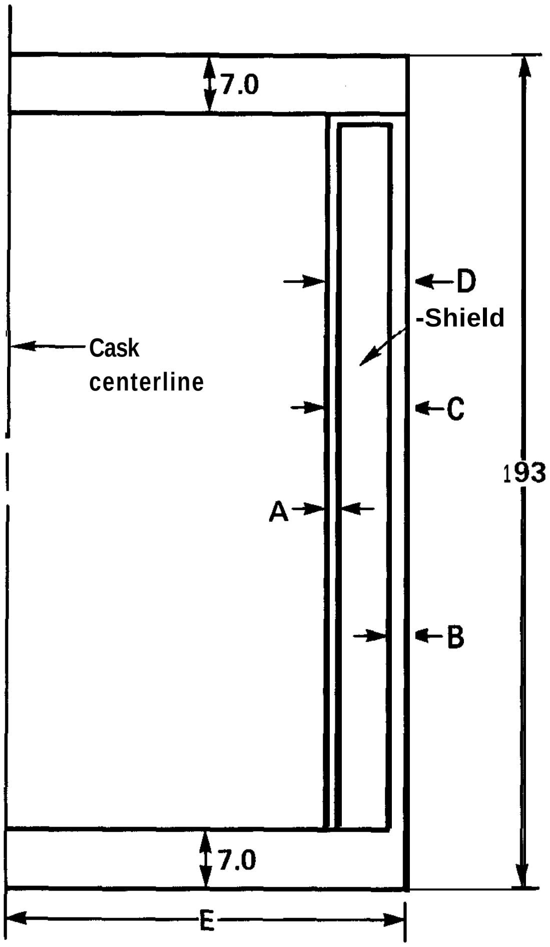
The six preliminary designs also are compared in terms of their capability to absorb thermal energy from potential fire environments. In terms of thermal capacities, the steel-shielded designs are capable of absorbing the most heat; the depleted uranium and lead designs have essentially equal capabilities. Lead has a melting temperature below the other cask shield materials, which is considered another factor significant to safety. The thermal expansion effect is also the most significant for lead shielded casks. From a thermal standpoint, lead is again the worst of the three candidate shield materials and is the material of choice.

Based on these structural and thermal evaluations, lead is selected as the gamma shield material for the representative cask designs.



Dim	Thickness (in.)	Material
	Truck Cask 1	
A	0.5	304SS
B	1.25	304SS
C	5.25	Lead
E	13.75	304SS
	Truck Cask 2	
A	0.5	304SS
B	1.25	304SS
C	4.25	Depleted uranium
E	12.75	304SS
	Truck Cask 3	
D	12.25	Steel
E	19.00	Steel

Figure 3-4 Preliminary truck cask designs with three types of gamma shielding, used for quasi-static loading response studies only.



Dim	Thickness (in.)	Material
	Rail Cask 1	
A	0.5	304SS
B	1.5	304SS
C	5.25	Lead
E	26.0	304SS
	Rail Cask 2	
A	0.5	304SS
B	1.5	304SS
C	4.0	Depleted uranium
E	24.6	304SS
	Rail Cask 3	
D	12.25	Steel
E	30.75	Steel

Figure 3-5 Preliminary rail cask designs with three types of gamma shielding, used for quasi-static loading response studies only.

3.5 Definition of Representative Cask Designs

Previous sections discuss the functions of a spent fuel cask which are important to safety in the event of a transportation accident. This section presents the basis for the selection of the representative spent fuel casks used in the response analyses. The response of these casks is evaluated when subjected to the forces of real world accident environments in later sections of this report. The definition of a representative cask involves the accomplishment of two major tasks: (1) a determination of what cask features important to safety require specific design definition, and (2) a selection of a design definition which considers the variety of design features that can accomplish a specific safety function.

The following subsections present the rationale for accomplishing these two tasks. Separate subsections consider features which are important to the containment, shielding, and subcriticality assurance functions of cask designs. An additional subsection considers the definition of those cask features whose principal purpose is to mitigate the damage to the cask caused by accident forces (principally the impact limiters).

3.5.1 Shielding Features

Based on the evaluations in Section 3.4, lead is selected as the gamma shield material for the representative cask designs. Under impact conditions, lead is not self-supporting and can slump. A properly designed cask has adequate thickness in each steel shell as well as a soft impact limiter to prevent any significant lead slump from occurring under the 30-foot drop test conditions. Bonding of the lead to the inner shell of the cask can provide resistance to lead slump, but bonding varies significantly with the cask design and the fabrication process. Lead slump effects and damage to the cask are maximized when there is no bonding between the lead and the inner wall of the cask. Therefore bonding of the lead is not assumed.

The neutron shield design will not be expected to significantly affect cask response to the mechanical loads associated with severe transportation accident environments. In fact, as indicated previously, the safety evaluations performed on all current casks presume that the capabilities of the neutron shield to reduce external radiation levels is lost as a result of the effects of transportation accident forces. On this basis, specifying the neutron shield design will not be necessary for the representative cask designs. However, this neutron shield, whether lost or maintained, will affect heat transfer. If a water neutron shield is maintained, it will exhibit high heat capacity as well as good heat transfer characteristics. If the water is lost, the empty tank containing air does not have high heat capacity, but provides an effective thermal barrier against heat from a fire. The post-fire effect of a neutron shield tank is to increase resistance to dissipation of internal heat, thereby increasing internal temperatures. Therefore, the volumetric characteristics of the neutron shield design must be considered in the definition of the representative casks.

3.5.2 Containment Features

The containment system includes the steel containment shell, the closure seal, the bolted-end closure, and the piping and valves in the containment-penetrating subsystems.

The steel shell is the containment feature most likely to be subjected to the full brunt of any severe transportation accident forces. The magnitude of any accident damage sustained by the shell provides a broad indication of the possibility and the magnitude of any resulting radiological hazard.

The containment seal can be subjected to damage by mechanical or thermal accident loads transmitted through the cask body to the seal region. However, the radiological hazard resulting from seal damage is limited to the spent fuel material which can escape from the confines of the cask through the damaged or deformed seal region. Rather than attempting to model one of several possible seal designs, a worst-case evaluation of seal performance can be made by presuming a loss of the seal functional capability and the release of radioactive material. Specific levels of damage to the cask must be exceeded as a result of accident forces, The bolted cask end-closure can be subjected to damage by mechanical loads transmitted through the cask body. Damage can also result from the mechanical loads which can be caused by severe thermal environments associated with certain transportation accidents. The end-closure, however, is a massive structure highly resistant to mechanically imposed loads, Furthermore, the closure bolts are designed with sufficient strength to resist tensile forces from corner or end drops of the cask. The recessed characteristics of all current closure designs provide significant protection against shearing of the many large-diameter bolts typically used to secure the end-closure to the cask body. Forces sufficient to cause significant damage to the cask containment shell could occur in many of the conceived severe accident events without compromising the gross integrity of the bolted end-closure. The converse, that is, significant damage to the end-closure without similar containment shell damage is certainly conceivable, but far from likely. From an evaluation standpoint, the definition of a specific closure in a representative cask design will add considerable complexity to the calculations of cask response to severe accident environments. For the above reasons, although the mass and configuration of the closure requires definition, the details of the closure design are not included in the representative cask design(s). Again, a specific level of damage to the cask containment is used as a surrogate measure to indicate damage to, and the occurrence of radioactive material leakage from, the cask closure region.

The penetration subsystems are typically located within the confines of the cask body with exterior valves situated within heavily protected enclosures. These subsystems are easily protected by design features. Unless accident loads are highly localized, damage done to the cask shell will dominate overall cask damage. Notwithstanding, a highly localized load can violate the containment function by providing an opening from the cask containment to the environment through a failed penetration subsystem. Such a violation of containment will limit the escape of any spent fuel material to that which can migrate or be driven out through the small-diameter, tortuous passageways presented by the damaged penetration system.

As a result of the above considerations, the details of a penetration subsystem are not included in any representative cask design. Damage to the containment shell again is used to indicate the possibility of a failed or damaged penetration subsystem.

3.5.3 Subcriticality Assurance Features

Subcriticality assurance features, are provided in casks used for the shipment of larger numbers of spent fuel assemblies. The spent fuel geometry control features and the neutron poisons can be subjected to transportation-accident-induced mechanical forces transmitted through the cask body. These features form an integral part of the overall cask structure internal to the containment shell. Significant damage to these features requires that significant damage be incurred by the total cask structure including the containment shell. Physical damage, taken alone however, does not affect the cask's subcriticality assurance function. A hydrogenous material, such as water, must surround the cask and be interspersed between the individual fuel rods and fuel assemblies before criticality can become a credible possibility.

For these reasons, the subcriticality features are not specifically modeled in the representative cask designs. Instead, a maximum estimate of the likelihood of a criticality incident is provided in Section 9.0. This estimate considers those transportation accident events in which the structural damage is sufficiently severe to cause gross fuel assembly damage. The estimate then evaluates the likelihood that such an event will involve the intimate presence of hydrogenous material in the accident scenario.

3.5.4 Damage-Mitigating Features

The principal damage-mitigating features provided in cask designs are the impact limiters. These devices are designed to be sacrificial and can be of two general types, hard and soft. In either case, they absorb some of the energy of impact by deforming. The ratio of the energy absorbed by the impact limiter to that transmitted to the cask depends on the accident severity and the type of impact limiter. The choice of an impact limiter is strongly affected by the choice of gamma shielding. If lead is the gamma shield material, soft impact limiters of balsa wood or rigid foam are typically used in cask designs. Soft impact limiters are designed to ensure that imposition of the accident test condition loads will not produce forces sufficient to cause lead slump.

Hard impact limiters in the form of bendable metal fins have been used in casks using depleted uranium as the gamma shield material. In these designs, the casks are more rigid. As a result, the forces transmitted through the cask body when the cask is subjected to the accident test conditions (specifically, the 30-foot cask drop onto an unyielding surface) are higher than those associated with casks using soft impact limiters. In either case, however, the cask design must meet the regulatory-defined post-test acceptance criteria.

A soft impact limiter is selected for the representative cask design for two major reasons. First, the soft impact limiter is consistent with the selection of the lead gamma shield. Second, and more significant, casks with soft impact limiters, if subjected to transportation accidents resulting in severe mechanical and thermal loads, will be more likely to incur damage.

3.5.5 Representative Cask Design Description

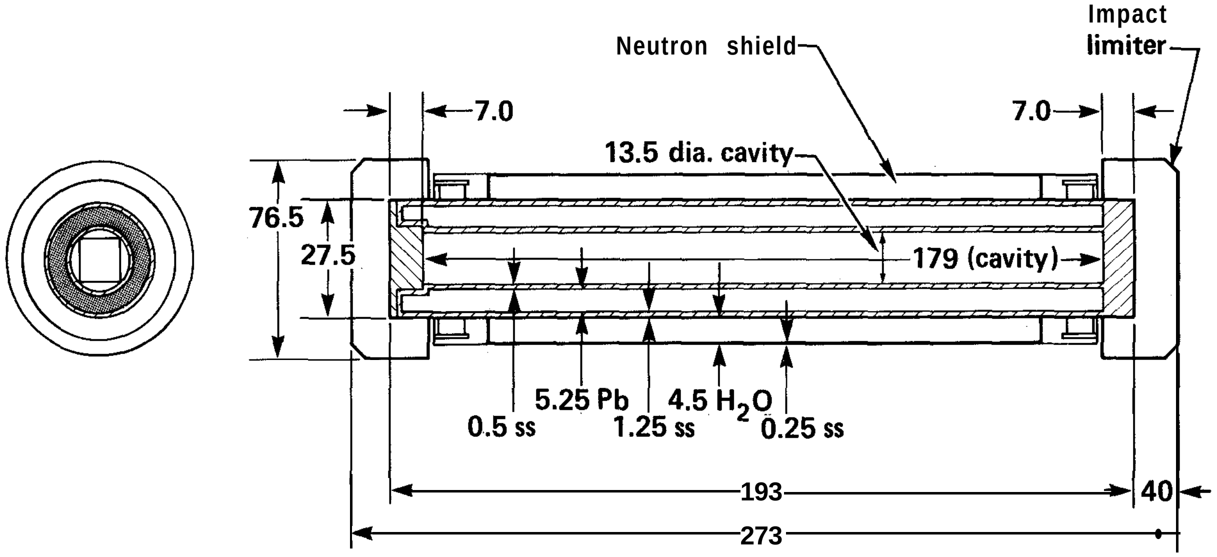
Two representative cask designs are developed: one for truck shipments and one for rail shipments of spent fuel. The representative truck cask design uses the same dimensions as the preliminary lead truck cask design (Fig. 3-4). The truck cask design allows transport of a single PWR fuel assembly. The representative rail cask design dimensions differ from the preliminary lead rail cask design (Fig., 3-5). The capacity of the rail cask is 21 PWR fuel assemblies which reflects the greater capacities of anticipated cask designs. Each design uses helium in the cask cavity.

Both designs include a lead gamma shield sized to meet current regulatory requirements. The truck cask gamma shield of 5.25 inches is thicker than the rail cask gamma shield of 4.00 inches to allow for the possibility of shipping fuel decayed less than 5 years by truck. The neutron shield dimensions reflect values typical of current cask designs. The cask shell structures, including the containment shell, are sized to support the lead shield. Specifically, the thickness of each cask steel shell is selected based on standard design practice; that is, the cask structure can withstand a force level typically generated from the accident test conditions. The resultant representative cask designs are indicative of current designs.[1-4]

The pertinent materials, weights, and dimensions of the representative truck and rail casks are shown in Figs. 3-6 and 3-7, respectively. The structural shell material is type 304 stainless steel. The lead shield is assumed to be unbonded to the steel shells. This fabrication assumption maximizes the potential for lead slump during transportation accidents involving impacts. Cask resistance to accident forces is thereby minimized, which introduces an element of conservatism to the results of this study. The impact limiters are made from balsa wood or rigid foam. Figure 3-8 shows the force deflection characteristics of the representative limiter design as a function of the presumed angle of impact between a cask and an impact surface. The impact limiter is sized to transmit a force of approximately 40 g if the cask is subjected to the impact environment specified by the accident test conditions.

3.6 Margins of Safety

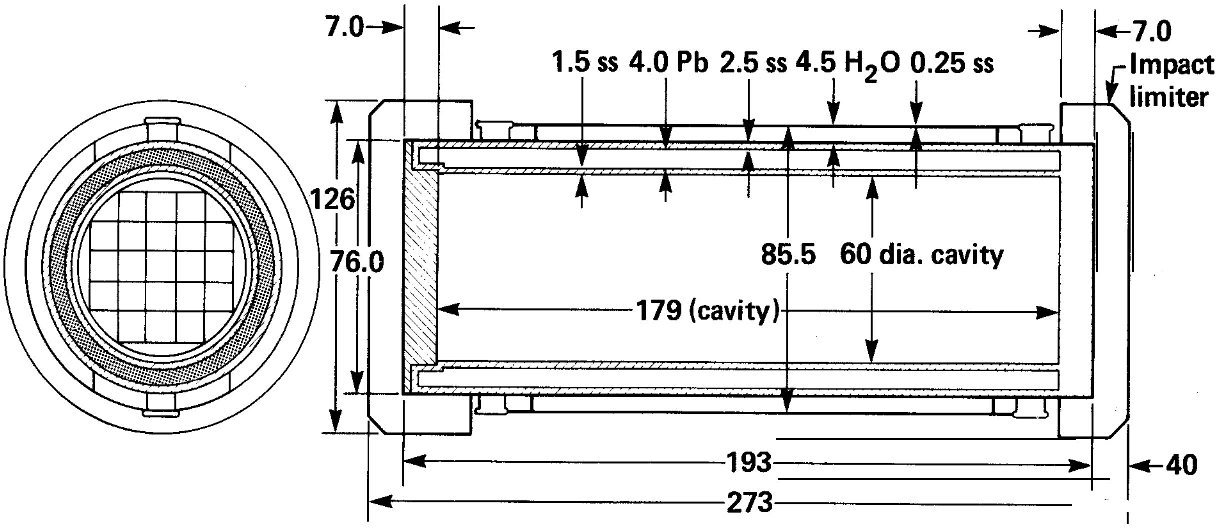
The representative casks are designed to meet the regulatory accident test conditions. However, before a cask is allowed to transport spent fuel, it must be certified by the U.S. Nuclear Regulatory Commission (NRC). The certification process requires that all activities related to the design, manufacture, use, and maintenance of the cask be documented in a Safety Analysis Report (SAR). The SAR is submitted to the NRC for review and approval. The analyses and evaluations in the SAR must demonstrate that the spent fuel cask meets all 10 CFR 71 requirements and has sufficient margins of safety included to protect the public from undue risk. In general, margins of safety are included by using established practices, codes, and standards such as the American Society of Mechanical Engineers (ASME) Code and the American



All dimensions in inches

Item	Weight, lbs
Body	32,000
Limiter	4,500
Contents	2,500
	39,000

Figure 3-6 Representative truck cask design used for dynamic structural and thermal response studies.



All dimensions in inches

Item	Weight, lbs
Body	122,500
Limiter	22,500
Contents	52,000
	197,000

Figure 3-7 Representative rail cask design used for dynamic structural and thermal response studies.

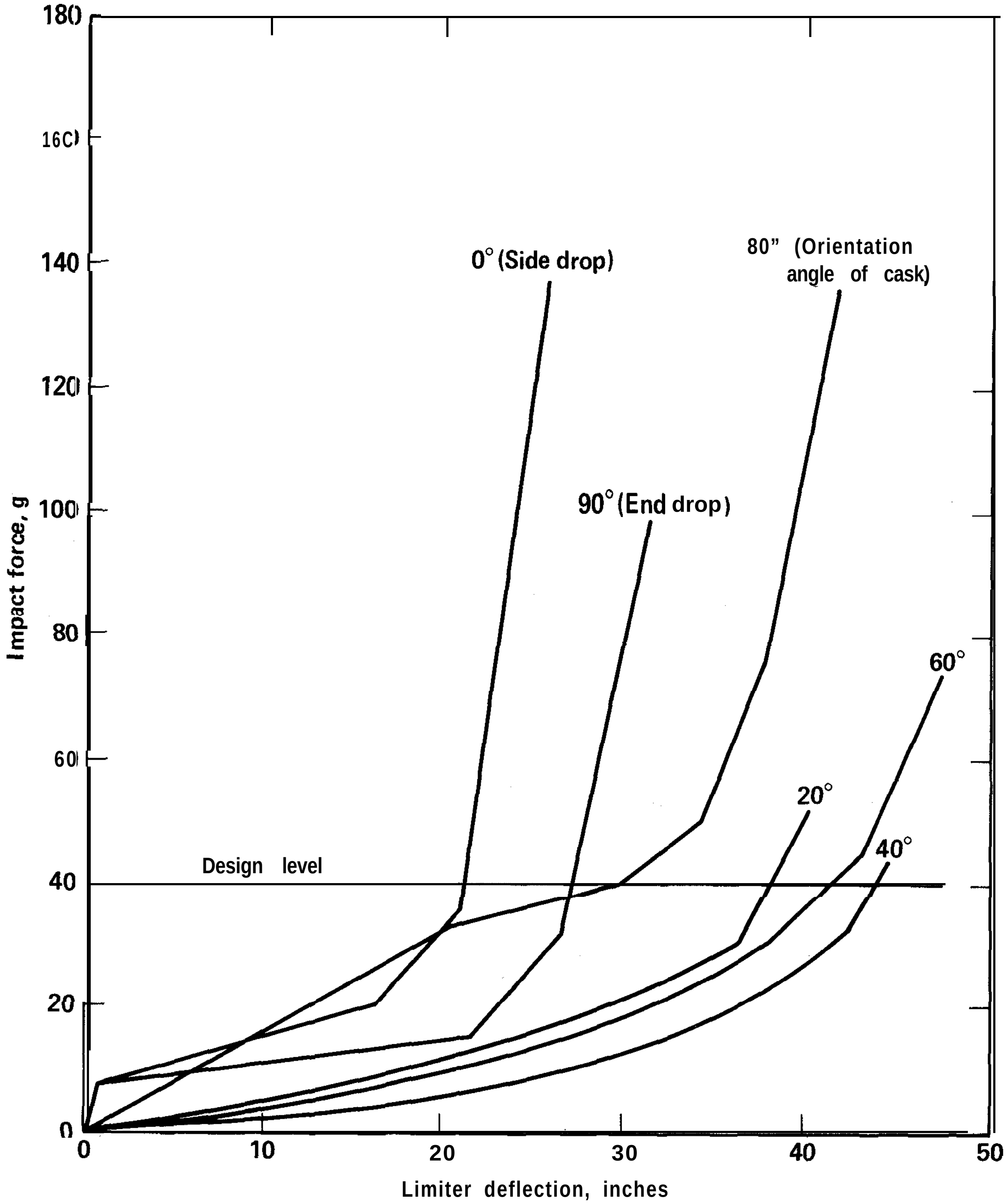


Figure 3-8 Force-deflection characteristics of the limiter design as a function of cask orientation at impact.

National Standards Institute (ANSI) Standards, and Regulatory Guides, all of which must be identified in the SAR.

Regulatory Guides are written by the NRC to provide guidance in many areas of licensing that result in acceptable margins of safety. For example, Regulatory Guide 7.6 adapts portions of the ASME Code, Section III to the design of spent fuel casks and recommends that elastic methods of structural analysis be used in the containment design.[6] Other Regulatory Guides relating to spent fuel casks are 7.4 (Leak Testing), 7.8 (Load Combinations), 7.9 (SAR Format), and 7.10 (Quality Assurance).[7-10]

Although there is no specific section in the ASME Code applicable to spent fuel casks, the ASME Code has been used extensively in designing, manufacturing, using, and maintaining spent fuel casks.[11] In general, materials adopted by the ASME Code provide a large margin of safety against rupture because the materials have high ductility. Also the use of elastic analysis for structural design usually results in a large margin of safety. For example, cask containments using 304 stainless steel are designed for the accident test conditions to ASME stress intensity limits that result only in slight yielding of the cask structure. In most cases, depending on the limiter design, the 304 stainless steel material can experience an off-set strain less than 1% under accident test conditions but rupture of 304 stainless steel occurs at strains greater than 30%. Therefore, large amounts of energy can be absorbed by the cask structure though large deformations under loading conditions exceeding the accident test conditions without catastrophic rupture occurring. To preclude brittle fracture failure from occurring at low temperatures, only materials with adequate toughness can be used in the structural design of spent fuel casks.[12,13,14]

In this study it is assumed that the representative casks have been properly designed and manufactured to appropriate codes and standards.[15,16] The representative cask designs are based on currently licensed cask designs and are likely to be certified if a SAR were prepared and submitted to the NRC. The margins of safety included in the cask design are representative of those included in currently licensed casks.

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4.0 REPRESENTATIVE CASK RESPONSE STATES, LEVELS, AND REGIONS

4.1 Introduction

If a shipping container is involved in an accident, a cask response is generated and damage can occur. The response depends on many elements, such as the magnitude of the loadings generated by the accident impact velocity, the object struck, and if a fire is involved, the flame temperature and the duration of the fire. The response can be different at different locations or by various components within a cask. Different cask designs can have different magnitudes and types of responses when subjected to the same accident conditions. The actual response is a result of the combined effect of all these factors. Normally, the higher the response, the greater the damage to the cask and, therefore, the greater the potential for an event with a radiological significance.

In order to determine the response, three methods are commonly used: analytical, experimental, and a combination of the two. In this study, the analytical method is used to estimate responses. Many different computer codes are used to perform the analyses. These computer codes, as pointed out throughout the report, are benchmarked against closed-form solutions and experimental data. Appendix H discusses benchmarking for some of these codes.

In order to calculate response by analysis, a proper selection of computer codes is essential. Every computer code has limitations. The proper selection of a code requires a thorough understanding of its limitations. Sections 6.0 and 7.0 discuss the method of analysis, including the assumptions used in the analysis and the modeling technique by which the cask structures are represented. Individual analyses and their results are also presented.

The purpose of estimating the response is to determine the degree of structural damage. Certain types of damage, such as damage at specific locations or to certain components within the cask structure, can result in radiological hazards. Other types of damage may appear to be large, but result in essentially no radiological hazards. In order to evaluate the consequences resulting from structural damage, it is necessary to relate the potential radiological hazard to the type of damage and cask response. Sections 4.2 and 4.3 qualitatively discuss the association between the structural and thermal damages and the potential radiation hazard. Section 8.0 provides a detailed discussion that relates the level of response to the level of potential radiological hazard.

Defining a specific response state is a very complex problem because response varies with different cask designs, severity of accidents, and location within the cask structure. In order to evaluate the level of damage between one response state and another, it is essential to establish some kind of measurement scale.

Response can be expressed in terms of many parameters, such as force, moment, displacement, stress, strain, and temperature. To establish a measuring scale with too many different types of response parameters will make any assessment unmanageable. The most effective approach is to identify one response parameter which provides both an adequate indication of cask structural damage and also an easy linkage to a radiological hazard estimate. This section discusses the selection of the parameters to represent the structural and thermal responses for the representative cask designs, the justification of the selections, and the discretized levels of response states used in this study.

4.2 Response States and Levels for Mechanical Loads

Various types of damage can occur to casks subjected to mechanical loads. The most important types of damage to a lead shielded cask are yielding, large dimensional changes, and rupture of the cask structure. Any parameter selected to represent the structural response state of the representative casks should indicate these types of structural damage.

Three engineering response parameters-- stress, strain, and displacement-- are considered as candidates for the single parameter to represent the response state for mechanical loads.

Stress is commonly used in structural analysis to represent the state of response. Both the American Society of Mechanical Engineers and the American

Institute of Steel Construction use stress as the parameter to define acceptance design limits in terms of yield and ultimate stress.[1,2] It is a good parameter for design within the elastic range of the material. When the response is beyond the elastic range, however, large dimensional changes can occur with only small changes in the stress level. The purpose of this study is to estimate the damage and consequence to the representative casks when subjected to severe accident conditions in which the response could exceed the elastic range. Therefore, stress is not the best parameter to represent the response state for mechanical loads applied to the representative casks.

Displacement is a parameter for measuring the dimensional change of structural elements. It is capable of describing the deformation shape for both small and large loading conditions. The deficiency in using displacement is that it cannot provide direct comparison with the design acceptance limits. Displacement cannot indicate directly when the structure has yielded or ruptured.

Strain is the most appropriate single parameter to represent the response state for mechanical loads. For a given material, dimensional changes occurring with loading conditions are directly related to strain. Strain can also indicate yielding and rupture when responses reach strain limits. Therefore, strain is selected for mechanical load responses of the representative casks.

Strain will most likely vary according to location within the structure. Under one specific accident load, strain at the inner shell is different from that at the outer shell, at the bolts, and at the enclosures. Sensitivity studies are conducted using the representative casks to find out the relationship between the strains at different locations or on different components inside the cask structure. This relationship helps to estimate the total cask damage level when strain at a particular component is identified. The strain on the inner shell of the cask structure is selected as the best single parameter to characterize mechanical load response states for the representative casks.

Although the response of a cask is continuous over a loading range, three discrete response levels are defined to relate ranges of response states and mechanical loads to potential radiological hazards. The response levels are defined as discrete levels of maximum effective strain on the inner shell of the representative cask structure. The maximum effective strain of the representative truck and rail cask impacting an unyielding surface can be significantly different as shown schematically in Fig. 4-1. The three discrete response levels or strain levels that bound the response state ranges are identified on the figure.

4.2.1 Structural Response Level, S_1

The first response level, S_1, is defined to be 0.2% strain at the inner shell. This level of strain is selected for the first response level because the structural material of the representative casks is 304 stainless steel which has a 0.2% offset yield point. For strains within the 0.2% yield strain (S_1), shown as range A in Fig. 4-1, the response of the structure is elastic and there is no permanent dimensional change after the loading is removed. This characteristic assures that little, if any, radiation release occurs when the cask is subjected to accident loads that are within range A because the seal and bolts remain functional. At 0.2% strain (S_1), the representative lead cask designs experience less than 40 g axial force on the lead for all orientations of impact. No lead slump occurs. The fuel basket remains functional. Up to 3% of the fuel rods can release limited amounts of radioactive material into the cask cavity under these loading conditions. Essentially all of the impact loads on the casks are absorbed by their impact limiters. These loads and releases are within the regulatory design conditions and release limits.

4.2.2 Structural Response Level, S_2

The second response level, S_2, is defined to be 2% plastic strain at the inner shell. For strains between 0.2% (S_1) and 2% (S_2), shown as range B in Fig. 4-1, the response of the structure is plastic, and small permanent dimensional changes occur. The dimensional changes can affect the cask

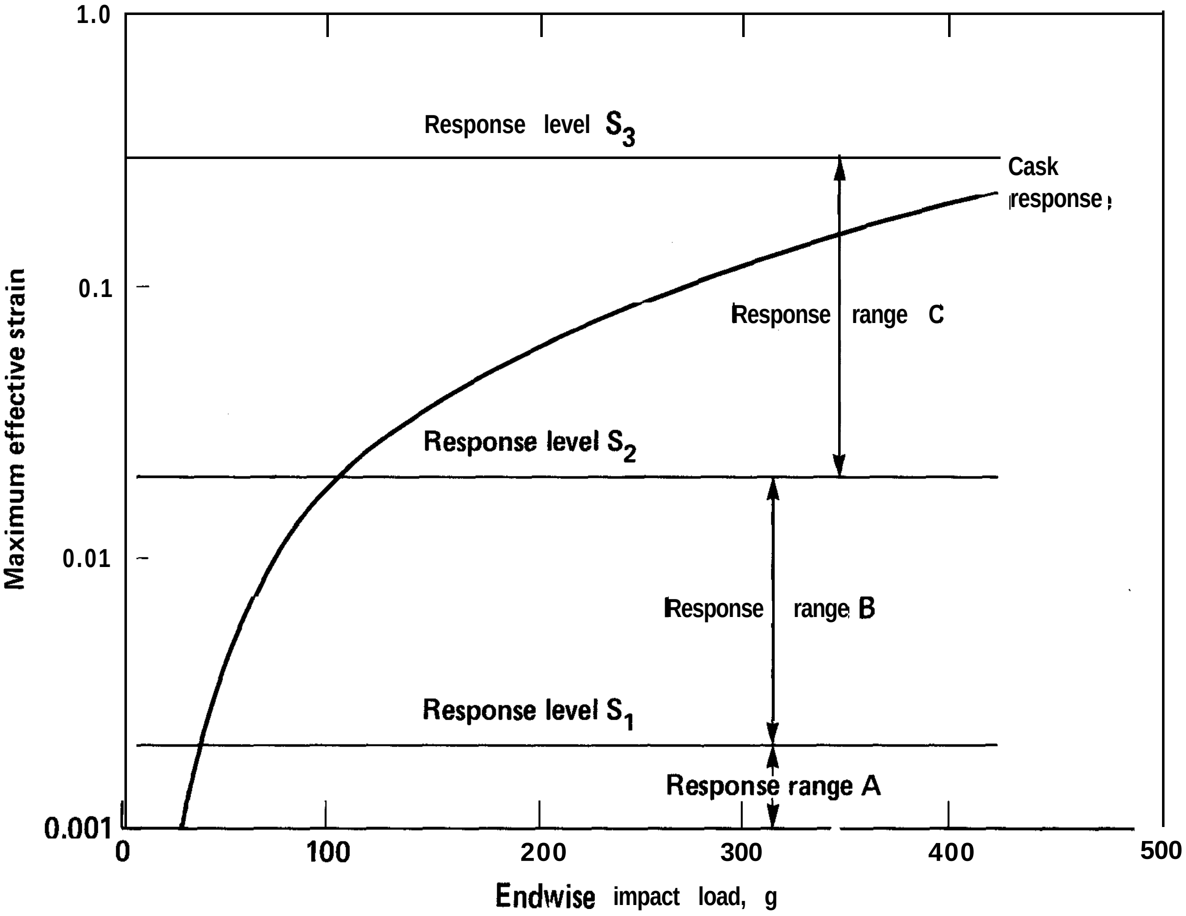

Figure 4-1 Schematic representation of cask response state for mechanical load.

closure seals and result in limited radioactive material releases. Also, a small dimensional change can result from limited lead slump which can result in an increase of radiation emanating from the cask. Up to 10% of the fuel rods can leak into the cask cavity under these loading conditions. The radiation hazards caused by seal leakage and lead slump in range B are near regulatory limits. The loads that produce the second response state are near the loads imposed by the accident test conditions. In this range, the impact loads on the representative casks are absorbed mostly by their impact limiters, but part of the loads are absorbed by the cask structure.

4.2.3 Structural Response Level, S3

The third response level, S_3, is defined to be 30% plastic strain at the inner shell. The 30% strain (S_3) level is below the fracture strain of 304 stainless steel, but the large distortions occurring with this strain level can cause local cracking in the welded regions. For strains between 2% (S_2) and 30% (S_3), shown as range C in Fig. 4-1, the response is plastic deformation with large dimensional changes occurring, particularly for strain near 30% (S_3). Any large distortions of the cask will likely cause seal leakage in the closure region, lead slump, localized weld cracking, and some crushing of the cask contents. All of the fuel rods are expected to release limited amounts of radioactive material into the cask cavity under these extreme loading conditions. The radiological hazards associated with this response can be outside of regulatory limits; however, there will not be any failure that will result in release of solids from fuel rods, except very small particles that may escape to the environment. In this response range, an increasing amount of the impact force is absorbed by the cask compared to the force absorbed by the limiter. In fact, at the 30% strain (S_3) level, the energy absorption by the representative casks may be eight times higher than the energy absorbed by the limiter.

4.2.4 Application of Response States and Levels

Each response state implies a force on the cask as a result of impacts upon various objects. The force is primarily determined by the impact velocity and the hardness of the object, but various combinations of velocity and object hardness can result in the same force. Consequently, the force associated with each structural response state can be related to various accident scenarios. Furthermore, the potential radiation hazard associated with these response states can be related to these same accident conditions.

Figure 4-2 shows schematically the structural response state of a representative cask in terms of strain as a function of both impact velocity and surface hardness-for endwise impacts. The combination of impact velocity and surface hardness for the strain levels 0.2% (S_1), 2% (S_2), and 30% (S_3) are also shown on the plot. For example, the impact velocities required to reach the 0.2% strain (SI) level, will be 30 mph for an unyielding object, 60 mph for an object of medium hardness, and 90 mph for a soft object. For very soft objects, the 0.2% strain (S_1) level can never be attained. Limiting the velocities impacting various objects can similarly be obtained corresponding to the 2% (S_2) and 30% (S_3) strain levels.

4.3 Response States and Levels for Thermal Loads

Various types of damage can occur to the representative casks subjected to thermal loads. The most important types of damage are degradation of the closure seal material, melting of the lead shield, dimensional changes to the structure, and alloying of the lead with the nickel in the 304 stainless steel structural material. Any parameter selected to represent the thermal response state of the cask should indicate the various types of thermal damage that can occur.

Two engineering response parameters, strain (thermally-induced) and temperature, are considered as candidates for the single parameter to represent the response state for thermal loads.

In Section 4.2, mechanical strain is selected as the single parameter to represent the response state for mechanical loads. Thermally induced strain provides a good indication of dimensional changes to the cask structure, but does not provide any indication of seal deterioration, melting of lead, or , alloying of lead with the nickel in stainless steel. Therefore strain is

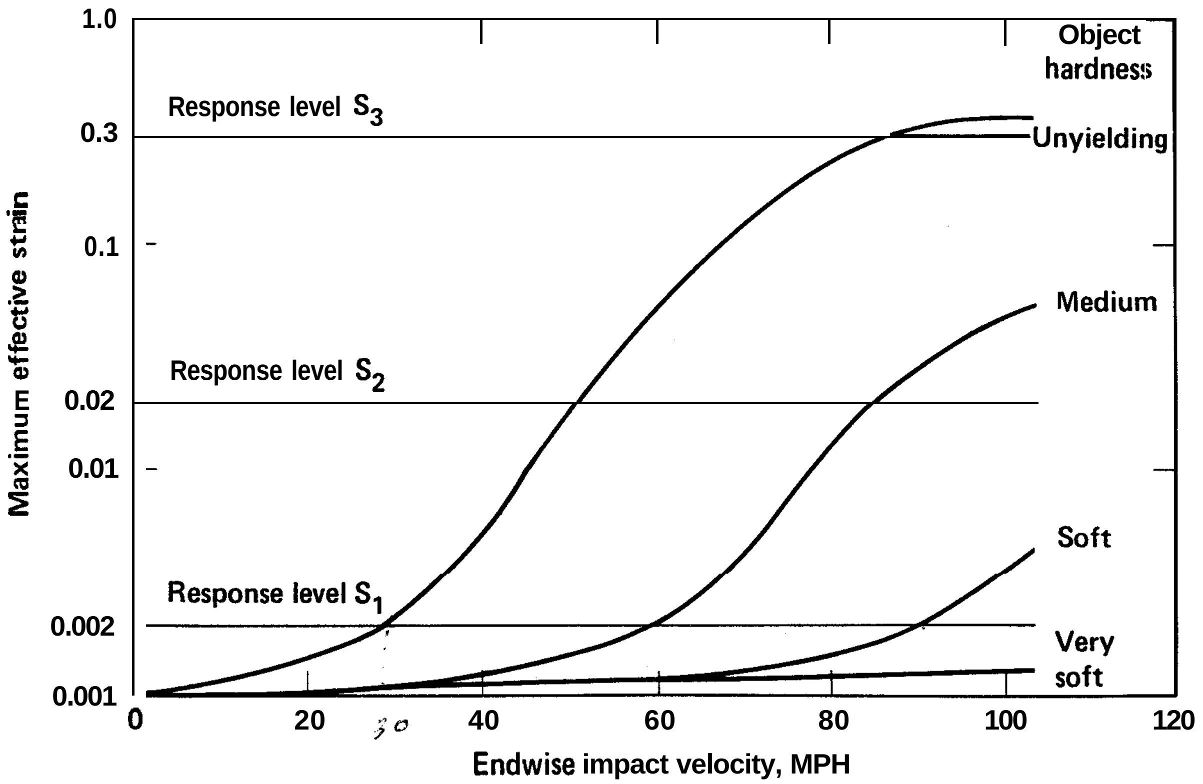

Figure 4-2 Schematic representation of cask structural response for various surface hardness and impact velocities.

determined not to be the best parameter to represent the response state for thermal loads.

Temperature is the best single parameter to represent the response state for thermal loads. Temperature provides an indication of seal deterioration, melting of lead, and alloying of lead with the nickel in stainless steel. It also provides an indirect measure of dimensional changes with lead melt. Therefore, temperature is selected for thermal load responses.

Temperature varies from location to location within the cask. For any specific fire-accident, the temperature at the inner shell is different from that at the outer shell, at the bolts, and at the enclosures. Sensitivity studies are conducted to find out the relationship between the temperatures at different locations and on different components inside the cask structure. This relationship provides a means to estimate the total cask damage level when the temperature at a particular component is identified. The temperature at the middle of the lead shield thickness is selected as the appropriate single parameter to characterize thermal load response states.

Although the response of a cask is continuous over a loading range, four discrete response levels are defined to relate ranges of response states and thermal loads to radiological hazard. The response levels are defined in terms of the temperature at the middle of the lead shield thickness. As an illustration of a cask exposed to a regulatory fire, Fig. 4-3 shows schematically the lead mid-thickness temperatures as a function of the thermal loads to the cask. The four discrete response levels, or lead mid-thickness temperatures, that bound the response state ranges are identified on the figure.

4.3.1 Thermal Response Level, T_1

The first response level, T_1, is defined as a temperature of 500°F at the middle of the lead shield thickness. This temperature is selected because the cask seals are below temperatures that can cause degradation of properties to such materials as silicon and fluorocarbons. Also, there is a significant margin between 500°F (T_1) and the melting point of lead at 621°F. For

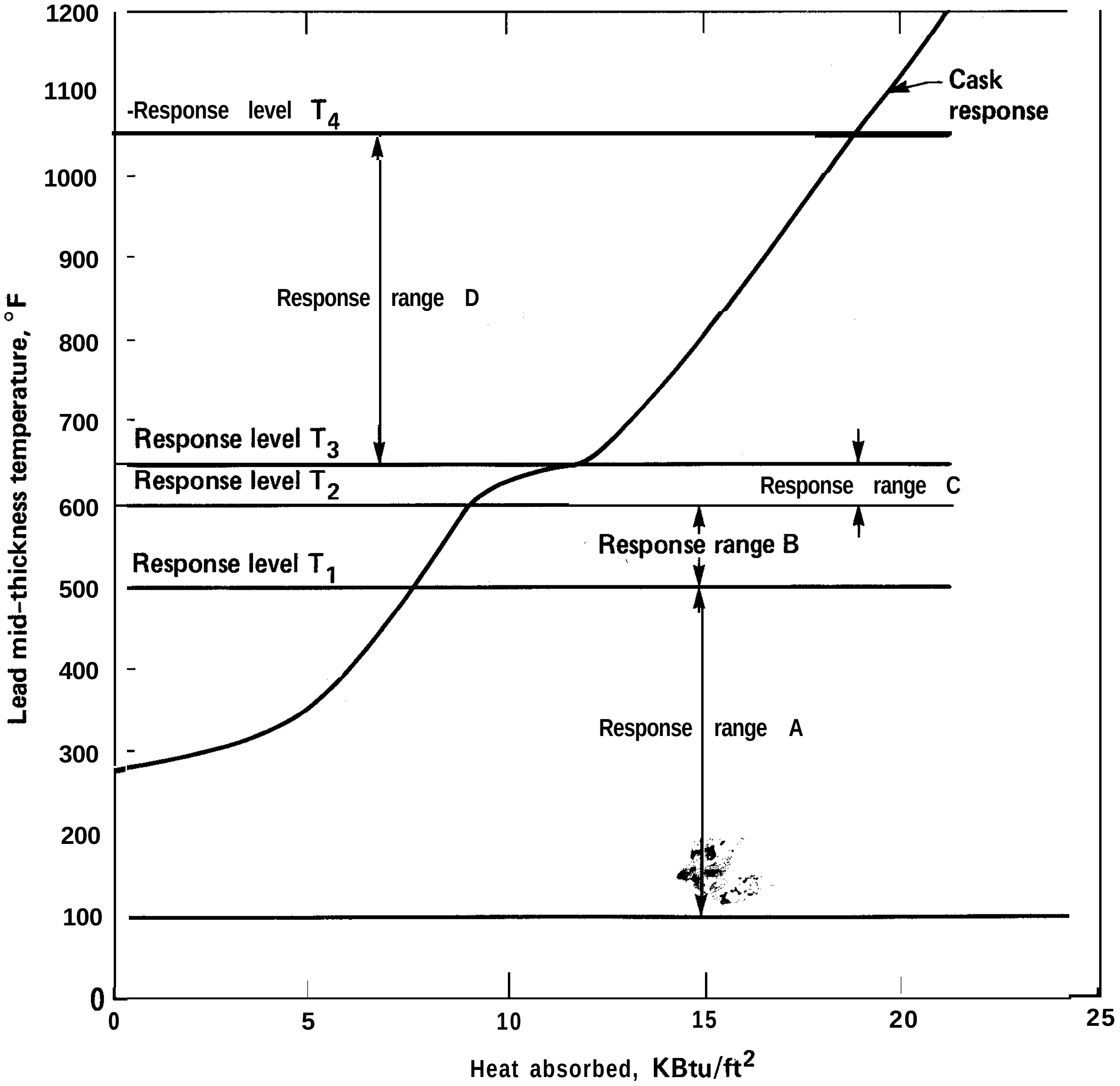

Figure 4-3 Schematic representation of cask response state for thermal load.

temperatures less than 500°F (T_1), shown as range A in Fig. 4-3, there is no significant damage to the cask due to thermal loads. However, it is assumed that the water in the neutron shield is released before the 500°F temperature (T_1) is reached. The release of the water forms a thermal barrier between the neutron shield wall and the cask outer wall which protects the cask from any fire. The release of the water also increases the neutron radiation surrounding the cask; however, all radiological hazards are within regulatory limits below this first level thermal response.

4.3.2 Thermal Response Level, T_2

The second response level, T_2, is defined as a temperature of 600°F at the middle of the lead shield thickness. Temperatures between 500°F (TI) and 600°F (T_2) are shown to be in range B in Fig. 4-3. In this temperature range, the lead at the outer stainless steel wall of the cask is still below 621°F, the melting point of lead. Even though the lead does not melt, the cask closure seals can degrade and potentially release limited radioactive material. Any radiological hazards caused by seal leakage and the loss of the neutron shield are likely to be within regulatory limits.

4 3.3 Thermal Response Level, T_3

The third response level, T_3, is defined as a lead mid-thickness temperature of 650°F. For temperatures between 600°F (T_2) and 650°F (T_3), shown as range C in Fig. 4-3, melting of the lead shield occurs. Lead melt results in a phase change with a lead density decrease of approximately 10%. The density change results in an increase in the lead volume and significant plastic straining of the inner cask wall. After the cask cools, the lead returns to its original density, and voids can occur in the lead shield owing to the increased volume from the plastic strain of the inner cask wall. The cask closure seals are assumed to leak. The increase in radiation level from the lead shield reduction and any radioactive material releases will likely be outside of regulatory limits.

4.3.4 Thermal Response Level, T_4

The fourth response level, T_4, is defined as a lead mid-thickness temperature of 1050°F. For temperatures in the range of 650°F (T_3) to 1050°F (T_4), shown as range D in Fig. 4-3, the lead shield thickness is reduced further due to differential thermal expansion between the liquid lead and stainless steel structural material. The fuel rods can also increase in temperature and begin to burst. For temperatures above 1050°F (T_4), the alloying of the lead with the nickel in the stainless steel structure can become significant and result in stress corrosion cracking.[3-5] In this response range, the further reduction in shielding and possible bursting of fuel rods increases the radiological hazards.

4.3.5 Application of Response States and Levels

Each response state implies a thermal load applied to the cask as a result of various fire conditions. The thermal load is determined by the fire characteristics. However, various fire characteristics can result in the same thermal load. Consequently, the thermal load associated with each thermal response state can be related to various accident conditions involving fires. Furthermore, the potential radioactive hazards associated with these response states can also be related to the same accident conditions.

Figure 4-4 schematically presents the thermal response of a cask in terms of the lead mid-thickness temperature as a function of both fire duration and fire location. The combination of fire duration and location for the temperature levels 500°F (T_1), 600°F (T_2), 650°F (T_3), and 1050°F (T_4) is also shown on the plot. For example, for a fire with a flame temperature of 1700°F, the time duration to reach the 500°F temperature (T_1) level, will be 1.3 hours for an engulfing fire, 2.3 hours for a fire tangent to the cask, and 3.6 hours for a fire 20 feet from the cask. For fires greater than 50 feet away, the 500°F temperature (TI) level can never be attained. Fire durations for the various fire locations can similarly be estimated corresponding to the 600°F (T_2), 650°F (T_3), and 1050°F (T_4) temperature levels.

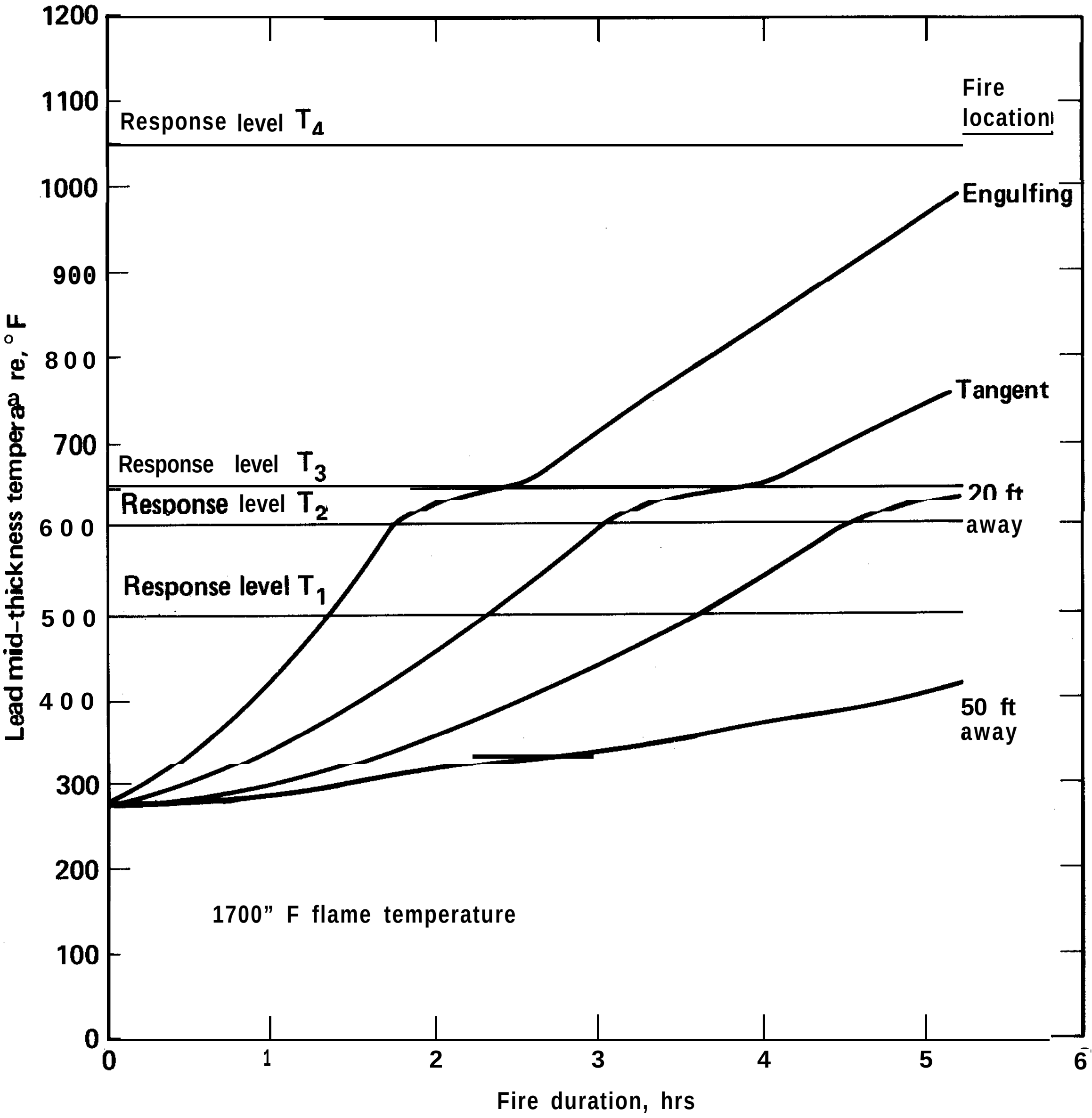

Figure 4-4 Schematic representation of cask response for various fire locations and fire durations.

4.4 Cask Response Regions

In some cases, a cask will be exposed to both mechanical and thermal loads. A range of combined structural and thermal responses for a cask can be represented by the response matrix shown in Fig. 4-5. The ordinate of the response matrix represents the structural response states; the abscissa represents the thermal response states; and the boundaries of the response regions are defined by the structural and thermal response levels.

There are 20 response regions denoted by $R(S_i,T_j)$ where Si is the structural response level and T_j is the thermal response level. Although only three discrete structural response levels are defined, a fourth unbounded level exists that consists of cask strain responses greater than 30% (S_3). Similarly, a fifth unbounded thermal response level exists which consists of cask temperature responses greater than 1050^oF (T_4). The first region, R(1,1), represents the cask response to combined mechanical and thermal loads within the 0.2% strain (S_1) and 500^oF temperature (TI) levels. Radioactive releases, if any, for cask responses in R(1,1) will be within regulatory limits. The twentieth region, R(4,5), represents the most extreme combined response state in which the potential radiological hazards will be a maximum. In general, the probability of occurrence of a particular combination of mechanical and thermal loadings decreases with the severity of these loads. The probabilities associated with each region of the load matrix are discussed in more detail in Section 5.0.

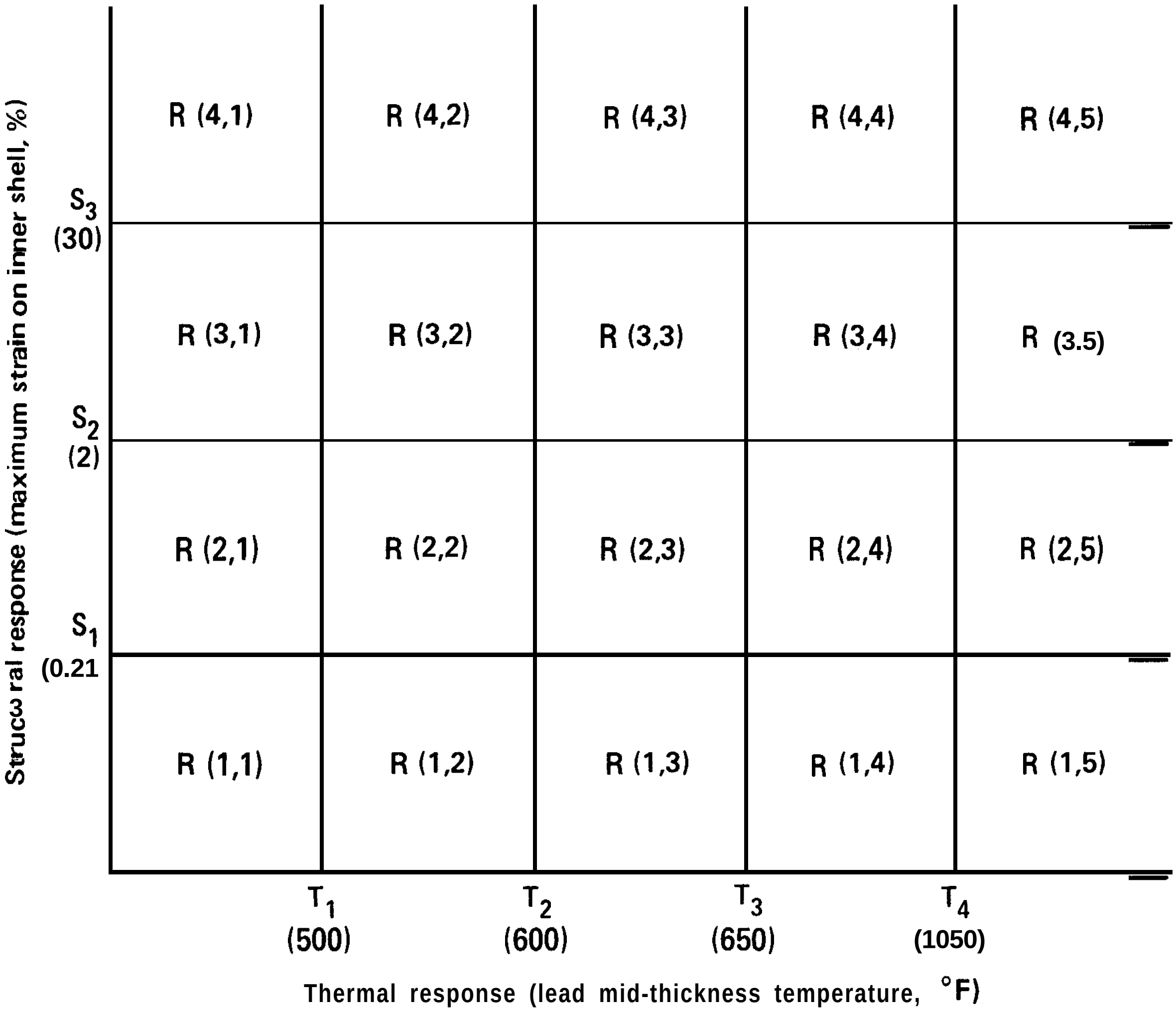

Figure 4-5 Matrix of cask response regions for combined mechanical and thermal loads.

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5.0 PROBABILITY ANALYSIS

5.1 Introduction

The emphasis of the discussion in Sections 6.0 and 7.0 is on the physical loads, both mechanical and thermal, which a spent fuel cask can experience in a transportation accident. Specifically, cask response states, evaluated in terms of containment vessel strains and lead shield temperatures, are related to basic accident parameters such as impact velocities and fire duration.

The relationships between cask responses to mechanical loads and the impact velocity of the cask are derived for several cask impact orientations involving interactions with objects of differing hardness. The effect of cask orientation on the strain-impact velocity relationship for an unyielding object is shown in Fig. 5-1 for the truck cask. The impact velocity, defined as the cask velocity in the direction perpendicular to the object impacted, is determined by the velocity of the cask due to the accident and the impact angle.

The thermal loading to a cask depends on the flame temperature and fire location as well as the duration of a fire. Thus, the relationship between cask response to thermal loads and the duration of a fire is affected by the flame temperature and location of the fire with respect to the cask. The effects of these parameters are illustrated in Fig. 5-2.

In summary, the following accident parameters, which affect the cask response to mechanical and thermal loads, are identified and are considered in the probability analysis:

- Mechanical loads
    - impact velocity
        - cask velocity
        - impact angle
    - cask orientation
    - hardness of the impacted object

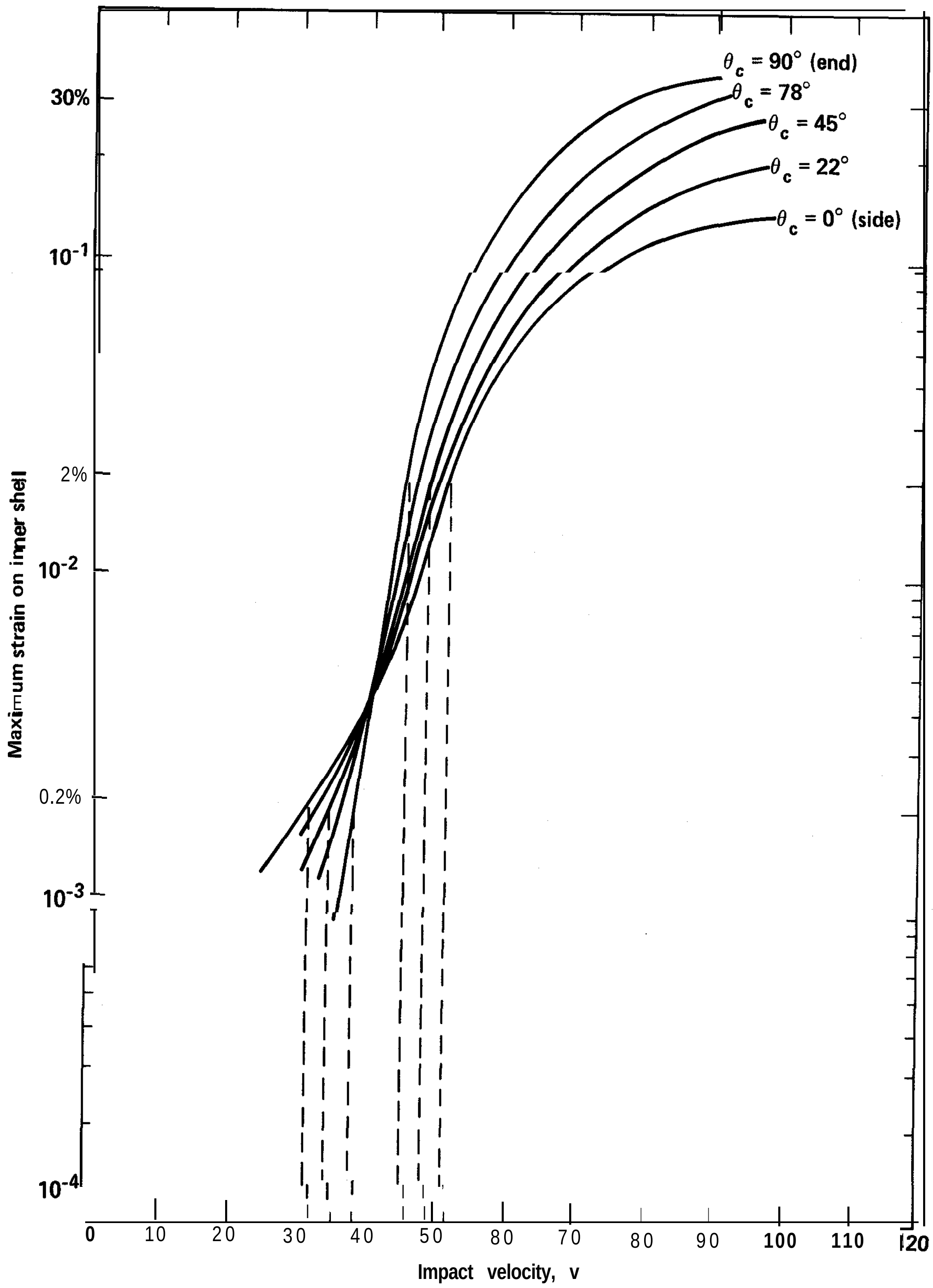


Figure 5-1 Effect of cask orientation on the strain-impact velocity relationship for a truck cask impacting an unyielding object.

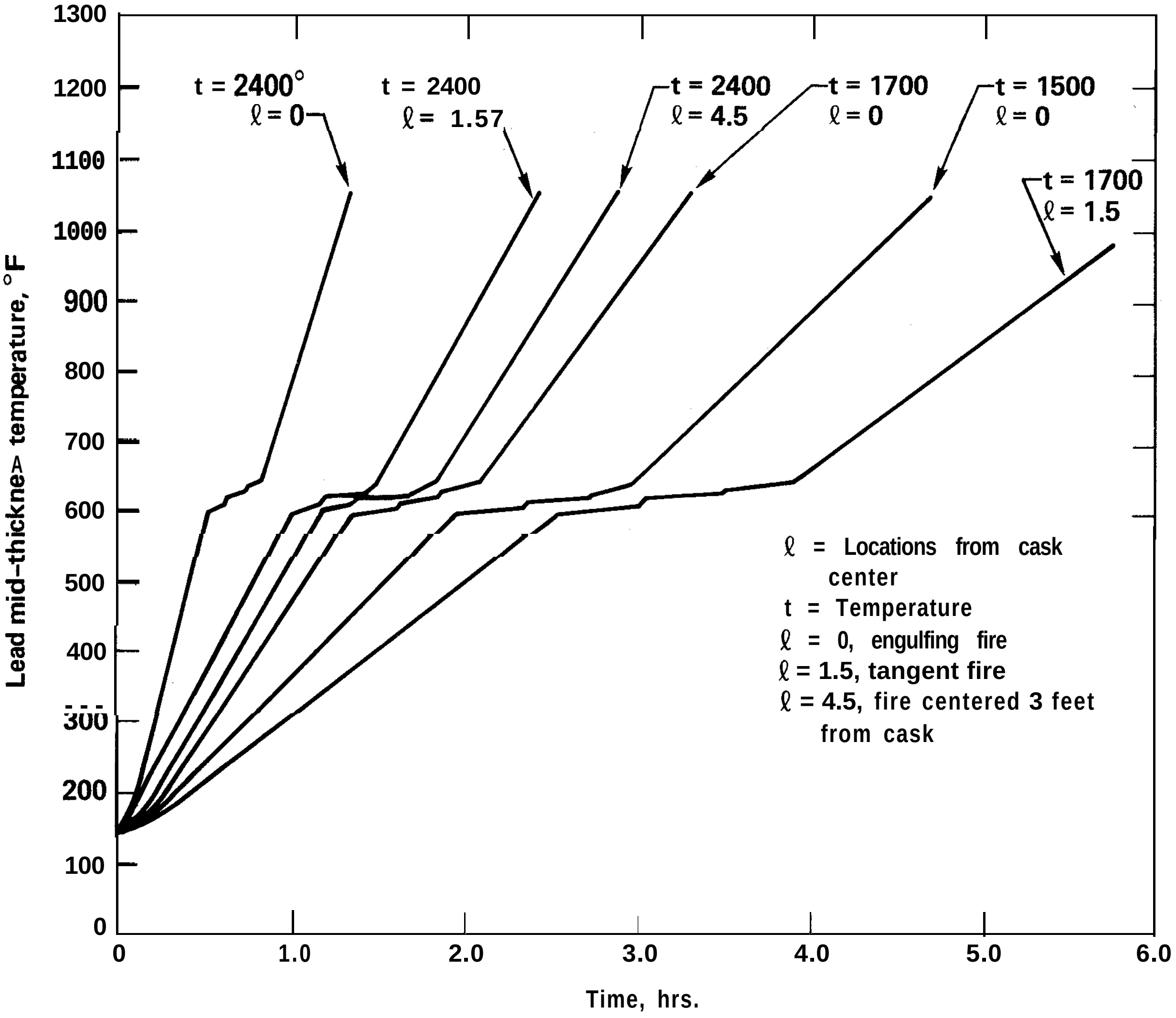


Figure 5-2 Effect of flame temperature and fire location on lead-temperature-time relationship for a truck cask.

- Thermal loads
  - fire duration
  - flame temperature
  - fire location with respect to the cask.

Because future accident conditions are unpredictable, i.e., random, the response state of a spent fuel cask cannot be predicted deterministically. Assessment of the response states and the subsequent damage and release of radioactive materials due to transportation accidents can only be expressed probabilistically.

The purpose of this section is to describe the probability analysis developed to estimate the likelihood that a spent fuel cask will attain various response states during a transportation accident. Section 5.2 catalogs the probability distributions used to describe the random variation associated with the accident parameters. The probability calculations are outlined in Section 5.3.

5.2 Probabilistic Inputs

Estimation of the likelihood of various cask response states, represented by the containment vessel strain and the lead mid-thickness temperature, is based on estimates of the distributions of the accident parameters which affect the response of the cask during a transportation accident. The distributions of the accident parameters are described in terms of a cumulative distribution function, F(x), if the parameter is quantitative, or a probability function, h(8), if the parameter is qualitative, e.g., the object impacted. The cumulative distribution function describes the likelihood that the parameter value is less than or equal to x, the argument of F(.), i.e.,

$$F(x) = P_r(X \leq x) \tag{5.1}$$

where X denotes the accident parameter. The probability function describes the likelihood of each θ or object, i.e.,

$$h(\Theta) = P_r(\Theta) \tag{5.2}$$

where θ denotes the qualitative object.

The distributions of the accident parameters used to estimate the likelihood of cask response states are presented in this section. Development of these distributions was discussed in Section 2.0. The data used to estimate accident rates and velocity distributions is summarized in Appendixes B and C. The method of estimation is discussed in Appendix G.

5.2.1 Mechanical Loading Parameter Distributions

Object hardness, impact velocity, and cask orientation are three mechanical loading parameters which have a significant influence on a cask's structural response in a transportation accident.

5.2.1.1 Object Hardness Distributions

Each of the accident scenarios, described in Section 2.0 and shown in Figs. 2-3, 2-4, and 2-5, identifies a type of accident, e.g., a collision, and the object or surface which a cask could impact, e.g., a truck, bridge abutment, or embankment. From these descriptions, object hardness is estimated. Thus, the distribution of hardness of the impacted object is described in terms of the probabilities of the accident scenarios. These are included in Figs. 2-3, 2-4 and 2-5 for highway and railway accidents.

5.2.1.2 Impact Velocity Distributions

5.2.1.2.1 Cask Velocity

The distribution of cask velocity during a transportation accident varies between accident scenarios. For example, the distribution of cask velocity experienced in truck-truck collisions is expected to differ from the distribution associated with accidents involving falls from bridges. In truck-truck accidents, the distribution depends on the speeds of the individual trucks at the time of the collision. For accidents involving falls from bridges, the cask impact velocity is determined by the fall height.

The following distributions of cask velocities are applicable to highway accidents:

V1: The truck velocity, adjusted for braking, prior to an accident
V2: The velocity due to bridge heights
V3: The vector sum of truck velocity, adjusted for braking, and velocity due to bridge heights
V4: The train velocities at grade crossing accidents.

As discussed in Subsection 2.5.1.2.1, the primary source of truck velocities is based on accident reports that estimate velocities prior to an accident. The observed data does not account for any reduction in velocity at impact due to braking efforts by the drivers. However, a North Carolina study provides data which allow for braking effects.' These results are used to adjust the basic cumulative distribution function of truck velocities as shown in Fig. 5-3. The adjustment is based on the identity

$$F_{V1}(s) = F\&s/S(s)] \tag{5.3}$$

where

$$6(s) = \begin{cases} 0.65 + \frac{0.35}{78} s & 0 \leq s \leq 78 \\ 1.0 & s \geq 78 \end{cases} \tag{5.4}$$

and $F_{V1}(.)$ and $F_I(.)$ denote the adjusted and initial truck velocity cumulative distribution functions, respectively. At velocities greater than 78 mph no credit for braking is assumed. As velocity decreased, the effect of braking increased, e.g., a 40 mph velocity is reduced to 33 mph, whereas a 10 mph velocity is reduced to 7 mph.

The four cumulative distribution functions used for the velocity of highway accidents are presented in Table 5.1. They are estimated from historical accident data using the method of estimation described in Appendix G.

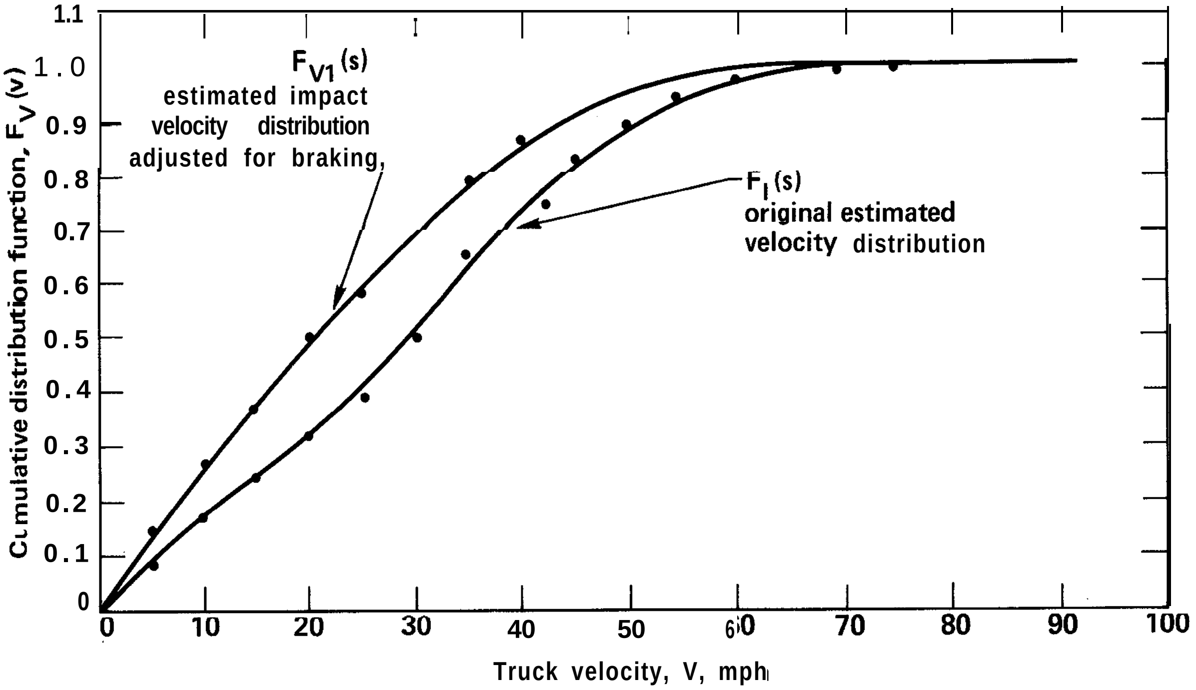


Figure 5-3 Distribution of vehicle velocities adjusted for braking.

Table 5.1
Cumulative Cask Velocity Distributions for Highway Analysis

Distributions							
V1		V2		V3		V4	
Cask Velocity,s (mph)	$F_S(s)$	Cask Velocity,s (mph)	$F_S(s)$	Cask Velocity,s (mph)	$F_S(s)$	Cask Velocity,s (mph)	$F_S(s)$
0.	0.	0.	0.	0.	0.	0.	0.
2.0	0.03834	7.74	0.00621	5.0	0.	2.0	0.06014
6.0	0.12916	10.94	0.01550	10.0	0.00141	6.0	0.17906
10.0	0.23508	15.48	0.04754	15.0	0.00821	10.0	0.29398
14.0	0.34886	18.95	0.1051	20.0	0.03387	14.0	0.40255
18.0	0.46237	21.89	0.1952	25.0	0.11129	18.0	0.50280
22.0	0.56877	24.47	0.3178	30.0	0.28292	22.0	0.59331
26.0	0.66345	26.81	0.4629	35.0	0.51279	26.0	0.67319
30.0	0.74353	28.95	0.6124	40.0	0.70110	30.0	0.74210
34.0	0.80877	30.95	0.7464	45.0	0.81951	34.0	0.80022
38.0	0.86020	32.83	0.8508	50.0	0.89168	38.0	0.84814
42.0	0.89961	34.61	0.9217	55.0	0.93543	42.0	0.88676
46.0	0.92881	36.29	0.9635	60.0	0.96178	46.0	0.91718
50.0	0.95009	37.91	0.9849	65.0	0.97751	50.0	0.94062
54.0	0.96547	39.46	0.9945	70.0	0.98680	54.0	0.95826
58.0	0.97634	41.67	0.9991	75.0	0.99227	58.0	0.97125
62.0	0.98383	43.08	0.9998	80.0	0.99547	62.0	0.98060
66.0	0.98908	44.45	0.9999	85.0	0.99766	66.0	0.98717
70.0	0.99261	56.86	1.0	90.0	0.99901	70.0	0.99169
74.0	0.99503			95.0	0.99961	74.0	0.99473
78.0	0.99670			100.0	0.99985	78.0	0.99672
82.0	0.99825			105.0	0.99995	82.0	0.99800
86.0	0.99910			110.0	0.99998	86.0	0.99881
90.0	0.99956			115.0	0.99999	90.0	0.99930
94.0	0.99979			150.0	1.0	94.0	0.99960
98.0	0.99990					98.0	0.99977
102.0	0.99995					102.0	0.99987
106.0	0.99998					106.0	0.99993
110.0	0.99999					110.0	0.99996
150.0	1.0					114.0	0.99998
						118.0	0.99999
						150.0	1.0

$F_S(s)$ = Probability that cask velocity is less than or equal to cask velocity listed.

V1: The truck velocity, adjusted for braking, prior to an accident

V2: The velocity due to bridge heights

V3: The vector sum of truck velocity adjusted for braking and velocity due to bridge heights

V4: The train velocities at grade crossing accidents

The following distributions of cask velocities are considered applicable to railway accidents:

TV1: The train velocities in collision accidents without braking

TV2: The train velocities in derailment accidents without braking

TV3: The velocities due to bridge heights

TV4: The vector sum of train velocities in derailment accidents and velocities due to bridge heights.

The cumulative distribution functions are presented in Table 5.2.

5.2.1.2.2 Impact Angle

The damage resulting from an accident is not controlled solely by the cask velocity at impact. A head-on impact is more severe then a sideswiping accident, even though both accidents can involve similar velocities. The reason is that accident severity is most directly related to the impact velocity, the component of the cask velocity vector perpendicular to the object impacted. The orientation of the cask motion, relative to the surface of the object impacted is called the impact angle, a. A 90^o impact angle defines a head-on impact, i.e., the impact velocity and cask velocity at impact are the same. An impact angle close to 0^o defines a sideswiping impact. In this case the impact velocity is a small fraction of the cask velocity. Mathematically, the impact velocity is the cask velocity times sine a.

As for cask velocities, the distribution of impact angle can depend on the accident scenario. For example, if the accident involves a collision with another vehicle on the highway, any impact angle is likely. Three impact angle distributions are used:

VV1: Uniform $(0^o,90^o)$ - any impact angle is equally likely

$$F(x) = x/90 \qquad 0^o \leq x \leq 90^o \qquad (5.5)$$

Table 5.2
Cumulative Cask Velocity Distributions for Railway Analysis

Distributions							
TV1		TV2		TV3		TV4	
Cask-Velocity,s (mph)	$F_S(s)$	Cask-Velocity,s (mph)	$F_S(s)$	Cask-Velocity,s (mph)	$F_S(s)$	Cask-Velocity,s (mph)	$F_S(s)$
0.	0.	0.	0.	0.	0.	0.	0.
2.0	0.09385	2.0	0.07543	7.74	0.00621	5.0	0.
6.0	0.26286	6.0	0.22036	10.94	0.01550	10.0	0.00232
10.0	0.40788	10.0	0.35480	15.48	0.04754	15.0	0.01244
14.0	0.53042	14:0	0.47634	18.95	0.1051	20.0	0.04814
18.0	0.63240	18.0	0.58341	21.89	0.1952	25.0	0.14919
22.0	0.71598	22.0	0.67534	24.47	0.3178	30.0	0.35837
26.0	0.78345	26.0	0.75225	26.81	0.4629	35.0	0.60624
30.0	0.83709	30.0	0.81495	28.95	0.6124	40.0	0.77834
34.0	0.87908	34.0	0.86477	30.95	0.7464	45.0	0.87230
38.0	0.91147	38.0	0.90385	32.83	0.8508	50.0	0.92649
42.0	0.93606	42.0	0.93246	34.61	0.9217	55.0	0.95855
46.0	0.95446	46.0	0.95386	36.29	0.9635	60.0	0.97727
50.0	0.96801	50.0	0.96920	37.91	0.9849	65.0	0.98792
54.0	0.97784	54.0	0.97991	39.46	0.9945	70.0	0.99379
58.0	0.98486	58.0	0.98720	41.67	0.9991	75.0	0.99692
62.0	0.98980	62.0	0.99204	43.08	0.9998	80.0	0.99852
66.0	0.99323	66.0	0.99516	44.45	0.9999	85.0	0.99932
70.0	0.99557	70.0	0.99713	56.86	1.0	90.0	0.99970
74.0	0.99714	74.0	0.99834			95.0	0.99987
78.0	0.99818	78.0	0.99906			00.0	0.99995
82.0	0.99886	82.0	0.99948			105.0	0.99998
86.0	0.99929	86.0	0.99972			110.0	0.99999
90.0	0.99957	90.0	0.99985			150.0	1.0
94.0	0.99974	94.0	0.99992				
98.0	0.99985	98.0	0.99996				
102.0	0.99991	102.0	0.99998				
106.0	0.99995	106.0	0.99999				
110.0	0.99997	150.0	1.0				
114.0	0.99998						
118.0	0.99999						
150.0	1.0						

$F_S(s)$ = Probability that cask velocity is less than or equal to cask velocity listed.

TV1: The train velocities in collision accidents without braking

TV2: The train velocities in derailment accidents without braking

TV3: The velocities due to bridge heights

TV4: The vector sum of train velocities in derailment accidents and velocities due to bridge heights

VV2: **Degenerate** (90°) - **impact is head-on only**

$$F(x) = \begin{cases} 0 & x < 90^{\circ} \\ 1 & x = 90^{\circ} \end{cases} \qquad (5.6)$$

VV3: Triangular $(0^{\circ},90^{\circ})$ - **head-on impact is most likely**

$$F(x) = x^2/90^2 \qquad 0^{\circ} \leq x\ 6\ 90^{\circ} \qquad (5.7)$$

The cumulative distribution functions are presented in Table 5.3.

5.2.1.3 Cask Orientation Distributions

The orientation of the cask with respect to the object impacted is called the orientation angle, β. It affects the severity of the cask response to mechanical loads. As described in Subsection 2.5.1.3 for impacts on surfaces, a 0° cask orientation defines a sidewise impact while a 90° cask orientation indicates impact of the cask on its end. Alternatively for impacts by train sills, a 0° cask orientation defines a head-on impact to the cask side while a 90° cask orientation indicates a near miss. Again, the cask orientation distribution can depend on the accident scenario, thus three distributions are used:

CT1: **Uniform** $(0^{\circ},90^{\circ})$ - **all cask orientation angles equally likely**

$$F(x) = x/90 \qquad 0^{\circ} \leq x \leq 90^{\circ} \qquad (5.8)$$

CT2: Triangular $(0^{\circ},90^{\circ})$ **- end orientation impact on surfaces or head-on impact to side of cask by train is most likely**

$$F(x) = x^2/90^2 \qquad 0^{\circ} \leq x \leq 90^{\circ} \qquad (5.9)$$

Table 5.3
Cumulative Impact Angle Distributions

Impact Angle, α (°)	Distributions VV1 $F_A(\alpha)$	 VV2 $F_A(\alpha)$	 vv3 $F_A(\alpha)$
0.	0.	0.	0.
5.0	0.05556	0.	0.00309
10.0	0.11111	0.	0.01235
15.0	0.16667	0.	0.02778
20.0	0.22222	0.	0.04938
25.0	0.27778	0.	0.07716
30.0	0.33333	0.	0.11111
35.0	0.38889	0.	0.15123
40.0	0.44444		0.19753
45.0	0.50000	8:	0.25000
50.0	0.55556	0.	0.30864
55.0	0.61111	0.	0.37346
60.0	0.66667	0.	0.44444
65.0	0.72222	0.	0.52160
70.0	0.77778	0.	0.60494
75.0	0.83333	0.	0.69444
80.0	0.88889	0.	0.79012
85.0	0.94444	0.	0.89198
90.0	1.0	1.0	1.0

$F_A(\alpha)$ = Probability that impact angle is less than or equal to impact angle stated in left-hand column.

VV1: Uniform (0°,90°) - any impact angle is equally likely

VV2: Degenerate (90°) - impact is head-on only

vv3: Triangular (0°,90°) - head-on impact is most likely

CT3: Triangular $(0^o, 90^o)$ - 45^o orientation impact on surface or 45^o impact on side of cask by train is most likely

$$F(x) = \begin{cases} x^2/2(45)^2 & 0^o \leq x \leq 45^o \\ 1-[(90-x)^2/2(45)^2] & 45^o \leq x \leq 90^o \end{cases} \qquad (5.10)$$

The cumulative distribution functions are presented in Table 5.4.

5.2.2 Thermal Loading Parameter Distributions

The thermal response of a cask, represented by the temperature reached at the middle of the lead shield thickness, is determined by three major thermal loading parameters: fire duration, flame temperature, and fire location with respect to the cask.

5.2.2.1 Fire Duration Distributions

The duration of a fire occurring during a transportation accident depends on a number of factors including

- the amount and type of fuel, combustibles, and other volatile materials available
- the availability and feasibility of fire fighting support.

The first factor is influenced by the type of accident. For example, a single truck accident is likely to involve a different fire environment than a truck-truck or truck-auto collision. Similarly, a truck hitting a bridge abutment is likely to cause a different type of fire than a truck jackknifing or overturning along the roadbed. To accommodate these possibilities, several fire duration distributions are considered in the analysis of both highway and railway accident fires. These distributions are generated using the simulation code developed at Sandia[2].

Table 5.4
Cumulative Cask Orientation Angle Distributions

Cask Orientation Angle, β (°)	Distributions CT1 $\overline{F_B(\beta)}$	 CT2 $\overline{F_B(\beta)}$	 CT3 $\overline{F_B(\beta)}$
0.	0.	0.	0.
5.0	0.05556	0.00309	0.00617
10.0	0.11111	0.01235	0.02469
15.0	0.16667	0.02778	0.05556
20.0	0.22222	0.04938	0.09877
25.0	0.27778	0.07716	0.15432
30.0	0.33333	0.11111	0.22222
35.0	0.38889	0.15123	0.30246
40.0	0.44444	0.19753	0.39506
45.0	0.50000	0.25000	0.50000
50.0	0.55556	0.30864	0.60494
55.0	0.61111	0.37346	0.69753
60.0	0.66667	0.44444	0.77778
65.0	0.72222	0.52160	0.84568
70.0	0.77778	0.60494	0.90123
75.0	0.83333	0.69444	0.94444
80.0	0.88889	0.79012	0.97531
85.0	0.94444	0.89198	0.99383
90.0	1.0	1.0	1.0

$F_B(\beta)$ = = Probability that cask orientation angle is less than or equal to cask orientation angle stated in left-hand column.

CT1: Uniform $(0^\circ, 90^\circ)$ - all cask orientation angles equally likely

CT2: Triangular $(0^\circ, 90^\circ)$ - end orientation impact is most likely

CT3: Triangular $(0^\circ, 90^\circ)$ - 45° orientation impact is most likely

The following fire duration distributions are used in the analysis of highway accident fires:

F1: Non-collision accident fires
F2: Off-road (or collision with fixed objects) accident fires
F3: Truck/truck collision accident fires
F4: Truck/automobile collision accident fires
F5: Truck/train collision accident fires.

These distributions are presented in Table 5.5. The distributions for accidents involving a truck colliding with a fixed object and a truck running off the highway are simulated separately but result in the same output.

The following train fire duration distributions are presented in Table 5.6 for analyzing railway accident fires:

TF1: Collision accident fires
TF2: Derailment accident fires
TF3: Other accident fires.

5.2.2.2 Flame Temperature Distributions

Flame temperature and fire duration are often correlated. Highly volatile and chemically reactive substances exhibit high reaction rates and high intensity (temperature), while substances with low reaction rates are consumed slowly and exhibit low intensity. However, information about the joint probability distribution of temperature and duration is not available. Also, the distribution of flame temperature can vary between accident scenarios due to several factors, including the likely amount of fuel available. This information is also not available, thus a simple flame temperature distribution is used in the probability analyses. This distribution, T_1, is based on a Weibull function for flame temperatures between 1400°F and 2400°F:

T1: Weibull (1400°F,2400°F)

Table 5.5
Cumulative Fire Duration Distributions for Truck Cask Analysis

Fire Duration, d (hours)	Distributions F1 $G_D(d)$	 F2 $G_D(d)$	 F3 $G_D(d)$	 F4 $G_D(d)$	 F5 $G_D(d)$
0.	0.	0.	0.	0.	0.
0.083	0.3311	0.0321	0.0035	0.0131	0.00238
0: 167	0.6596	0.2821	0.0451	0.1653	0.07222
0.250	0.8551	0.5860	0.1572	0.4179	0.16427
0.333	0.9625	0.7754	0.3488	0.6516	0.31099
0.417	0.9801	0.8769	0.5001	0.7878	0.43757
0.500	0.9897	0.9358	0.6034	0.8725	0.54957
0,583	0.9944	0.9643	0.6771	0.9161	0.64690
0.667	0.9970	0.9800	0.7322	0.9456	0.73075
0.750	0.9985	0.9902	0.7750	0.9662	0.80265
0.833	0.9992	0.9949	0.7960	0.9761	0.86416
0.917	0.9996	0.9973	0.8123	0.9838	0.87612
1.0	0.9998	0.9989	0.8257	0.9898	0.88589
1.083	0.99991	0.9995	0.8367	0.9936	
1.167	0.99996	0.9998	0.8459	0.9964	0.89828
1.250	0.99999	0.99995	0.8535	0.9984	
1.333	1.0	0.99998	0.8596	0.9993	0.90934
1.417		0.99999	0.8652	0.9997	
1.500		1.0	0.8696	0.9999	0.91874
1.583			0.8737	0.99996	
1.667			0.8779	0.99997	0.92730
1.750			0.8812	0.99999	
1.833			0.8847	1.0	0.93452
1.917			0.8882		
2.0			0.8917		0.94126
3.0			0.9287		0.96792
4.0			0.9503		0.98247
5.0			0.9641		0.99056
6.0			0.9773		0.99643
7.0			0.9905		1.0
8.0			1.0		

$G_D(d)$ -**Probability that fire duration is less than or equal to fire duration stated in left-hand column.**

F1: **Non-collision accident fires**

F2: **Off-road (or collision with fixed objects) accident fires**

F3: **Truck/truck collision accident fires**

F4: **Truck/automobile collision accident fires**

F5: **Train collision accident fires**

Table 5.6
Cumulative Fire Duration Distributions for Rail Cask Analysis

Fire Duration,d (hours)	Distributions		
	TF1 $G_D(d)$	TF2 $G_D(d)$	TF3 $G_D(d)$
0.	0.	0.	0.
0.083	0.00238	0.01009	0.00943
0.167	0.07222	0.09213	0.09180
0.250	0.16427	0.17603	0.17574
0.330	0.31099	0.29164	0.29183
0.417	0.43757	0.39717	0.39789
0.500	0.54957	0.49517	0.49648
0.583	0.64690	0.58120	0.58291
0.667	0.73075	0.65917	0.66075
0.750	0.80265	0.72958	0.73139
0.833	0.86416	0.79154	0.79373
0.917	0.87612	0.80544	0.80765
1.0	0.88589	0.81870	0.82036
1.167	0.89828	0.83308	0.83454
1.333	0.90934	0.84752	0.91874
1.500	0.91874	0.86071	0.86292
1.667	0.92730	0.87388	0.87564
1.833	0.93452	0.88537	0.88704
2.0	0.94126	0.89665	0.89792
3.0	0.96792	0.94290	0.94342
4.0	0.98247	0.96790	0.96821
5.0	0.99056	0.98166	0.98239
6.0	0.99643	0.98868	0.98941
7.0	1.0	0.99380	0.99403
8.0		0.99702	0.99754
9.0		0.99910	0.99928
10.0		0.99978	0.99985
11.0		1.0	1.0

CD(d) = Probability that fire duration is less than or equal to fire duration stated in left-hand column.

TF1: Collision accident fires

TF2: Derailment accident fires

TF3: Other accident fires

$$F(x) = \left[1 - e^{-\left(\frac{x-1400}{550}\right)^{1.83}}\right] \Big/ \left[1 - e^{-\left(\frac{1000}{550}\right)^{1.83}}\right] \qquad 1400^{\circ}F \leq x \leq 2400^{\circ}F \qquad (5.11)$$

This distribution covers the range of flame temperature achievable in typical hydrocarbon fires.[2] These types of fires constitute the majority of fires which occur in transportation accidents. The cumulative distribution function is presented in Table 5.7.

5.2.2.3 Fire Location Distributions

The location of a fire has a significant affect on the heat flux to which a cask is exposed and hence on the temperature attained at the middle of the lead shield thickness. An engulfing fire typically produces a greater heat flux exposure to the cask and results in higher cask temperatures than a fire of the same temperature, size, and duration that is adjacent to the cask. The greater the distance of the fire from the cask, the less the thermal interaction and effective exposure.

As with the other fire parameters, no historical data is available for developing a distribution of fire location with respect to the cask. In lieu of such information, a uniform distribution of cask to fire location is assumed. The fire locations are varied between the truck and rail casks in proportion to the size differences between the two casks. The fire location distributions, L_1, used are:

Truck fires - Uniform (0 ft, 30.75 ft)

$$F(x) = x130.75 \qquad 0\ \text{ft}\ 6\ x\ 6\ 30.75\ \text{ft} \qquad (5.12)$$

Train fires - Uniform (0 ft, 43 ft)

$$F(x) = x/43 \qquad 0\ \text{ft}\ 6\ x\ 6\ 43\ \text{ft} \qquad (5.13)$$

Table 5.7
Cumulative Flame Temperature Distribution

Flame Temperature, t (^{o}F)	$G_T(t)$
1400	0.
1500	0.04551
1600	0.15306
1700	0.29588
1800	0.45059
1900	0.59847
2000	0.72714
2100	0.83069
2200	0.90849
2300	0.96342
2400	1.0

$G_T(t)$ = Probability that flame temperature is less than or equal to temperature stated in left-hand column.

The cumulative distribution functions are presented in Table 5.8. A fire is considered engulfing if it is within 1/4 foot of the center of a truck cask or within one foot of the center of a rail cask.

5.3 Probability Calculation

The purpose of the probability calculation is to estimate the likelihood that specified sets of cask responses will be realized if an accident occurs. The calculation is based on combining the probabilistic information about the accident parameters with the probabilities of the various accident scenarios. The probability estimate is then combined with an estimate of the expected accident rate/truck or train-mile to estimate the expected frequency/mile of cask response in specified response regions. Once the radiological hazards for each cask response region are characterized, the risk, i.e., probability times hazard, associated with transporting spent fuel is estimated.

As described in Section 4.0, the potential cask response represented by the containment vessel strain and the lead mid-thickness temperature due to a transportation accident are partitioned into 20 response regions R(i,j), $i=1,\ldots,4$, $j - 1,\ldots,5$, consisting of the combination of 4 structural response regions and 5 thermal response regions:

Structural Response Region	Condition
i=1	Less than 0.2% strain ($<S_1$)
2	Between 0.2% (S_1) and 2% (S_2) strain
3	Between 2% (S_2) and 30% (S_3) strain
4	Greater than 30% strain ($>S_3$)

Table 5.8
Cumulative Fire Location Distributions

Fire Location, ℓ (feet)	Distributions Truck $G_L(\ell)$	 Train $G_L(\ell)$
0.	0.	0.
1.0	0.03175	0.02326
2.0	0.06349	0.04651
6.0	0.19048	0.13953
10.0	0.31746	0.23256
14.0	0.44444	0.32558
18.0	0.57143	0.41860
22.0	0.69841	0.51163
26.0	0.8455	0.60465
30.00	0.9756	0.69767
30.75	1.0	
34.0		0.79070
38.0		0.88372
42.0		0.97674
43.0		1.0

$G_L(\ell)$ = **Probability that fire location is less than or equal to fire location stated in left-hand column.**

Thermal Response Region	Condition
j=1	Less than 500°F lead mid-thickness temperature ($<T_1$)
2	Between 500°F (T_1) and 600°F (T_2) lead mid-thickness temperature
3	Between 600°F (T_2) and 650°F (T_3) lead mid-thickness temperature
4	Between 650°F (T_3) and 1050°F (T_4) lead mid-thickness temperature
5	Greater than 1050°F lead mid-thickness temperature ($>T_4$)

The probabilities estimated in the probability analysis are the likelihood of the cask response being in each one of the response regions.

The initial step in modeling the probability calculations is to relate the containment vessel strain to impact velocity and the lead mid-thickness temperature to effective fire duration. The first part is done by developing strain-impact velocity curves for several object hardnesses. Similarly, the lead mid-thickness temperature-fire duration models are developed for several fire locations and a 1700°F flame temperature.

Given a fixed impact angle and cask orientation, the probability that containment vessel strain is within a given region is derived from the distribution of the impact velocity via the strain-impact velocity curves. For example, given a truck cask, using Fig. 7-3 and assuming an unyielding object and an end-on cask orientation, a strain between 0.2% (S_1) and 2% (S_2) corresponds to an impact velocity between 38 mph and 46 mph. Thus, assuming a head-on impact, i.e., 90° impact angle, the probability of the containment vessel strain being between 0.2% (S_1) and 2% (S_2), denoted $P(0.2 \leq S_t \leq 2)$, is equal to the probability that the cask velocity is between 38 mph and 46 mph. Recognizing the fact that the relationships between strain and cask velocity are conditional on the impact angle, cask orientation, and object hardness, the identity involving the strain and cask velocity probabilities can be written mathematically as:

$$P(0.2<S_t\leq 2|\text{head-on, end-on impact with unyielding object})=F_S(46)-F_S(38) \quad (5.14)$$

where $F_S(.)$ denotes the appropriate cumulative distribution function of cask velocity.

Taking into consideration the fact that the impact angle and cask orientation are variable, and recognizing that the hardness of the object impacted is identified by an accident scenario, the probability of the containment vessel strain given a specific accident scenario is obtained by averaging the probability in Equation 5.14 with respect to the appropriate distributions for impact angle and cask orientation. Mathematically,

$$P(0.2<S_t<2|A_k) = \int_\alpha \int_\beta \{F_S[s_2(\alpha,\beta,A_k)|A_k]-F_S[s_{0.2}(\alpha,\beta,A_k)|A_k]\}$$

$$x\ dF_A\ (\alpha|A_k)dF_B\ (\beta|A_k) \quad (5.15)$$

where Ak identifies an accident scenario and $F_S(.)$, FA (.) and F_B (.) are the cumulative distribution functions for cask velocity, impact angle, and cask orientation, respectively. Equation 5.15 recognizes that the cask accident velocity corresponding to 0.2% (S_1) and 2% (S_2) strain depends on the impact angle, cask orientation, and hardness of the object impacted, i.e., the accident scenario.

As illustrated in Fig. 5.1, changing the cask orientation corresponds to varying the strain-impact velocity curve. This change is included in the probability analysis by developing strain-impact velocity curves for 0^0, 45^0, and 90^0 cask orientation for each level of hardness of the impacted object. It is assumed, given a fixed impact angle, that the impact velocities for intermediate angles can be approximated by:

$$v_\%(\beta) = \begin{cases} v_\%(0^0) + \frac{\beta}{45}\,[v_\%(45^0) - v_\%(0^0)] & 0^0 < \beta \leq 45^0 \\ v_\%(45^0) + \frac{(\beta-45)}{45}\,[v_\%(90^0) - v_\%(45^0)] & 45^0 < \beta < 90^0 \end{cases} \quad (5.16)$$

That is, a linear interpolation is assumed between the 0^{o} and 45^{o} curves and between the 45^{o} and 90^{o} curves. Notationally, $v_{\%}(\beta)$ denotes the impact velocity corresponding to strain percent, %, for cask orientation angle, β. The corresponding strain-impact velocity curves for several β's are illustrated in Fig. 5-l.

The impact angle a relates the cask impact velocity to the cask accident velocity. If the impact is head-on, i.e., $\alpha=90^{o}$, then the impact velocity equals the accident velocity. On the other hand, if a is less than 90^{o}, then the impact velocity is less than the accident velocity. Since the velocity distributions V1 through V4 and TV1 through TV4 are distributions for accident velocities, it is necessary to transform the impact velocity corresponding to a strain level to an accident velocity. This transformation, for a fixed cask orientation angle, β, is given by

$$s_{\%}(\beta,\alpha) = v_{\%}(\beta)/\sin\alpha \qquad (5.17)$$

where $v_{\%}(\beta)$ represents impact velocity and $s_{\%}(\beta,\alpha)$ is the corresponding accident velocity for the given impact angle.

To illustrate how cask orientation and impact angle are handled in the calculations, we consider structural response region $i=2$, i.e., between 0.2% (S_1) and 2% (S_2) strain, being attained when a cask hits a concrete object at a 45^{o} orientation angle and a 35^{o} impact angle. From Table 5.9 for accident scenario No. 8 the impact velocities for 0.2% (SI) and 2% (S_2) strain are $v_{0.2\%}(45^{o})$ = 35 mph and $v_{2\%}(45^{o})$ = 49 mph. (Note: for other orientation angles β, Equation 5.16 would be used to evaluate v%(B).) Using Equation 5.17, the vehicle velocities necessary to result in impact velocities of 35 mph and 49 mph, if the angle of impact is 35^{o}, are (since sin 35^{o} = 0.57378) :

$$\begin{aligned} s_{0.2\%}(45^{o},35^{o}) &= v_{0.2\%}(45^{o}) \,/\, 0.57378 \\ &= 61 \text{ mph} \end{aligned}$$

Table 5.9
Probability Inputs for Highway Analysis

Accident index	Probability ×10-3	P(fire)	Fire duration	Temperature	Location		Cask orientation	Impact angle	Speed	Strain-impact velocity curve	Damagestate upper boundaries <0.2% 0°	<0.2% 45°	<0.2% 90°	<2% 0°	<2% 45°	<2% 90°	<30% 0°	<30% 45°	<30% 90°
						Distributions													
1	34.002	0.004	F1	T1	L1		CT1	VV1	V1		150	150	150	150	150	150	150	150	150
2	8.093		F2																
3	431.517		F4																
4	133.201	0.008	F3																
5	7.701	0.011	F5				CT3	VV2	V4	5	9	14	150	20	27				
8	38.113	0.009	F2				CT1	VV1	V1		150	150	150	150	150				
7	1.039	0.004					CT3	VV2	V2	4	42	150	38	59	150	64			
8	3.986									2	32	35	38	51	49	46			
9	0.079									3		58	84		101	150			
10	0.006									2		35	38		49	46			
11	0.001									1								113	76
12	0.299						CT2	VV3	V1	2								150	150
13	0.062																		
14	0.011																		
15	0.850						CT1	VV1			150	150	150	150	150	150			
6	40.079																		
17	5.111																		
18	37.050																		
19	23.063	0.011	F1							3	32	58	84	51	101				
20	1.981									2		35	38		49	46			
21	0.297									1								113	76
22	13.192						CT2	VV3	V3	3	32	58	84		101	150		150	150
23	1.076									2		35	38		49	46			
24	0.170									1								113	76
25	8.894						CT1	VV1	V1		150	150	150	150	150	150		150	150
26	9.412																		
27	32.517																		
28	83.493	0.012																	
29	54.603																		
30	20.497	0.130																	
31	9.705	1.0																	

$$s_{2\%}(45^{o},35^{o}) = v_{2\%}(45^{o}) \; / \; 0.57378$$
$$= 85.40 \text{ mph}$$

Given a fire, the thermal response of the cask, represented by the lead mid-thickness temperature is related to the duration of the fire. This relationship, illustrated in Fig. 5-2, depends on both flame temperature and fire location. Using an argument analogous to the development of the probability corresponding to a structural response region, the probability that the cask thermal response is in a specific region, for example, between $600^{o}F$ (T_2) and $650^{o}F$ (T_3) or thermal response region j=3, is given by

$$P(600<T<650|A_k \text{ with a Fire}) = \iint\limits_{t\ell} \{G_D[d_{650}(t,\ell)|A_k] - G_D[d_{600}(t,\ell)|A_k]\} \times dG_T(t)dG_L(\ell) \quad (5.18)$$

where $G_D(.)$, $G_T(.)$, $G_L(.)$ denote the fire duration, flame temperature, and fire location cumulative distribution functions, respectively. Again, the fire duration, $d_{\Omega}(t,\ell)$, corresponding to a lead mid-thickness temperature, ^{o}F, depends on the flame temperature and fire location. This is denoted in the argument of the fire duration distribution function. Also, the fire duration distribution varies with the accident scenario.

The basic mid-thickness temperature of the lead shield-fire duration curve is based on a $1700^{o}F$ real engulfing fire. The effects of the other fire parameters are included in the analyses by adjusting this basic curve. For fires that deviate from a $1700^{o}F$ fire, the same temperature is reached within the shield, but the time to reach this temperature is shorter or longer depending on the flame temperature. If the flame temperature is greater than $1700^{o}F$, the same lead mid-thickness temperature is reached in a shorter time; whereas if the flame temperature is below $1700^{o}F$, it takes longer to produce the same temperature in the middle of the lead shield thickness. Thus, for a given lead mid-thickness temperature, the effects of different flame temperatures for an engulfing fire are modeled by the identity

$$d_{o_F}(t,0) = 6(t)\ d_{o_F}(1700^o,0\ \text{ft}) \qquad (5.19)$$

A list of the factors 6(t) is presented in Table 5.10.

For fire location, as the distance between the fire and the cask increases, heat exposure decreases, and a longer duration fire is needed to produce the same temperature in the middle of the lead shield thickness as an engulfing fire. Thus, the effect of fire location on the lead shield temperature-fire duration relationship is modeled by a multiplicative factor. The model used is

$$\begin{aligned} d_{o_F}(t,\ell) &= \delta(\ell)\ d_{o_F}(t^o,0\ \text{ft}) \qquad (5.20) \\ &= \delta(\ell)\ \delta(t)\ d_{o_F}(1700^o,0\ \text{ft}) \end{aligned}$$

where the factor $\delta(\ell)$ is given by

$$\delta(\ell) = 0.78e^{(0.7732+0.06287\ell)} \qquad \ell > 1.5\ \text{ft} \qquad (5.21)$$

for a truck cask and

$$\delta(\ell) = 0.78e^{(0.62874\ +\ 0.0847111)} \qquad \ell > 4\ \text{ft} \qquad (5.22)$$

for a rail cask. In both cases, location is measured from the center of the cask, which is mathematically assumed to represent the location of an engulfing fire. Development of the flame temperature and fire location models in Equations 5.19 through 5.22 is discussed in Subsections 2.5.2.3 and 2.5.2.4. The effect on the basic lead mid-thickness temperature-fire duration curve for a truck cask is shown in Fig. 5-2.

Equations 5.15 and 5.18 are expressions for estimating the probability that the containment vessel strain is within a given structural response region, e.g., between 0.2% (S_1) and 2% (S2) strain, and the probability, given a fire, that the lead mid-thickness temperature is within a given thermal response region, e.g., between 600°F (T2) and 650°F (T3), respectively. Both expressions are conditional on a given accident scenario. A cask response

Table 5.10
Heat Flux Factors for Flame Temperatures (Engulfing Fire)

Flame Temperature, t (°)	$\delta(t)$
1400	1.72
1500	1.43
1600	1.21
1700	1.0
1800	0.86
1900	0.73
2000	0.64
2100	0.56
2200	0.49
2300	0.44
2400	0.39

expressions are conditional on a given accident scenario. A cask response region involves a combination of structural responses and thermal responses. Assuming that strain is independent of the lead shield temperature, these probabilities can be multiplied to estimate the probability associated with a response region. For example, for response region R(2,3), i.e., strain between 0.2% (S_1) and 2% (S_2) and lead mid-thickness temperature between 600^{0}F (T_2) and 650^{0}F (T_3), the probability, given accident scenario Ak is:

$$P[R(2,3)|A_k]=P(Fire|A_k)[\int_\alpha \int_\beta \{F_S[s_2(\alpha,\beta,A_k)|A_k]-F_S[s_{0.2}(\alpha,\beta,A_k)|A_k]\}$$

$$\times\ dF_A\ (\alpha|A_k)dF_B\ (\beta|A_k)][\int_t \int_\ell \{G_D[d_{650}(t,\ell)|A_k]-G_D[d_{600}(t,\ell)|A_k]\}$$

$$\times\ dG_T(t)dG_L(\ell)] \quad (5.23)$$

where the probability of a fire is included in the expression. Similar expressions hold for each of the response regions R(i,j).

Two response regions correspond to accidents involving either no fire or fire only. In these cases, it is assumed that there is no cask thermal response and no cask structural response. For no fire, the response regions are denoted R(i,0), and the probabilities are

$$P[R(i,0)|A_k]=[1-P(Fire|A_k)]\ P[s_{\ell,i}\le S\le s_{u,i}|A_k] \quad (5.24)$$

where $s_{\ell,i}$ and $s_{u,i}$ denote the lower and upper strain limit for the ith region, respectively. For fire only, the response regions are denoted R(0,j), and the probabilities are

$$P[R(0,j)|\text{Fire only}]=P[d_{\ell,j}\le T\le d_{u,j}|\text{Fire only}] \quad (5.25)$$

where $d_{\ell,j}$ and du,j denote the lower and upper shield temperature for the jth region, respectively.

The final step in the probability calculation is to combine the probabilities over all accident scenarios. Thus, for response region R(i,j),

$$P[R(i,j)] = \sum_{A_k} P(A_k)\, P[R(i,j)\,|A_k)\,] \qquad (5.26)$$

where $P(A_k)$ is the likelihood of accident scenario A_k given an accident. Tables 5.9 and 5.11 summarize the value of $P(A_k)$; $P(Fire|A_k)$; choice of distributions for each accident scenario; and the structural response region limits for OD, 45°, and 90° cask orientation for a truck cask and rail cask, respectively.

The actual probability calculations described in Equations 5.23 and 5.26 are done by a computer code, called TASP (Transportation Accident Scenario Probabilities). The inputs into the code are appropriate distributions for the accident parameters. These are combined for each accident scenario using Equation 5.23 and averaged over accident scenarios using Equation 5.26. The integration in Equation 5.23 is based on approximating the integrals by sums. Details of the integration are discussed in Appendix G. A flow chart of TASP is given in Fig. 5-4.

The results of the probability calculations are presented and discussed in Section 9.0.

Table 5.11
Probability Inputs for Railway Analysis

		Distributions									Damagestate upper boundaries								
											<0.2%			<2%			<30%		
Accident index	Probability $\times 10^{-2}$	P(fire)	Fire duration	Temperature	Location		Cask orientation	Impact angle	Speed	Strain-impact velocity curve	0°	45°	90°	0°	45°	90°	0°	45°	90″
1	3.0400	0.01	TFl	T1	L1		CT1	VV1	TV1		150	150	150	150	150	150	150	150	150
2	8.5878	↓	TFl	↓	↓			↓	t		t	t	↓	t	t	t	↓	↓	↓
3	0.1615	↓	TF2	↓	↓		CT3	VV2	TV3	4	55	150	36	72	150	60	↓	↓	↓
4	0.0122	↓	↓	↓	↓		↓	↓	↓	3	↓	47	40	↓	69	66	↓	↓	↓
5	0.0010	↓	↓	↓	↓		↓	↓	↓	2	↓	↓	38	↓	60	46	150	128	105
6	0.9002	↓	↓	↓	↓		↓	↓	↓	1	↓	↓	↓	↓		↓	↓	↓	↓
7	0.6192	↓	↓	↓	↓		↓	↓	↓	2	↓	↓	↓	↓	4	↓	↓	↓	↓
8	0.3433	↓	↓	↓	↓		CT1	VV1	TV1		150	150	150	150	150	150	150	150	150
9	0.5092	↓	↓	↓	↓		CT2	VV3	TV4	3	55	47	40	72	69	66	150	150	150
10	0.0415	↓	↓	↓	↓		↓	↓	↓	2	↓	↓	38	56	60	6	150	126	105
11	0.0066	↓	↓	↓	↓		↓	↓	↓	1	↓	↓	t	t	t	4	150	128	105
12	1.4437	↓	↓	↓	↓		CT1	VV1	TV2	3	↓	↓	40	60	69	66	150	150	150
13	0.1178	↓	↓	↓	↓		↓	↓	↓	2	↓	↓	38	56	60	48	150	128	105
14	0.0186	↓	↓	↓	↓		↓	↓	↓	1	↓	↓	↓		↓	↓	↓	↓	↓
15	0.0465	↓	↓	↓	↓		CT2	VV3	↓	2	↓	↓	↓		↓	↓	↓	↓	↓
16	0.0096	↓	↓	↓	↓		↓	↓	↓	↓	↓	↓	↓		↓	↓	↓	↓	↓
17	0.0017	↓	↓	↓	↓		↓	↓	↓	↓	↓	↓	↓	I	↓	↓	I	↓	↓
18	16.4477	↓	↓	↓	↓		CT1	VV1	TV1		150	150	150	150	150	150	150	150	150
19	3.2517	↓	↓	↓	↓			↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	↓
20	10.0146	↓	↓	↓	↓			↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	↓
21	0.8408	↓	↓	↓	↓			VV2	TV2	5	11	16	150	27	49	150	↓	↓	↓
22	15.9981	↓	↓	↓	↓			VV1	TV1		150	150	150	150	150	150	↓	↓	↓
23	31.9865	↓	↓	↓	↓			↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	↓
24	6.5000	0.90	TF3	↓	↓		I	↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	↓

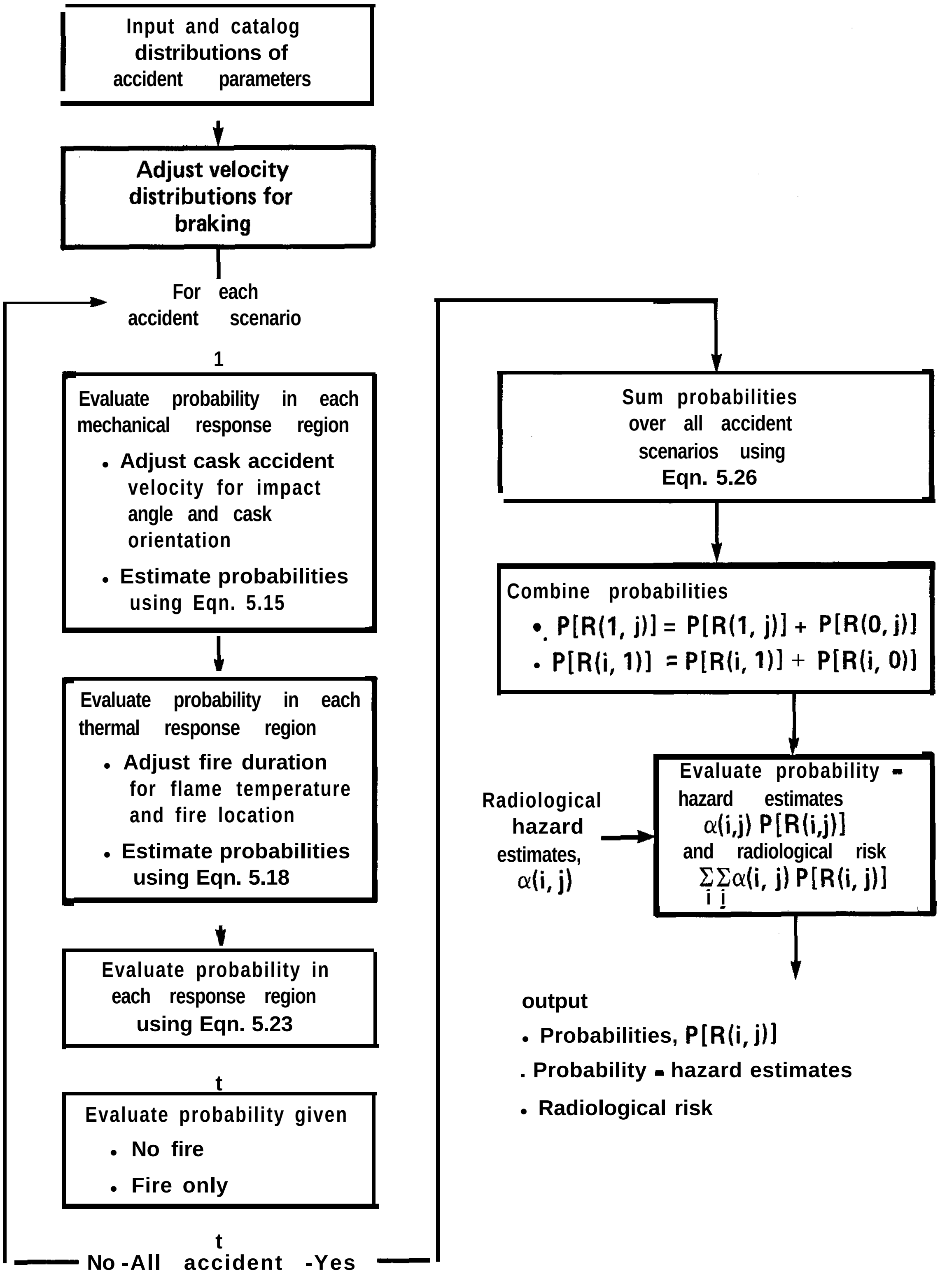


Figure 5-4 Flow chart of TASP computer code.

6.0 FIRST-STAGE SCREENING ANALYSIS

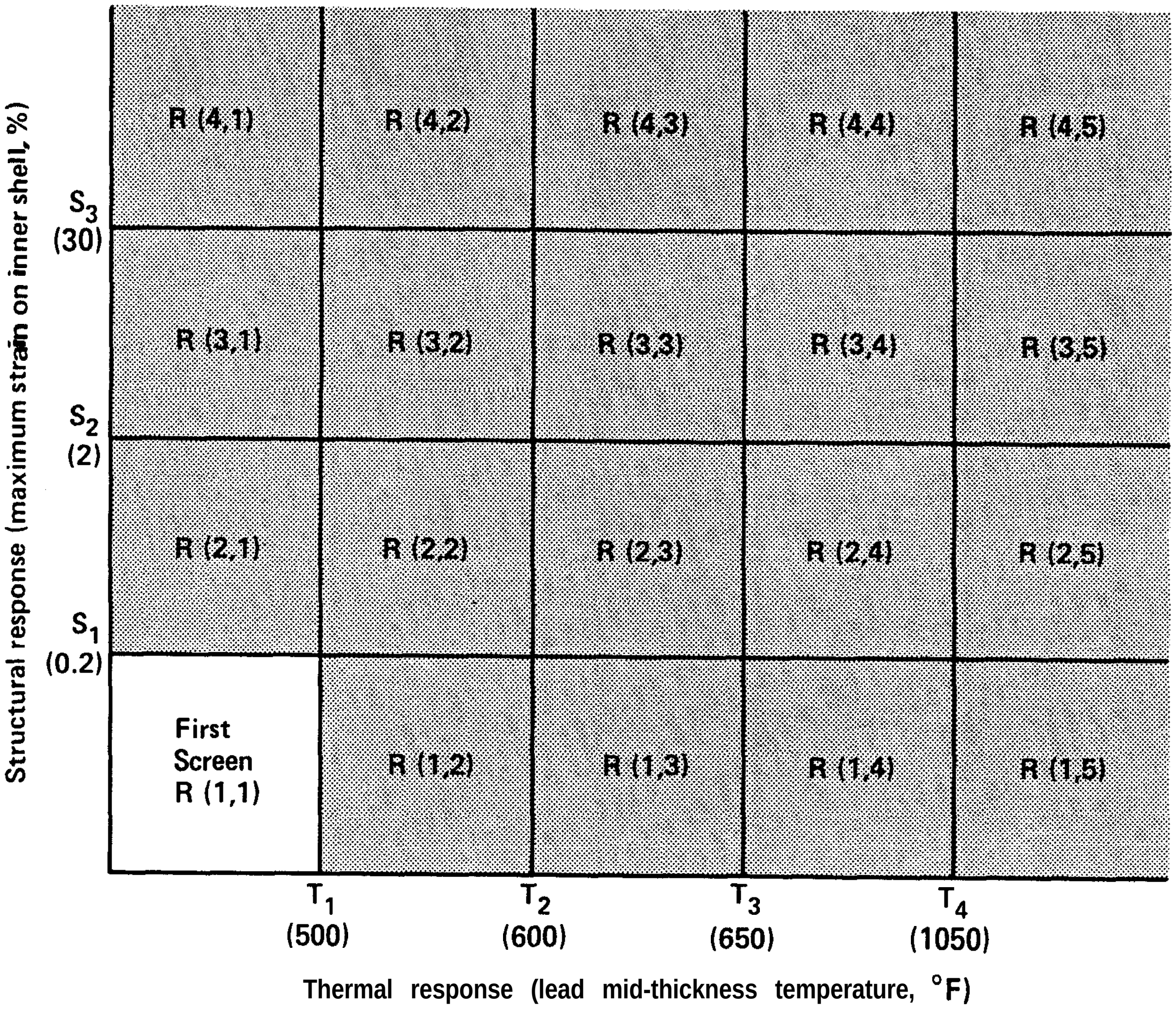
6.1 Introduction

A two-stage screening process is used to evaluate the level of protection provided by licensed fuel casks against real accident loading conditions. Response regions are developed on the basis of cask performance and are described in terms of damage. The response regions are used to sort or screen accident events in terms of the analytically predicted performance of the representative casks. Figure 6-1 shows the 20 response regions defined in Section 4.0. In the first-stage screening, the intent is to determine by analysis which accident-caused loading conditions can result in cask responses that will fall within the first response region R(1,1). Cask responses in this region are less than or equal to responses implied by the 10 CFR 71 accident test conditions. The second-stage screening analysis identifies accidents which produce loading conditions that can cause cask responses outside the R(1,1) region. The first-stage screening analysis is discussed in this section; the second-stage screening analysis is discussed in Section 7.0.

Within the R(1,1) region, the cask structural response does not exceed a strain level of 0.2% (SI) on the inner shell of the cask. The cask thermal response does not exceed a temperature level of 500°F (TI) at the middle of the lead shield thickness. Within the R(1,1) region, all the major cask components important to safety during transportation accidents are expected to remain fully functional, and the cask meets regulatory requirements. The cask responses within the R(1,1) region do not exceed the responses that would be expected if the cask were subjected to the accident test conditions of 10 CFR 71. Since cask responses within the R(1,1) region do not result in any significant damage to the cask, no radiological release beyond the regulatory limit is expected from the accident causing this level of damage. In fact, in most cases, releases, if any, would be much less than regulatory limits.

The first-stage screening analysis follows this procedure:

- For each representative cask, dynamic structural and transient thermal analyses are performed to calculate responses to a range of loading



Note:

- o The radiological hazard of cask responses falling in region R(1,1) are negligible and less than limits specified in existing regulations (10 CFR 71).
- o The radiological hazard of cask responses falling outside region R(1,1) can exceed the limits specified in existing regulations (10 CFR 71).

Figure 6-l Identification of first-stage screening.

conditions for the accident scenarios identified in Section 2.0. The loading conditions for the accident scenarios are defined by three mechanical loading parameters and three thermal loading parameters. The mechanical loading parameters are impact velocity, object hardness, and cask orientation. The thermal loading parameters are fire duration, flame temperature, and fire location with respect to the cask.

- The structural response is calculated for various impact velocities. The impact velocity is equal to the component of the accident velocity perpendicular to the surface impacted. It is arrived at by multiplying the accident velocity by the sine of the impact angle. Since the impact angle is not precisely known, it is assumed to follow selected probability distributions depending on the accident scenario under study.

- For each accident scenario, the loading conditions that result in cask responses within the R(1,1) region are determined by comparing the cask response with the response levels of 0.2% strain (S_1) on the inner shell for mechanical loads and 500^oF (T_1) at the mid-thickness of the lead for thermal loads.

- For each accident scenario, the probability of occurrence of the specific loading conditions that could result in cask responses within the R(1,1) region is estimated as described in Section 5.0, using the data bases identified in Section 2.0.

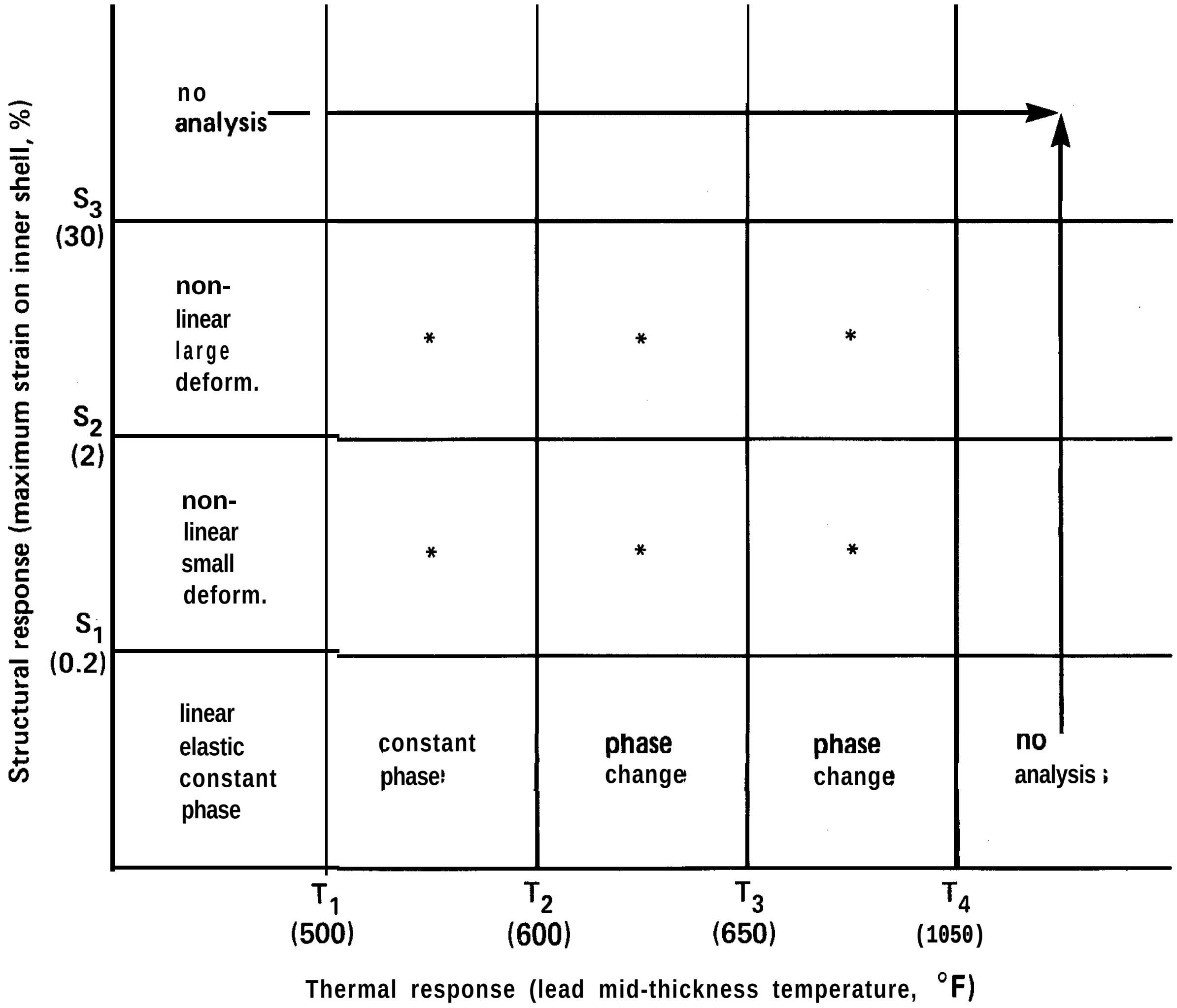
- The fraction of accidents with loading conditions that could result in cask responses within the R(1,1) region is calculated by summing the individual occurrence probabilities associated with each accident scenario.

The major differences between the first-stage and second-stage screening analyses involve the methods used in the structural and thermal analyses. For the first-stage screening analysis, less sophisticated methods of analysis can be reliably used. For structural responses below the 0.2% strain (SI) level, dynamic linear elastic analysis can be used with high confidence to evaluate mechanically induced structural responses. For responses beyond the 0.2% strain (SI) level, 2% strain (S_2) and 30% strain (S_3), dynamic nonlinear analysis is required. For thermal responses below the 600°F temperature (T_2) level, standard transient heat transfer analysis methods can be used. These methods include transient heat transfer by conduction, radiation, and convection. Responses beyond the 600°F temperature (T_2) level include melting of the lead shield, which requires that the transient analysis method include the consideration of phase changes of materials, Figure 6-2 is a schematic diagram showing the general methods of analysis used in the cask response calculations for each of the response regions. Analyses are not performed to calculate responses beyond the 30% strain (S3) and 1050°F temperature (T_4) levels since the uncertainties in calculational results would be large. However, in Section 8.0, the potential radiological significance is estimated for responses beyond these levels.

In order to consolidate the many variables and analyses required to cover the wide range of potential accident situations, the following approaches and assumptions are used in this study.

(1) Casks used for spent fuel shipments are assumed to be properly designed, fabricated, maintained, and operated in accordance with regulations. The intent of this evaluation is not to assess the probability and potential effects of cask defects or deficient or misapplied operational procedures.

(2) The accident loading parameter distributions in Section 5.0 are generated from the accident data identified in Section 2.0 and are assumed to represent loadings which could be experienced by a spent fuel cask. These accident data are derived from several broad data bases and are independent of any specific transportation route. The frequency of occurrence of certain accident scenarios and their loading conditions can



*Combined analysis

Figure 6-2 Methods of analysis used in cask response determinations.

experience some variations depending on the specific routing selected. These variations are considered minor for purposes of this study.

(3) In evaluating highway and railway accidents involving impacts, any damage done to the cask is assumed to result from striking a single object. Real accidents can involve impact with multiple objects; however, for impacts into the harder objects of interest, almost all of the energy involved in the accident is associated with the initial impact. In certain cases, such as accident scenarios involving impacts with bridge railings, conservative assumptions are made. In this scenario, it is assumed that the bridge railing does not cause the transport vehicle to stop but instead allows the cask to fall off the bridge and onto the surface below. The cask response is calculated for falling off the bridge and striking the surface below. Damage to the cask caused by hitting the bridge railing is not significant to the overall evaluation. Conservatism is further introduced in the probability portion of the evaluation because a cask is assumed to fall off a bridge whenever the truck hits the bridge railing.

(4) The representative truck and rail casks selected for this study and described in Section 3.0 are defined to meet regulatory requirements and generally reflect the designs of casks on the roads and railways today. In actual shipments there will be a variety of cask designs. For all of the accident conditions analyzed, most, if not all, would be expected to exhibit degrees of damage equal to or less than those calculated for the representative casks. Ideally the screening analyses would have used a variety of cask designs with their commensurate variety of potential responses. The results of using a representative cask design for the screening process undoubtedly results in an underestimate of the fraction of accidents leading to cask responses in the R(1,1) region. Conversely, the fraction of accidents leading to cask responses in the other regions is most likely overstated.

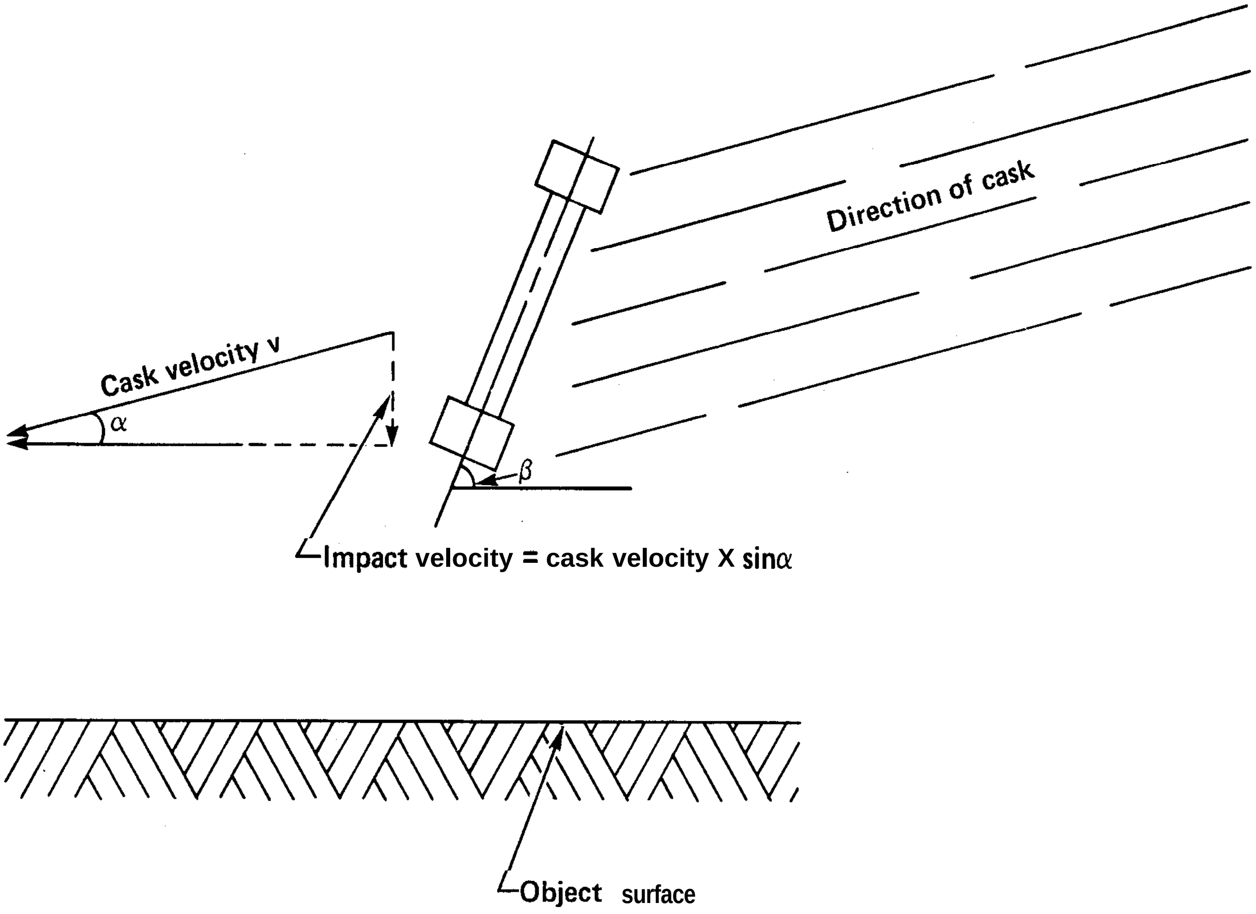
(5) If there is a lack of data or any unknown factors involved in the structural and thermal analyses or in the accident definition, one of two approaches is followed. Either reasonable assumptions are made from sensitivity study results, or conservative assumptions are made. This approach reduces the need to significantly expand the current data base or unnecessarily complicate the analysis.

Section 6.2 discusses the structural response analysis for impact loads on the representative truck casks. The response analysis determines which accident loading conditions can result in responses that are less than the 0.2% strain (S_1) level within the inner shell of the cask. Section 6.3 discusses the thermal response analysis for thermal loads on the cask that result in responses within the 500°F temperature (T_1) level at the mid-thickness of the lead shield. In Section 6.4 the probabilities of occurrence are estimated for highway and railway accident loading conditions that could result in cask responses falling in the R(1,1) region.

6.2 Structural Response Analysis-

Impact loads dominate the structural evaluation. Other loads such as crushing and projectile loads are determined to have little effect on the structural screening analysis. The significance of these loads is discussed in Appendix E. Many accident loads are easily screened out. Minor accidents involving low impact loads, like a rollover or impact with low-resistance objects such as a cask hitting a tree, motorcycle, or automobile, are screened out because the maximum forces generated in these impacts cannot cause significant damage to the cask.

The structural response of a cask to loads generated by potentially significant accidents involving impacts with harder objects at high velocities are calculated. There are three parameters that are considered in estimating structural response. These are shown in Figure 6-3 for impacts on surfaces as impact velocity, cask orientation angle, β, and object hardness. Response calculations are made for various impact velocities and cask orientation angles. The impact velocity is the component of the cask velocity vector



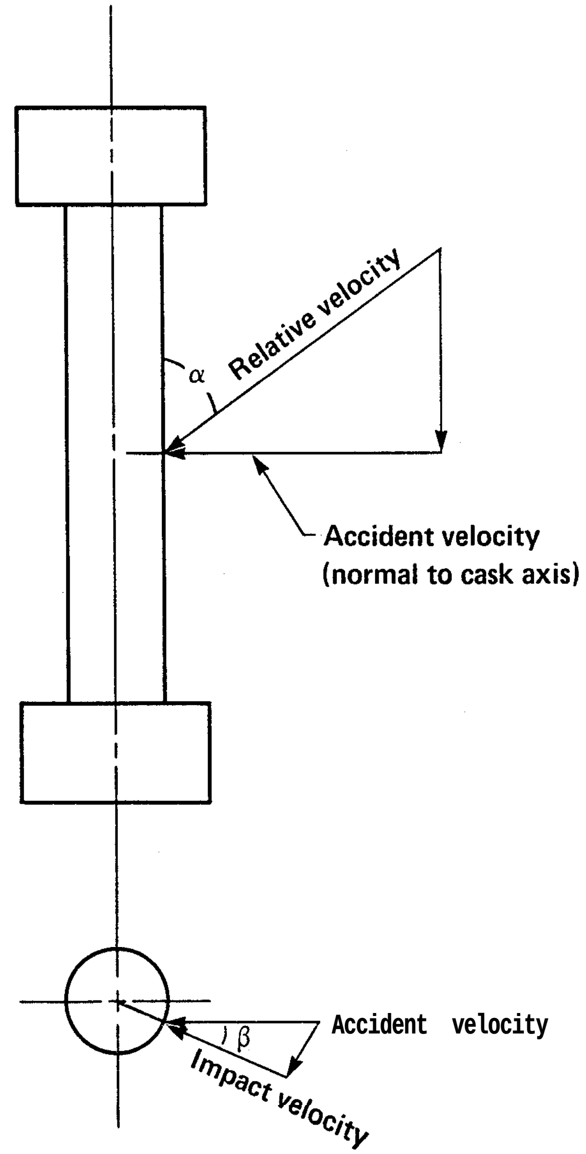
- Object **surface hardness**
- Impact velocity: **Cask velocity component perpendicular to the object surface is defined as impact velocity.**
- **Cask orientation is defined by angle β, the angle between the cask longitudinal axis and the surface of the object struck**

Figure 6-3 **Three impact loading parameters considered in the** response **analysis for impacts on surfaces.**

perpendicular to the surface impacted. The angle of impact, a, represents the angle between the cask velocity direction and the surface of the impacted object. When an accident occurs, the cask velocity vector can be in any direction. However, it can always be decomposed into two components: one perpendicular to the impacted object surface and one parallel to it. In the cask response calculation, only the velocity component perpendicular to the object surface is considered. The velocity component parallel to the object surface introduces a sliding-friction effect to the cask structure. The sliding-friction effect will not produce any significant structural deformation to the cask; therefore, it is ignored. The angle defining the cask orientation is the angle between the cask longitudinal axis and the surface of the object struck. Object hardness needs to be considered because casks can strike objects such as concrete abutments, roadbeds, hard rock, soft rock, hard soil, and water. The hardness of the objects and their responses to impact vary over a wide range.

In some accidents, such as rail grade crossing accidents, the impact limiters on the cask can be bypassed and the side of the cask can be struck directly. Once again the mechanical loads depend on the impact velocity; the orientation of the cask and the hardness of the object struck. Figure 6-4 defines these three loading parameters for this type of accident, The impact velocity is the component of the relative velocity of the cask and object that is perpendicular to the cask axis. The angle of impact, a, represents the angle between the relative velocity direction and the cask axis. For the purposes of this study, the impact angle is conservatively assumed to be 90^o, that is perpendicular to the cask axis in all cases. Also, it is assumed that the impact occurs at the mid-plane of the cask to cause the most damage. The cask orientation angle, β, is the angle at which the impact occurs on the cask surface. In the worst case the cask is hit at 0^o or head-on. For orientation angles near 90^o, the cask is essentially not struck. The object hardness depends on the object hitting the cask, such as a train sill or a small bridge column.

Two methods of analysis are used in performing the first-stage screening: quasi-static and linear elastic dynamic. The quasi-static method is used to screen out minor accidents involving low-resistance objects such as poles and



- Object hardness
- Impact velocity: Relative velocity component perpendicular to cask surface.
- Cask orientation angle, β: the angle between the accident velocity and impact velocity.

Figure 6-4 Three impact loading parameters considered in the response analysis for impacts with objects such as train sills.

automobiles. A variety of tools are used to accomplish the quasi-static evaluation, including engineering formulas, impact test data, and a computer code called NIKE 2-D, the 2-D designation indicating the two-dimensional modeling option.[2] The linear elastic method is used to perform a dynamic response analysis of the cask structure for accidents involving impacts with hard, massive objects in which cask damage cannot be ruled out by the quasi-static evaluations.

The IMPASC code is a linear elastic dynamic code within the SCANS computer program that can be operated on a personal computer.[3] IMPASC is developed specifically for analyzing dynamic impacts of shipping casks when the casks are subjected to loadings generated as a result of imposition of 10 CFR 71 accident test conditions. The code which is inexpensive to run can be used to analyze oblique impacts and to analyze non-linear behavior of an impact limiter. The deficiency is that IMPASC can model only collisions with unyielding surfaces and cannot handle real surfaces, such as soil or concrete. Also, IMPASC cannot assess lead slump.

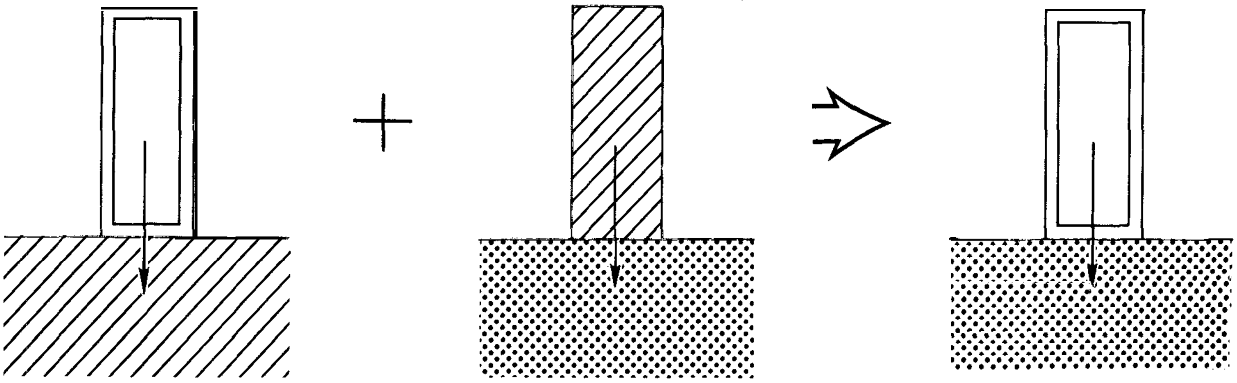
In order to perform the dynamic response calculations, the IMPASC code is used in conjunction with two other codes called NIKE 2-D/3-D and DYNA 2-D/3-D; the 2D/3-D designation indicating that either two- or three-dimensional modeling can be performed.[2,4] The NIKE 2-D/3-D and DYNA 2-D/3-D codes are powerful finite element codes suitable for dynamic impact analysis. IMPASC is used to evaluate cask responses for impacts on an unyielding surface for various cask orientations. DYNA and NIKE are used to evaluate cask responses for endwise and sidewise impacts on unyielding and real surfaces. IMPASC is benchmarked against NIKE as discussed in Appendix E.

A cost-effective equivalent damage technique is used to estimate the response of the representative casks impacting real surfaces. The basic assumption in the equivalent damage technique involves conservation of energy; that is, the total energy of the falling cask is absorbed by deformation of the cask and the surface that it hits. In order to estimate the energy absorbed by the surface, the cask is first modeled as a rigid body and the impact surface as deformable and energy-absorbent. This model is used to establish the force on a rigid cask generated by a real surface and the deformation of the real surface for several impact velocities. Next, calculations are made with the representative cask impacting an unyielding surface at different impact velocities. This establishes the impact forces on the cask and the corresponding cask deformations.

In order to account for the energy absorbed by an actual surface, the force determined from the first analysis, i.e., a rigid cask hitting a deformable surface, is applied to the representative cask to determine a corresponding cask deflection and an associated velocity. By summing both the cask and surface deflections and again considering the defined force level, an equivalent impact velocity on an unyielding surface can be estimated for a representative cask impacting a real surface. Figure 6-5 illustrates this analysis process for the case of a vertical end-drop of a cask without impact limiters. The process is discussed in detail, including the benchmark calculation, in Appendix E.

Three surfaces are used to represent the range of credible impact surfaces. These surfaces simulate hard rock, soft rock/hard soil, and tillable soil. Soft rock and hard soils are similar for impact and are represented as a single surface. Real surfaces exhibit complex response characteristics but can be considered to deform elastically during the early part of an impact, with a subsequent energy dissipation phase. The exact nature of the energy dissipation mechanism is not well known; therefore, for simplicity, an elastic-plastic formulation is used. The parameters used in this formulation, namely, the initial elastic modulus, the poisson ratio, and the yield stress are calibrated to approximate an equivalent energy-absorbent medium. To provide the calibration, penetration data[5] are used as discussed in Appendix E. Reasonable predictions of penetration are possible using the approximate elastic-plastic formulation. The resulting calibrated parameters are listed in Table 6.1 for each surface.

Subsection 6.2.1 describes the structural response analysis for highway accidents. The 31 accident scenarios identified in Section 2.0 are individually analyzed to determine the loading conditions that could cause



(a) Rigid cask impacts real surface

$$\left(\frac{F}{W}\right) g = \frac{V_1^2}{2d_{c1}}$$

(b) Representative cask impacts unyielding surface

$$\left(\frac{F}{W}\right) g = \frac{V_2^2}{2d_{s1}}$$

(c) Representative cask impacts real surface

$$\left(\frac{F}{W}\right) g = \frac{V_3^2}{2(d_{s1} + d_{c1})}$$

Figure 6-5 Equivalent damage technique.

Table 6.1
Material Parameters Selected for Real Surfaces

Surface type	Young's Modulus (psi)	Poisson Ratio	Yield Stress (psi)
Hard Rock	7,000,000	0.28	25,000
Soft Rock/Hard Soil	3,640,000	0.2	4,000
Tillable Soil	6,000	0.4	1,000

cask responses of 0.2% strain (S_1) or less. Subsection 6.2.2 describes a similar response analysis performed for 24 railway accident scenarios. Subsection 6.2.3 discusses the structural response results.

6.2.1 Cask Response Analysis for Highway Accidents

The representative truck cask described in Section 3.5 is used to perform the highway accident response analysis. Appendix E discusses the computer models of the cask and the detailed structural calculations used in the analysis. The structural evaluations use the highway accident scenarios presented in Figs. 2-3 and 2-4. The results of the response evaluations are described in Subsection 6.2.1.1 for accidents involving minor forces and in Subsection 6.2.1.2 for accidents in which the forces are potentially significant.

6.2.1.1 Response to Minor Accidents

Accident scenarios which result in minor forces are determined with an evaluation of cask performance under static loads. A static crushing force of 1.6 million pounds is applied to the cask side. The resulting strain calculated at the inner shell is less than 0.2% (S_1). When crushing the cask from the end, 3.2 million pounds of force generates a strain of less than 0.2% (S_1). Assuming that the sidewise impact force is linearly applied, the force/unit length that could cause local deformation can be estimated. The representative cask can resist a linear force of 100,000 pounds/foot, generating a strain of less than 0.2% (S_1). The linear force required to crush objects in many accidents is much less than 100,000 pounds/foot, and thus these accidents are screened out (placed in the R(1,1) response region).

The maximum force that an object generates during a high velocity impact can be estimated using quasi-static methods. By substituting equivalent static forces for inertial forces due to deceleration, calculations indicate that objects such as automobiles or truck trailers cannot generate forces greater than 100,000 pounds/foot-of-contact, even at high impact velocities. The automobile, as this calculation indicates, is a relatively soft object when compared with the massive steel cask and is severely damaged. The energy generated by the high-velocity impact of the automobile is almost totally absorbed in the destruction of the automobile, and no impact force greater than 10,000 pounds/foot is applied to the shipping cask. Also, for such a relatively light object (<5,000 pounds), the massive cask (50,000 pounds) will accelerate the object, hence reducing the impact forces to values significantly less than the 10,000 pounds/foot.

Many other low-resistance objects, such as trees, road signs, utility poles, motorcycles, trailers, and trucks, are also in this relatively soft object category. All these objects pose no threat to the cask and require no further analysis. Table 6.2 identifies all objects that can generate a maximum quasi-static force less than 100,000 pounds/foot at any velocity. The percentage of accidents involving these objects is 94.7%.

The remaining highway accidents involve stronger and more massive objects, such as trains, bridge columns, abutments, and certain real surfaces such as roadbeds. The analysis of these accidents is described in the next subsection.

6.2.1.2. Response to Other Accidents

Truck accident scenarios involving impacts with trains, running off bridges or over embankments, and running into slopes or massive concrete structures require dynamic structural analysis. The cask dynamic response is analyzed for impacts with the principal objects involved in these accidents.

Figure 6-3 shows the variables considered in the dynamic response analysis: cask orientation, object hardness, and impact velocity. The IMPASC code is used only for unyielding targets. Different methods of analysis are used for soft objects, depending on their hardness. Hard objects are considered unyielding surfaces. The impact analysis application for these objects is presented in Subsection 6.2.1.2.1. Cask responses for relatively soft objects are discussed in Subsection 6.2.1.2.2

Table 6.2
Evaluation of Quasi-Static Force for Minor Highway Accident&/

	Accident Scenario	Frequency	Total Force (lb)	Linear Force (lb/ft)
1.	Soft objects (cones, animals, etc.)	0.034	<1,000	< 1,000
2.	Motorcycle	0.008	<20,000	<10,000
3.	Automobile	0.432	<50,000	<10,000
4.	Truck, bus	0.133	~400,000	<70,000
5.	Train	0.008		b/
6.	Other (rocks, furniture, etc.)	0.038	<50,000	~10,000
7-11	Bridge railing	0.005		b/
12-14	Columns, abutments	<0.001		b/
15.	Bridge bottom structure	<0.001	<100,000	<30,000
16.	Wall barrier, post	0.040	<50,000	<50,000
17.	Signs, cushions	0.005	<10,000	~10,000
18.	Curb, culvert	0.037	<10,000	<10,000
19-21	Into slope	0.025		b/
22-24	Over embankment	0.014		b/
25.	Over embankment (draining ditch)	0.009		c/
26.	Trees	0.009	<100,000	~70,000
27.	Other (fences, bushes, etc.)	0.033	<50,000	<10,000
28.	Overturn	0.083		c/
29.	Jackknife	0.055		c/
30.	Other (cargo shift, etc.)	0.020	<1,000	<1000
31.	Fire only	0.010		No load
		1.000		

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a/ Accident scenarios are screened out as minor except those designated for dynamic analysis.

b/ Linear force may exceed 100,000 lb/ft. Dynamic analysis is required.

c/ Fall impact distance is <15 ft.; therefore the linear force is <100,000 lb/ft.

6.2.1.2.1 Response for Impacts with Unyielding Surfaces

This subsection assesses cask response during impact with objects such as hard rock, which have a hardness close to the unyielding surface specified in regulations. The analysis considers variations in two parameters: cask orientation angle and impact velocity. IMPASC is used to calculate the cask response for cask orientation angles, β, of 0^{o}, 10^{o}, 30^{o}, 50^{o}, 70^{o}, and 90^{o} and impact velocities of 30 mph, 38 mph and 45 mph. The 0^{o} cask orientation angle represents an impact to the side of the cask, whereas the 90^{o} cask orientation angle is an impact to the end of the cask.

For the 90^{o} angle case, the effects of truck cab crushing and lead slump pressures are considered. The sensitivity study results are given in Fig. 6-6. The results indicate that, for the representative truck cask, a line connecting the endwise and sidewise strain responses conservatively bounds the strain responses for all other cask impact orientations. Therefore, for cask orientations from $0\text{-}90^{o}$, the structural strain responses can be linearly interpolated between the sidewise and endwise strain responses. The strain in the inner cask shell can reach 0.2% (SI) at an impact velocity of 32 mph for sidewise impacts and an impact velocity of 38 mph for endwise impacts.

6.2.1.2.2 Response for Real Objects

The equivalent damage technique estimates the representative truck cask response for endwise impacts on real surfaces. A rigid body with the outer dimensions and weight of the truck cask is dropped onto various surfaces from heights up to 480 feet and with equivalent velocities up to 120 mph. Figure 6-7 plots the interface forces for endwise impacts of the rigid body on tillable soil, soft rock/hard soil, and hard rock.

The impact force exceeds 1000 g for hard rock and 200 g for soft rock/hard soil. By comparison, an impact force of 40 g is presumed to cause a 0.2% strain (S_1) at the inner shell of the representative truck cask. For impact forces up to 40 g, the kinetic energy of the representative cask will be almost entirely absorbed by the cask's impact limiter. Above this force level, cask deformation will begin. Because 40 g << 200 g, soft and hard rock

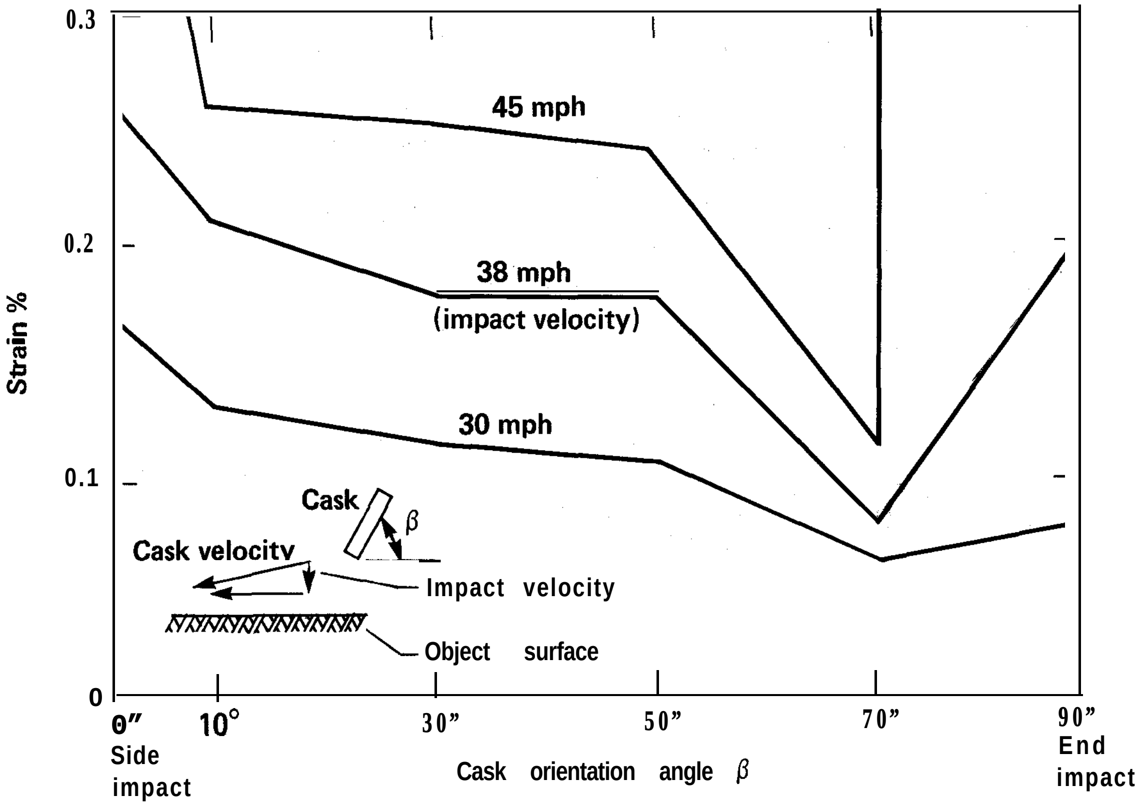

Figure 6-6 Strain versus impact velocity and cask orientation for the representative truck cask impacting an unyielding surface.

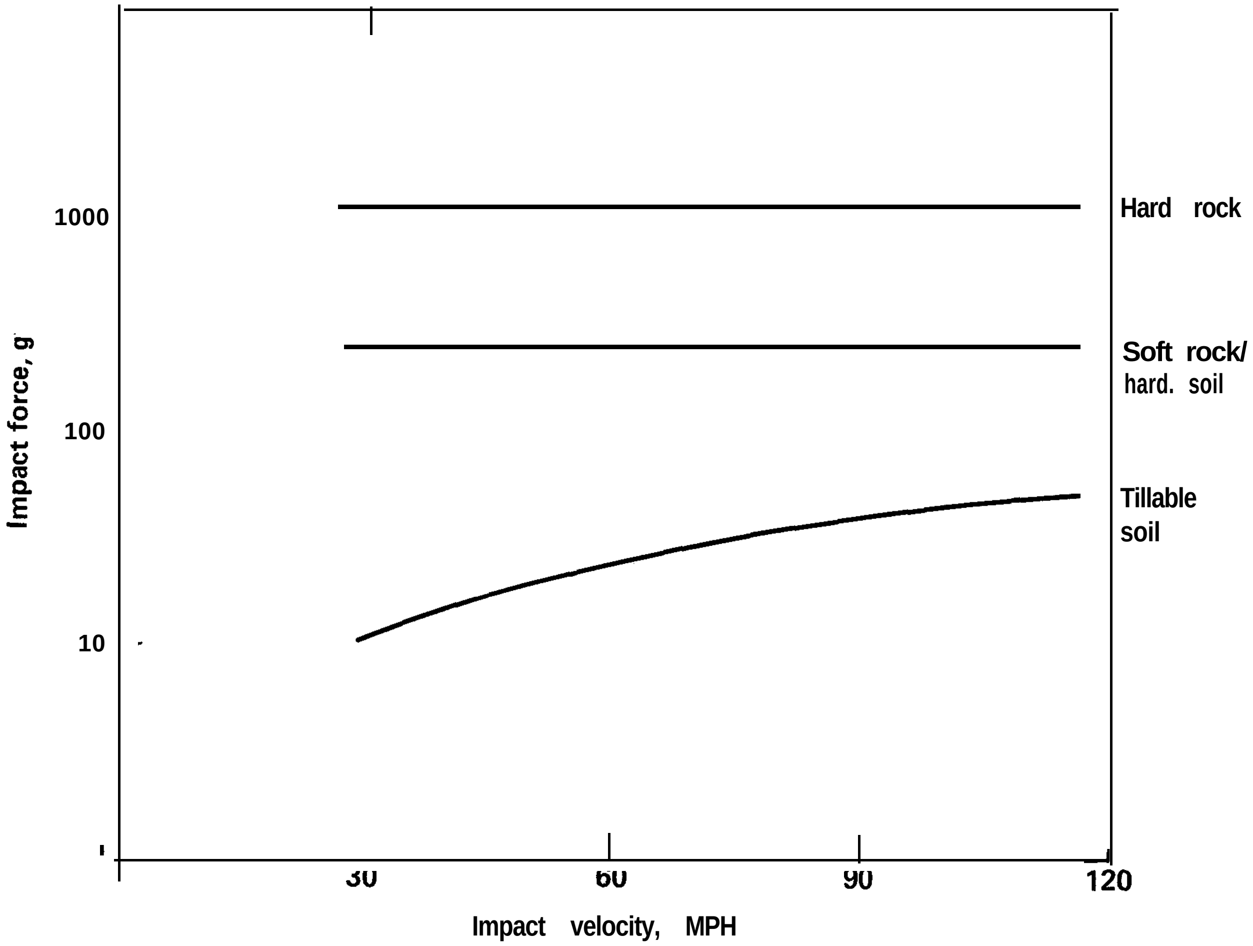

Figure 6-7 Impact force for a rigid truck cask dropped endwise onto real surfaces.

are treated as an unyielding surface. For impacts on tillable soils, the results shown in Fig. 6-7 indicate that significant energy can be absorbed by the soil at an impact force of 40 g. In this case, the representative cask can impact soil surfaces endwise at velocities up to 84 mph without exceeding the 0.2% strain (SI) level.

A similar equivalent damage evaluation is performed for sidewise drops onto various surfaces. To evaluate grade-crossing accidents, sidewise impacts by train sills are also analyzed to determine conditions which could cause 0.2% strain (S_1) at the inner shell. Table 6.3 summarizes the impact velocities needed to attain the 0.2% strain (SI) level for sidewise and endwise impacts on various surfaces, including water.

At the 0.2% strain (S_1) level and below, representative truck cask responses to impacts on hard or soft rocks are essentially equivalent to impacts on an unyielding surface for all orientation angles. Endwise and sidewise impact velocities of 38 mph and 32 mph respectively produce 0.2% strain (S_1) levels. For endwise impacts on soil, significant energy is absorbed by the soil, which allows the maximum impact velocity to increase to 84 mph.

For cask impacts on water at a 45° orientation, an impact velocity of 150 mph will not cause the strain to exceed the 0.2% (S_1) level. One-hundred-fifty mph is defined as the maximum credible impact velocity that can be attained based on review of the historical data base. This velocity corresponds to a drop height of 750 feet.

Head-on impact by locomotive sills at velocities greater than 9 mph can cause the 0.2% strain (S_1) level to be exceeded. The train sill goes between the impact limiters and strikes the side of the cask.

6.2.2 Cask Response Analysis for Railway Accidents

The representative rail cask described in Section 3.5 is used to perform the railway accident response analysis. The computer model of the cask and the detailed structural calculations used in the response analysis are discussed in Appendix E. The railway accident scenarios in Fig. 2-5 are used

Table 6.3
Impact Velocities Required to Reach the 0.2% Strain (S_1) Level for Objects Impacted in Highway Accidents

Object Impacted	Impact Velocity at 0.2% Strain (mph)		
	Cask Orientation Angle (°)		
	0	45	90
Hard Rock	32	35[a]	38
Soft Rock	32	35[a]	38
Tillable Soil	32	58[a]	84
Water	42	150	38
Train Sill	9	14	150

[a] Impact velocities at these orientation angles are linearly interpolated between the two bounding values.

as the basis for the structural evaluations. The results of the response evaluations are provided in Subsection 6.2.2.1 for minor accidents and in Subsection 6.2.2.2 for accidents in which the damage to a cask could be significant.

6.2.2.1 Response to Minor Accidents

Train accidents are primarily derailments or collisions with other trains. Collisions not involving derailment are usually minor. In non-derailment cases, the only events that must be considered are those in which the coupler of one rail car can override the impacted car and cause damage to a rail car or cask. Rail cars specially designed for casks place the cask in the center of the car. In general, collisions not involving derailment do not generate enough force for the coupler of an adjacent car to penetrate a rail cask because the coupler is too short, as shown in Fig. 6-8. In those cases where the force is great enough for the coupler to strike the cask, it is assumed that the cars derail and the coupler strikes the side of the cask. Impacts with small structures such as poles and retaining walls or impacts with the superstructure of locomotives or other cars cannot significantly damage a cask.

A rail cask is larger than a truck cask and requires greater forces to damage it. A 1.6-million-pound static crush (100,000 pounds/foot) is required on the side of the representative rail cask to cause a 0.2% strain (SI) at the inner shell; whereas a 13.0-million-pound static force is required on the end of the cask to cause a similar level of strain. Based on the first-stage screening of the truck cask, dynamic impact analysis of the rail cask has to be considered only for derailment-caused impacts with massive objects or surfaces adjacent to railroad right-of-ways. Derailments that result in rollovers onto the adjacent railbed involve falls that are less than 15 feet and impact velocities less than 22 mph. These impact velocities can partially crush the rail cask impact limiters but cannot cause any significant damage to the cask.

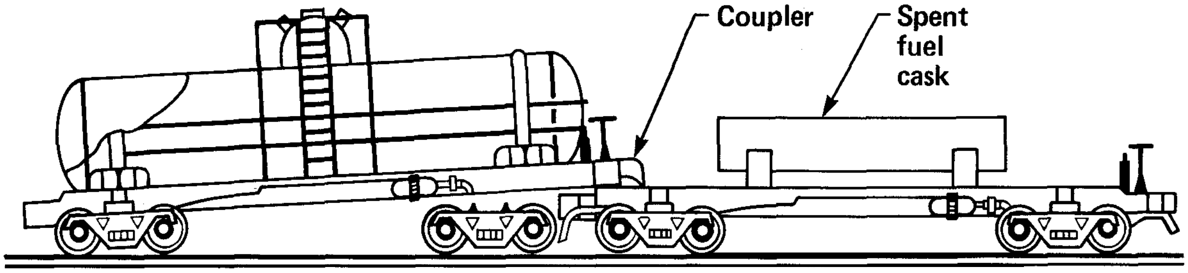

Figure 6-8 Rail car coupler override of spent fuel cask car.

Table 6.4 summarizes the 24 railway accident scenarios with their frequencies of occurrence. Those accident scenarios that can cause only minor cask damage are identified. The total fraction of minor accidents is calculated by summing the individual frequencies. The percentage of accidents screened out as minor is 96.1%. The remaining accidents involve derailments and impacts with massive objects such as train couplers, bridge columns, and abutments, and with surfaces such as rock. Subsection 6.2.2.2 discusses the analyses performed on the representative rail cask for these accidents.

6.2.2.2 Response to Other Accidents

Railway accident scenarios involving derailments and falls off bridges or run-offs over embankments or into slopes or massive concrete structures require dynamic analysis. These accidents may involve impacts with a variety of surfaces: hard rock, soft rock/hard soil, and tillable soil. The dynamic response of the cask for impacts with each of these objects is analyzed.

Three parameters are considered significant in the dynamic response analysis as shown in Figs. 6-3 and 6-4: cask orientation, object hardness, and impact velocity. Again, different methods of analysis are used to analyze objects of different hardness. Hard objects are considered unyielding surfaces and the impact analysis applicable for these objects is presented in Subsection 6.2.2.2.1 below. Cask responses for relatively soft objects are discussed in Subsection 6.2.2.2.2.

6.2.2.2.1 Response for Impacts with Unyielding Surfaces

This subsection assesses cask response during impact with objects such as rock that has a hardness close to the unyielding surface specified in regulations. The analysis considered variations in two parameters: cask orientation angle and impact velocity. IMPASC is used to calculate the cask response for cask orientation angles, β, of 0°, 10°, 30°, 50°, 70°, and 90° and impact velocities of 30 mph, 45 mph, and 60 mph. The 0° cask orientation angle represents an impact to the side of the cask, whereas the 90° cask orientation angle is an impact to the end of the cask.

Table 6.4
Evaluation Summary of Minor Railway Accident&

	Accident Scenario	Frequency	Total Force (lb)	Linear Force (lb/ft)
1.	Grade crossing	0.030	<400,000	<70,000
2.	Non-derailment	0.086	<500,000	<62,500
3-7	Over bridge	0.008		b/
8.	Over embankment - ditch	0.003		c/
9-11	Over embankment - other	0.006		b/
12-14	Into slope	0.016		b/
15-17	Columns, abutments	<0.001		b/
18.	Other structures	0.164	~500,000	762,500
19.	Locomotive superstructure	0.033	<500,000	<62,500
20.	Rail car superstructure	0.100	<500,000	<62,500
21.	Coupler/sill	0.008		b/
22.	Roadbed	0.160		c/
23.	Earth	0.320		c/
24.	Other, fire cargo shift	0.065	<10,000	~10,000
	Total	1.000		

a/ Accident scenarios are screened out as minor except those designated as significant for dynamic analysis.

b/ Linear force may exceed 100,000 lb/ft. Dynamic Analysis is required.

c/ Fall impact distance is <15 ft; therefore the linear force is <100,000 lb/ft.

The sensitivity study results are given in Fig. 6-9. For the 90° angle case, the effects of lead slump pressure and the crushing of the front end of the rail car are included. The results indicate that, for the representative rail cask, a line connecting the endwise and sidewise strain responses conservatively bounds the strain responses for all other cask orientations. Therefore, for cask orientations from 0-90°, the structural strain responses can be linearly interpolated between the sidewise and endwise strain responses. The strain in the inner cask shell can reach 0.2% (S_1) at an impact velocity of 55 mph for sidewise impacts and an impact velocity of 38 mph for endwise impacts.

6.2.2.2.2 Response for Real Objects

The equivalent damage technique estimates the representative rail cask response for endwise impacts on real surfaces. A rigid body with the outer dimensions and weight of the rail cask is dropped onto various surfaces from heights up to 480 feet and with equivalent velocities up to 120 mph. Figure 6-10 plots the interface forces for endwise impacts on tillable soil and soft rock/hard soil. Calculations are not performed for impacts on hard rock. It is apparent from the soft rock/hard soil cask results that a hard rock surface is essentially an unyielding surface with respect to the representative rail cask.

The impact force exceeds 400 g for soft rock/hard soil. The impact forces required for significant energy absorption by tillable soil exceed 40 g at velocities above 40 mph. Since the cask is designed to withstand an impact force of 40 g, it is presumed that such a force causes less than a 0.2% strain (S_1) at the inner shell of the representative rail cask. For impact forces up to 40 g on hard or soft rock surfaces, the kinetic energy of the representative cask will be almost entirely absorbed by the cask's impact limiter. For soil impacts, the kinetic energy will be absorbed by both the soil and the cask impact limiter.

A similar equivalent damage evaluation is performed for sidewise drops onto various surfaces. Table 6.5 summarizes the impact velocities needed to

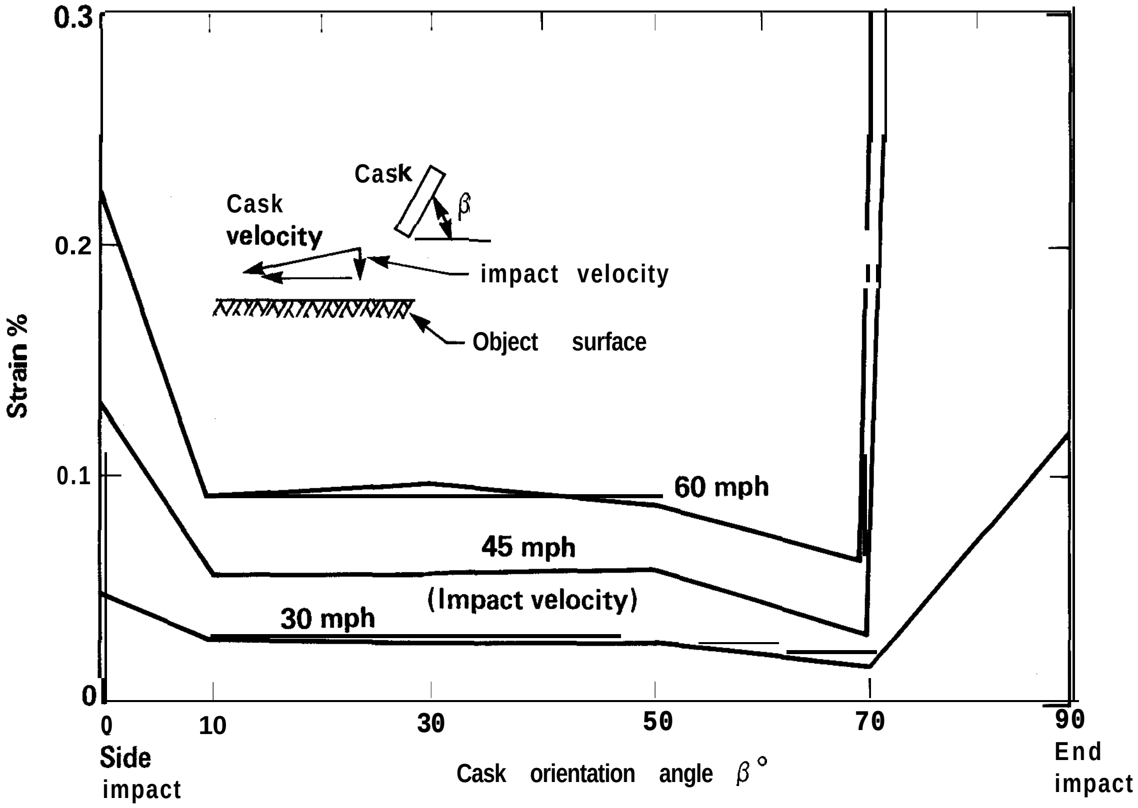

Figure 6-9 Strain versus impact velocity and cask orientation for the representative rail cask impacting an unyielding surface.

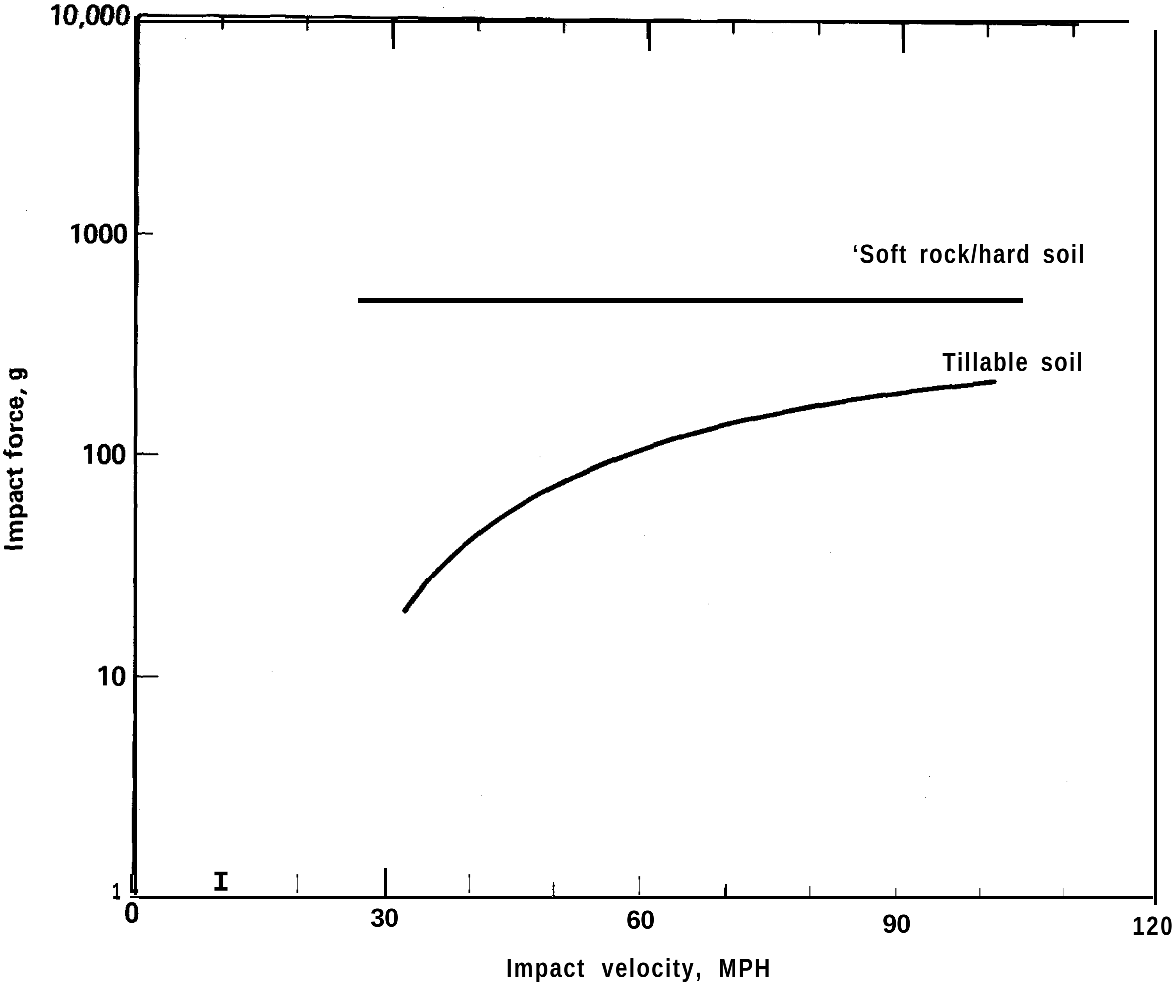

Figure 6-10 Impact force versus impact velocity for a rigid rail cask dropped endwise onto real surfaces.

Table 6.5

Impact Velocities Required to Reach the 0.2% Strain (S_1) Level for Objects Impacted in Railway Accidents

	Impact Velocity at 0.2% Strain (mph)		
	Cask Orientation Angle (°)		
Object Impacted	0	45	90
Hard Rock	55	47	38
Soft Rock	55	47	38
Tillable Soil	55	47	40
Water	55	150	38
Train Sill	11	16	150

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[a] Impact velocities at these orientation angles are linearly interpolated between the two bounding values.

attain the 0.2% strain (S_1) level for sidewise and endwise impacts on various surfaces, including water.

At the 0.2% strain (S_1) level and below, the representative rail cask responses to impacts on hard rock, soft rock, or soil are essentially equivalent to impacts on an unyielding surface for all orientation angles. For cask impacts on water at a 45^o orientation, an impact velocity of 150 mph can be reached without exceeding the 0.2% strain (S_1) level.

Head-on impacts by locomotive sills at velocities greater than 11 mph could cause the 0.2% strain (S_1) level to be exceeded. The train sill goes between the impact limiters and strikes the side of the cask.

6.2.3 Discussion of Structural Analysis Results

This section has thus far addressed highway and railway accidents that can generate structural cask responses less than the 0.2% strain (S_1) level. Cask structural responses within the 0.2% strain (S_1) level are in the elastic range and would not lead to any significant radiological releases. Cask response within these constraints will meet requirements imposed by existing regulations.

For those accidents requiring a dynamic structural calculation, the dynamic structural response of the cask is calculated using primarily elastic analysis methods. Dynamic elastic response methods are routinely used to analyze structures, and the results can be used with confidence.

Current and future cask designs are expected to be stronger than the selected representative cask designs and would be able to withstand higher mechanical loads before the 0.2% strain (S_1) level is reached, If a higher mechanical loading is required to cause the cask containment shell to reach the elastic limit, then a higher fraction of accidents will be screened out or shown to result in radiological hazards less than those in current regulations.

In July 1984, in Old Dalby, England, the United Kingdom Central Electricity Generating Board performed a train crash test with a steel spent fuel cask.[6] The 100-mph train crash subjected the cask to a force greater than 8 million pounds but caused only minor deformation to the outside of the cask. The primary response of the cask structure was elastic. In fact, the force the train applied to the steel cask was less than 40% of the International Atomic Energy Agency test condition loads,[7] which are similar to the test conditions specified in 10 CFR 71. Therefore, the actual percentage of highway and railway accidents that are within the envelope of current accident test conditions and radiation hazard limits specified in regulations, are likely to be higher than the percentages indicated in Section 6.4.

6.3 Thermal Response Analysis

Thermal loads due to large fires dominate the thermal evaluation. Other thermal loads due to torch fires or cask burial in debris that result from self-heating are insignificant and are eliminated in the thermal screening analysis. Each type of accident is evaluated for its potential for causing damage to a spent fuel cask, such as melting of the lead shield or damage to the cask seal. Even accidents involving only impact of a spent fuel transport truck with small objects or the adjacent roadbed can result in a fire that could burn up to an hour because of the diesel fuel being carried by the truck. Other accidents involving impacts with tanker trucks, locomotives, and tank cars, each of which carry considerable amounts of fuel, can cause fires that could last for a few hours.

The intent of this section is to determine the fraction of accidents that will not cause a temperature exceeding $500^{o}F$ (TI) at the middle of the lead shield thickness of the representative casks. Heating the cask structure to $500^{o}F$ (T_1) does not result in any significant deterioration of the cask components. This statement applies to cask seals, which are the component whose failure could signify the earliest onset of a potential radioactive release.

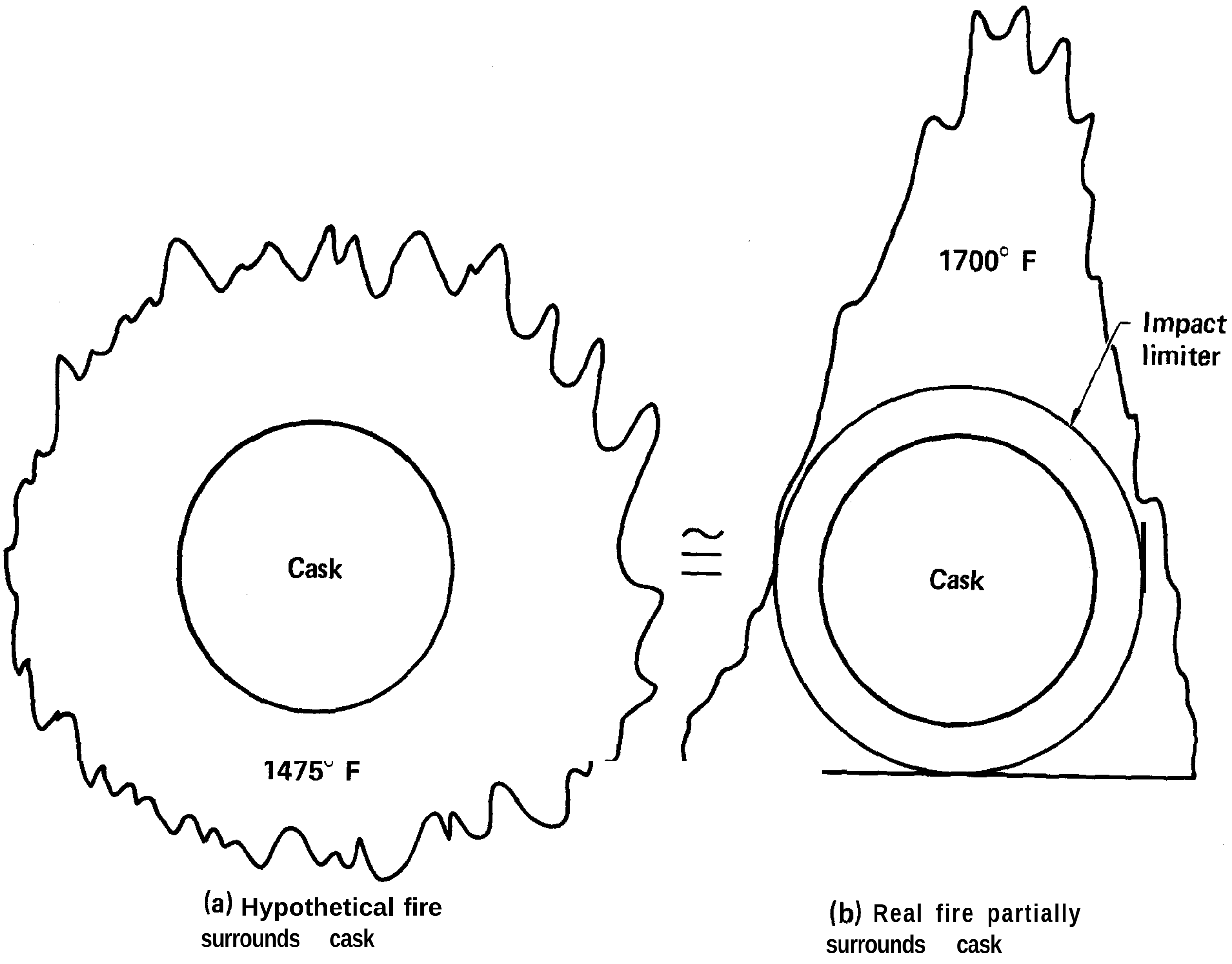
A finite element computer code called TACO 2-D is used to perform the thermal analysis of the cask.[8] Sensitivity studies indicate that a one-dimensional (1-D) heat transfer model can be used, which simplifies the analysis, reduces computing time, and provides suitably conservative results. In all of the analyses, the representative casks neutron shield tank water is lost prior to the fire. The thin outer shell of the remaining neutron shield tank provides a thermal barrier to the fire. Loss of the shield water reduces heat transfer into the cask; it also removes a significant heat absorber, water.

Currently licensed cask designs are reviewed to relate the temperatures at the mid-plane of the cask to the temperatures at other locations, particularly the closure seals. Valve boxes located where they can be exposed to heat loads and temperatures approaching those in the middle portion of the cask are also considered. These sensitivity studies confirm the selection of the lead shield temperature as the most appropriate and conservative measure of cask thermal response.

Fire accidents have three loading parameters that can affect the response of a spent fuel cask: fire duration, flame temperature, and fire location. These loading parameters vary widely when considering all fire accidents. Longer fire durations and higher flame temperatures increase the thermal loads to the cask and affect temperature responses. The proximity of the cask to a fire is also important. The closer a cask is to a fire, the higher the thermal load; the worst case is a cask being engulfed by a fire.

In order to reduce the large amount of analysis otherwise required to cover a wide range of fire accidents, a simplified calculational method is developed. The method includes the following steps:

1. A reference fire condition is established to perform the thermal response analysis for the representative truck and rail casks. The first step in accomplishing this task is to relate the thermal condition specified in 10 CFR 71 to real fire conditions. As shown in Fig. 6-11, a cask is completely surrounded by fire in the accident test conditions used to guide design; whereas the cask would most likely be only partially surrounded by a fire in a real situation because of the shielding effects of the ground, transport vehicle, or other cask-supporting surfaces. For



(a) Hypothetical fire surrounds cask

(b) Real fire partially surrounds cask

Figure 6-11 Comparison of an engulfing hypothetical fire and a real fire.

the same flame temperature, the average heat flux into the cask in a real engulfing fire is 0.78 of the heat flux on the cask in the hypothetical engulfing fire. A flame temperature of 1700°F is required for a real engulfing fire, including ground or transport vehicle shielding effects, to provide the same average heat flux and temperature response as the 1475°F hypothetical engulfing fire. The 1700°F real engulfing fire is the reference fire condition.

2. The heat fluxes and temperature responses of the truck and rail casks are calculated as a function of fire duration. These evaluations are performed using a 1-D model and the thermal parameters for the accident test conditions.

3. Based on sensitivity studies in Appendix F, the time to reach a specific temperature is approximately proportional to the incident heat flux on the cask caused by the fire. A fire that causes a heat flux twice that of the reference fire can heat a cask to a specified temperature in one-half the time. Conversely, a fire that causes a heat flux one-half the amount takes twice as long to heat the cask to a specified temperature. Using this correlation and the results from step 2, the fire durations required to reach the 500°F temperature (T_1) level are calculated for a range of heat fluxes that cover a wide range of real fire conditions.

4. The variation of heat loads on the representative casks is determined as a function of the flame temperature and location. The heat load variations are normalized to the engulfing real fire condition and defined as flux factors for flame temperature and load factors for fire location.

5. Using the fire duration results from step 3 and the heat flux factors from step 4, the fire duration required to reach the 500°F temperature (T_1) level is derived for a wide range of flame temperatures and locations.

The thermal response analysis of highway fire accidents is performed based on the above calculational method. The analysis appears in Subsection 6.3.1. The 31 highway accident scenarios are analyzed to determine the thermal loading conditions that can cause a temperature response of 500°F (T_1) or less at the mid-thickness of the lead shield of the representative truck cask. Subsection 6.3.2 describes a similar response analysis performed for 24 railway fire accident scenarios that could involve the representative rail cask. The thermal response results are discussed in Subsection 6.3.3.

6.3.1 Cask Response Analysis for Highway Fire Accidents

The representative truck cask described in Section 3.5 is used to perform the highway accident response analysis, Appendix F discusses the cask model and the detailed thermal calculations used in the response analysis.

The temperature response of the representative truck cask is calculated for a hypothetical engulfing fire with a 1475°F flame temperature. A flame emissivity of 0.9 is assumed. The temperature at the middle of the lead shield thickness is plotted in Fig. 6-12 as a function of fire duration. The lead mid-thickness temperature reaches 500°F (T_1) in 1.08 hours which is twice the regulatory fire duration. The total heat absorbed by the cask in reaching the 500°F temperature (T_1) is 5,000 Btu/ft^2 which results in an average thermal flux of approximately 4,630 Btu/hr-ft^2 compared with the initial rate of 17,000 Btu/hr-ft^2. The average thermal flux is lower because the thermal barrier formed by the water jacket rapidly reduces the heat flow into the cask during the first 10 minutes as shown in Fig. 6-13. These heat fluxes are equivalent to those on a cask in a real engulfing fire with a flame temperature of 1700°F.

For engulfing fires, the heat flux from the fire onto the surface of the truck cask depends on radiation heat transfer caused by the flame temperature. The average heat flux on the representative truck cask is calculated as a function of flame temperature for a hypothetical engulfing fire. The heat flux is then reduced by a factor of 0.78 to adjust the results

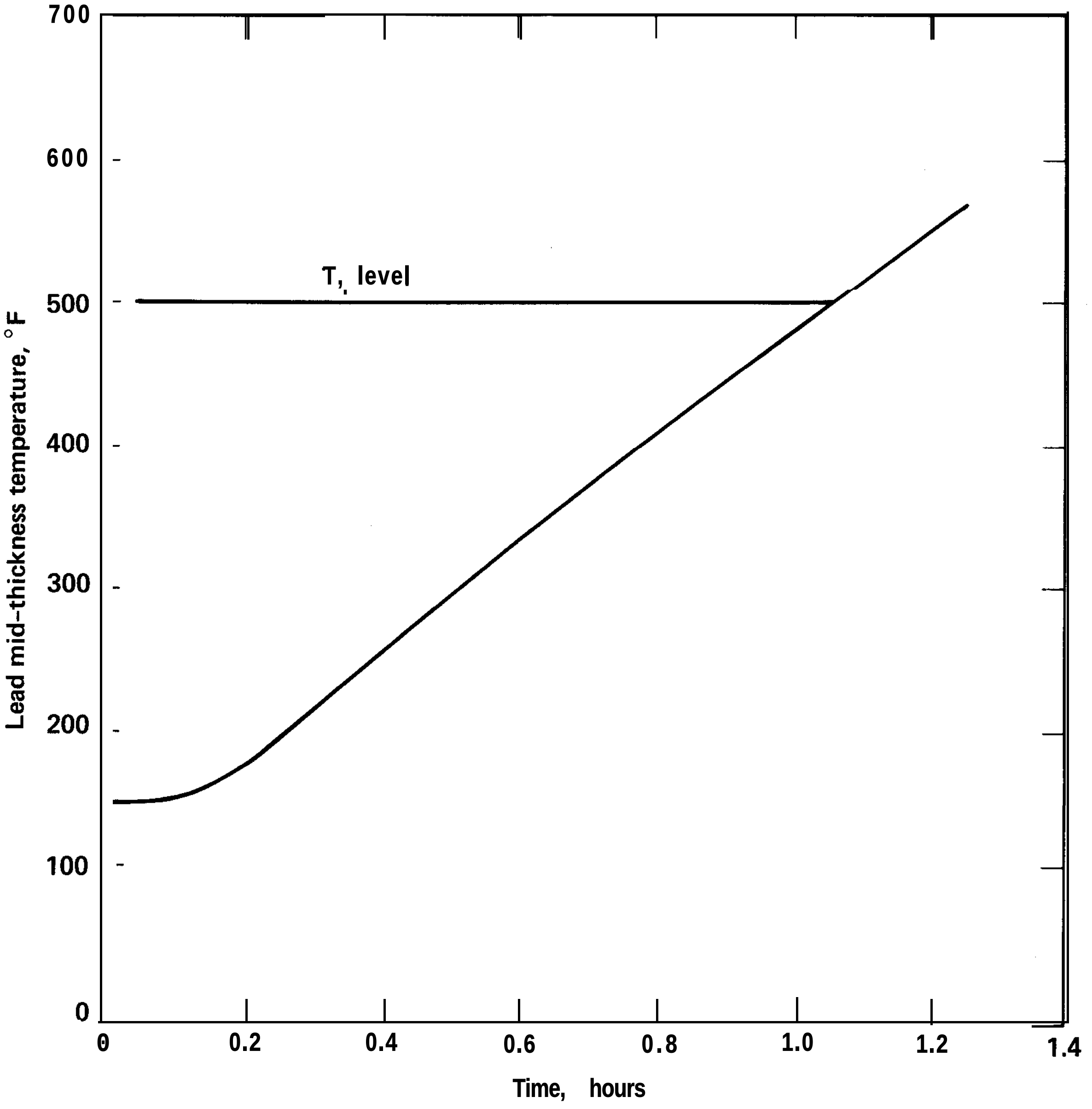


Figure 6-12 Representative truck cask temperature response to a hypothetical 1475°F (equivalent to a real 1700°F) fire versus fire duration.

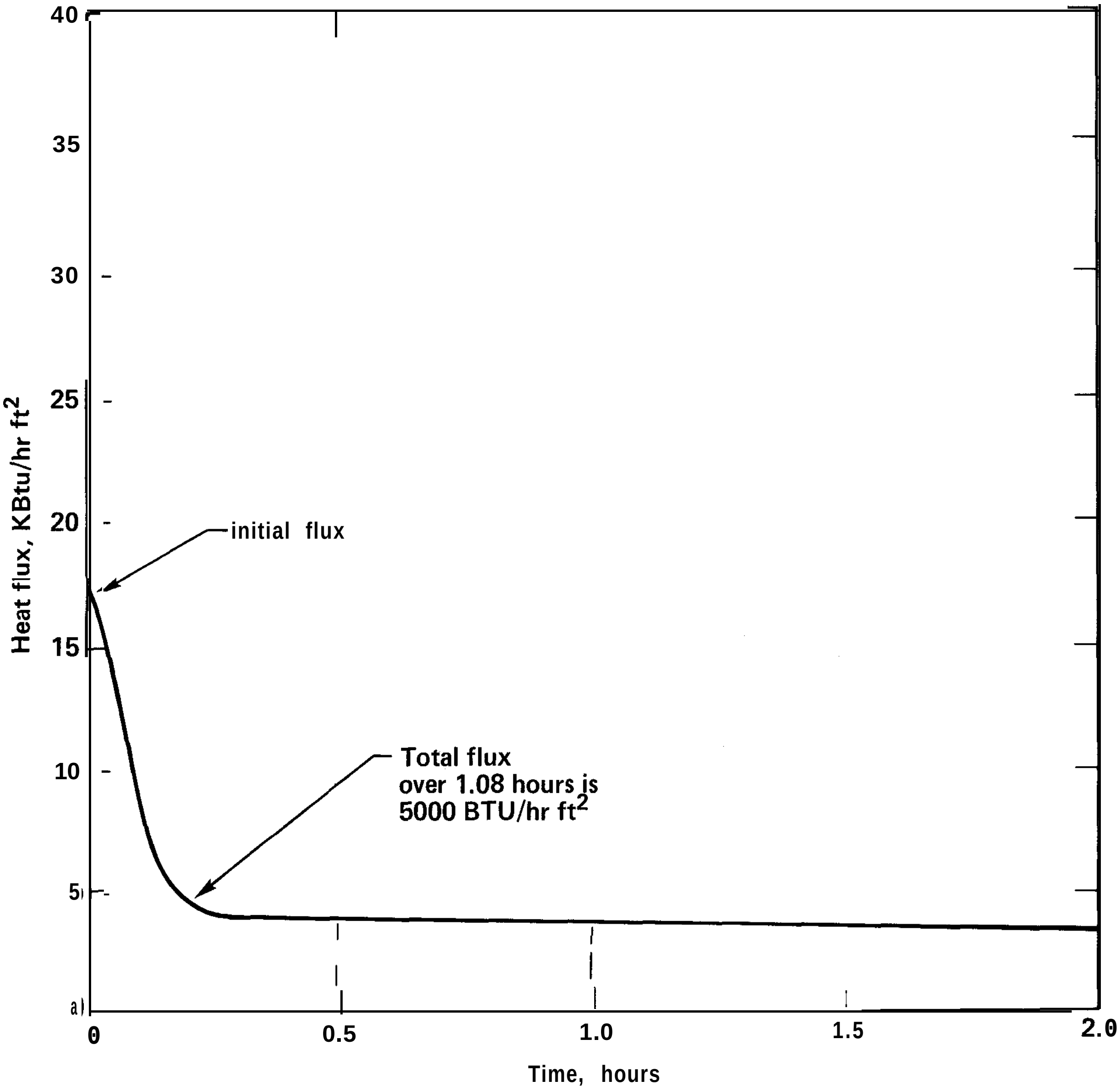


Figure 6-13 Heat flux versus fire duration for the representative truck cask exposed to the regulatory 1475°F fire.

for real fire conditions. This normalized heat flux factor is plotted in Fig. 6-14 as a function of flame temperature. For a 1700°F real fire, the average thermal flux on the representative cask is 4,630 Btu/hr-ft^2 and the heat flux factor is 1.0. As the flame temperature increases, the thermal flux increases, and the fire duration required to reach the 500°F temperature (T_1) level decreases.

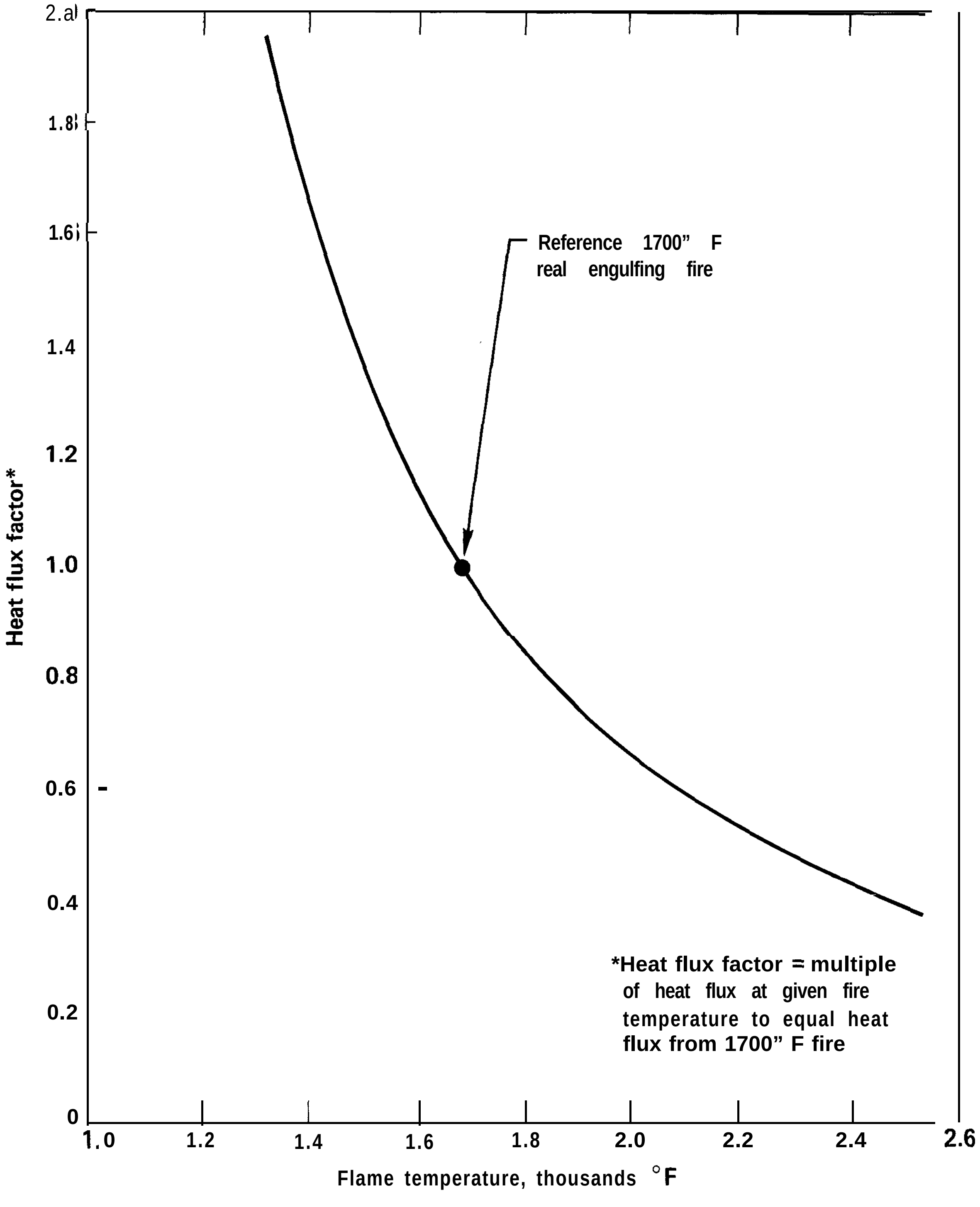
The heat load to the truck cask also depends on the location of the fire with respect to the cask. In terms of location, an engulfing fire provides the maximum heat load to the cask. The heat load decreases rapidly as the distance between the fire and the cask increases. Figure 6-15 shows the effect of distance between cask and fire for the truck cask where the heat load factor is normalized with respect to a real engulfing fire.

The heat flux and load factors are used to calculate the change required in the 1.08 hour reference fire to reach the 500°F temperature (TI) level for a variety of flame temperatures and durations. The fire durations for the wide range of fire conditions are calculated using the probabilistic code described in Section 5.0.

6.3.2 Cask Response Analysis for Railway Fire Accidents

The representative rail cask in Section 3.5 is used to perform the railway fire accident response analysis. The computer analysis of the cask and the detailed thermal calculations are provided in Appendix F.

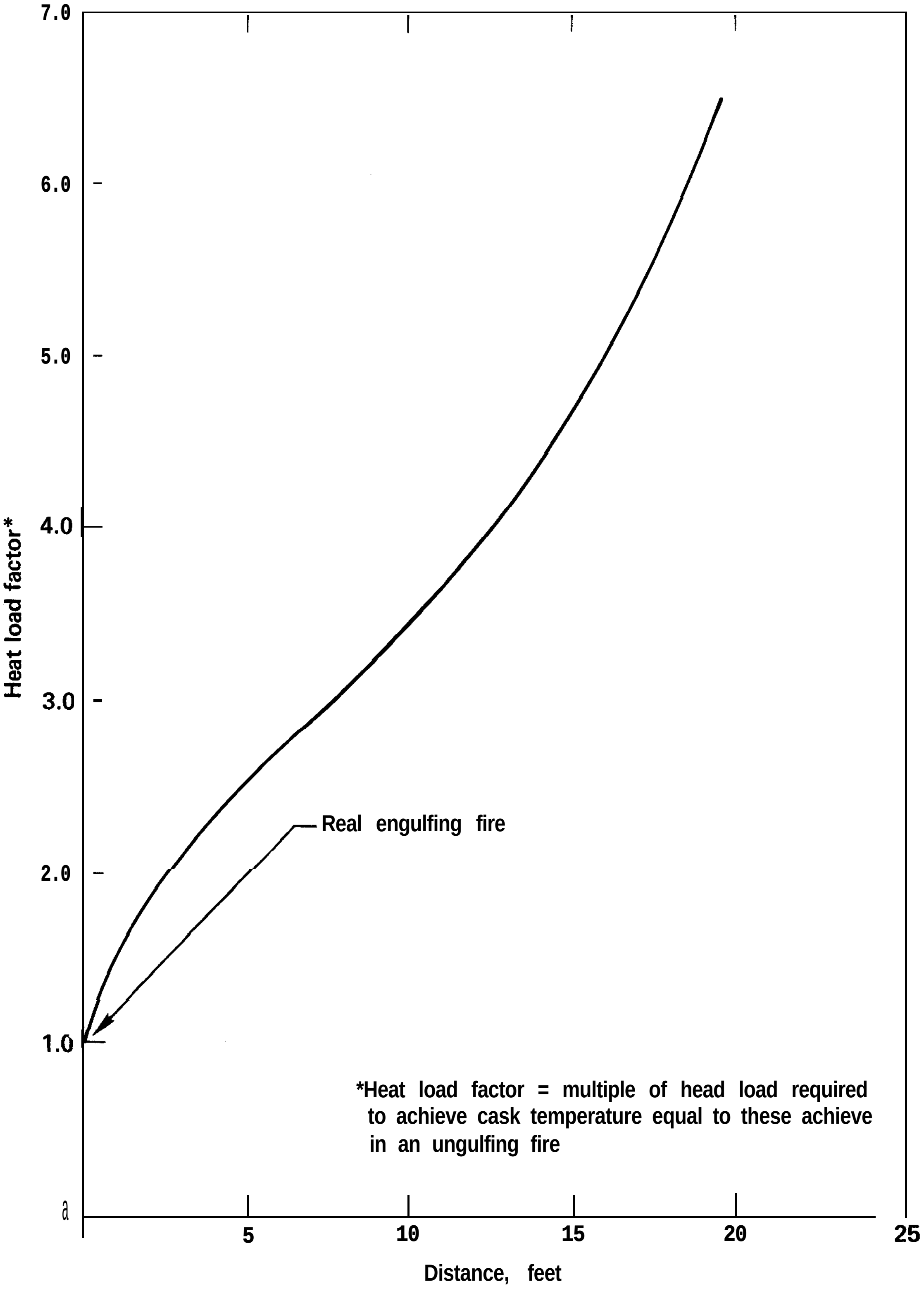
The temperature response of the representative rail cask is calculated for a hypothetical engulfing fire with a flame temperature of 1475°F and flame emissivity of 0.9, The temperature at the middle of the lead shield thickness is plotted in Fig. 6-16. The lead mid-thickness temperature reaches 500°F (TI) in 1.35 hours which is more than twice the regulatory fire duration. The total heat absorbed by the cask in reaching the 500°F (T_1) level is approximately 6,000 Btu/ft^2 which results in an average heat flux of approximately 4,445 Btu/hr-ft^2. These heat fluxes are equivalent to those on a cask in a real engulfing fire with a flame temperature of 1700°F.



Reference 1700" F real engulfing fire

*Heat flux factor = multiple of heat flux at given fire temperature to equal heat flux from 1700" F fire

Figure 6-14 Average heat flux factor versus temperature for the representative truck cask.



Real engulfing fire

*Heat load factor = multiple of head load required to achieve cask temperature equal to these achieve in an ungulfing fire

Figure 6-15 Heat load factor for real fire versus location of representative truck cask.

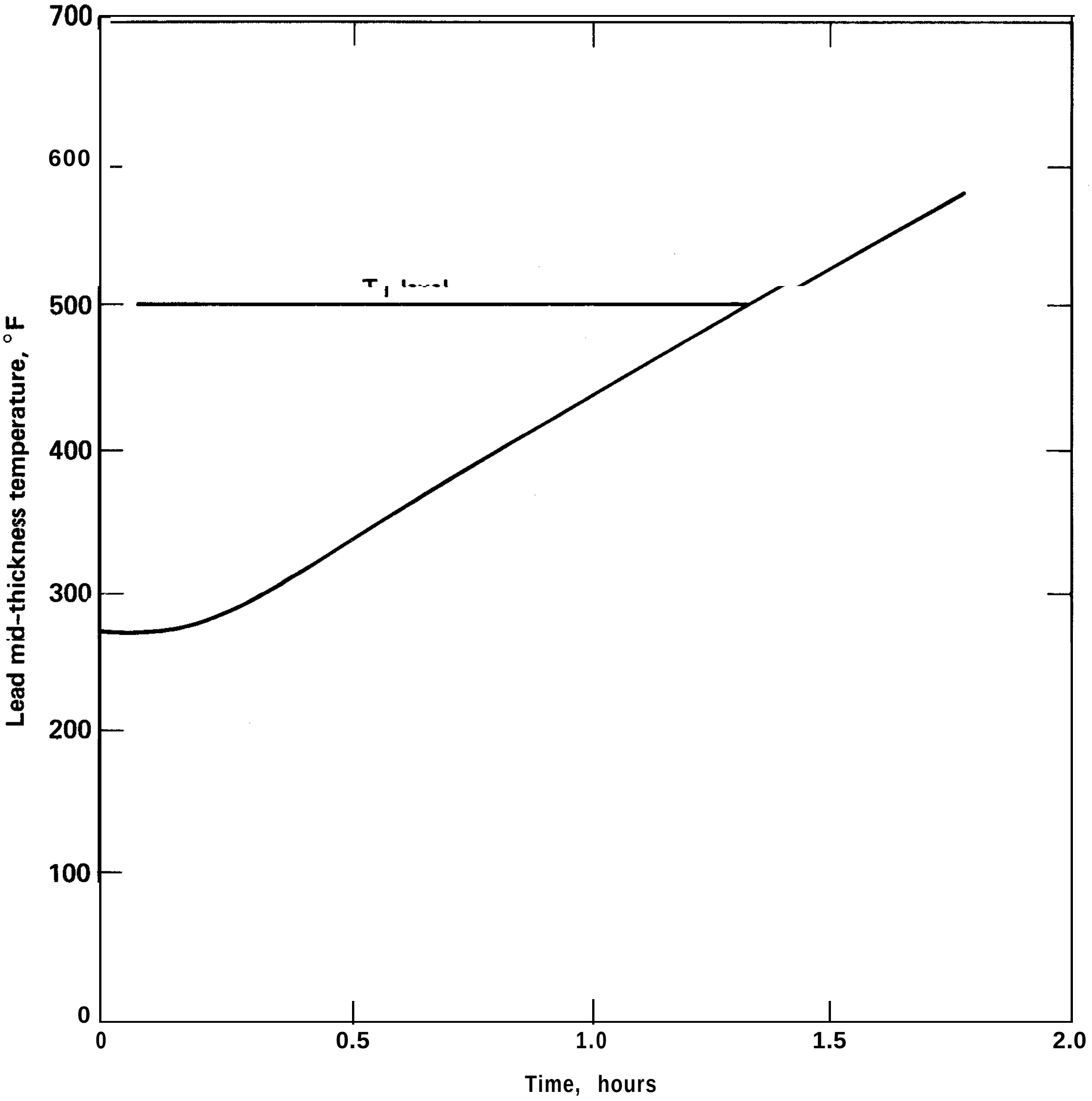


Figure 6-16 Representative rail cask temperature response to a hypothetical 1475°F (equivalent to a real 1700°F) fire versus fire duration.

For engulfing fires, the heat flux from a fire to the surface of the rail cask depends primarily on radiation heat transfer and is determined by the flame temperature. The heat flux dependency on the flame temperature is essentially the same as that for the truck cask discussed in Subsection 6.3.1. The average heat flux factors in Fig. 6-14 are used to adjust for flame temperature for the rail cask.

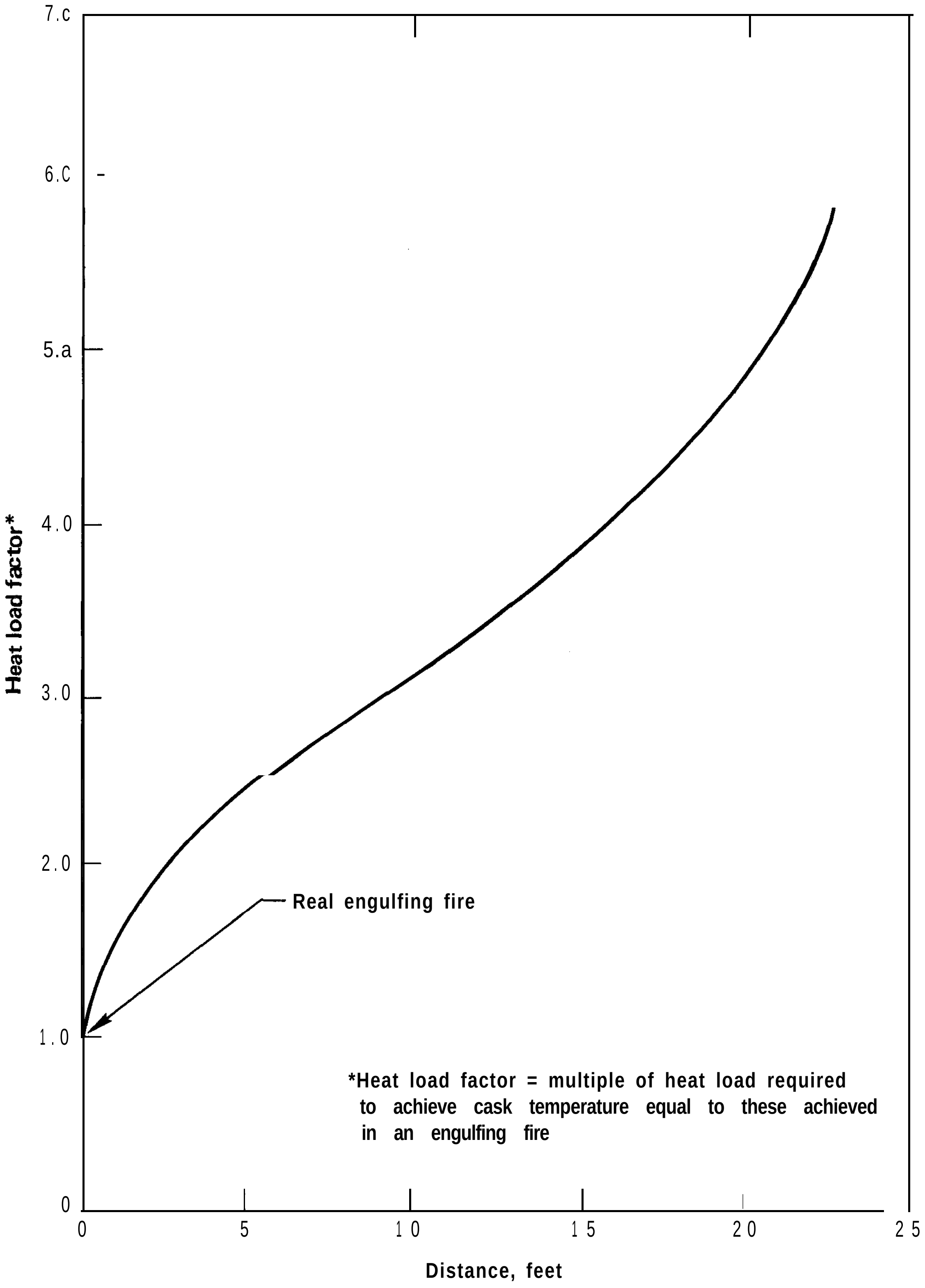
The heat load to the rail cask also depends on the location of the fire with respect to the cask. An engulfing fire provides the maximum heat load to the cask. The heat load decreases rapidly as the distance between the fire and the cask increases. Figure 6-17 shows the effect of distance between the cask and fire for the representative rail cask. The heat load factor is normalized with respect to an engulfing fire.

The heat flux and load factors are used to calculate the change required in the 1.35 hour reference fire to reach the 500°F temperature (T_1) level for a variety of flame temperatures and durations. The fire durations are calculated using the probabilistic code described in Section 5.0 for the wide range of fire conditions.

6.3.3 Discussion of Thermal Analysis Results

This section addresses highway and railway fire accidents which generate cask temperature responses less than or equal to the 500°F temperature (T_1) level. These accidents result in heating the cask structure to temperatures at which no significant deterioration of the cask components is expected, As a result, the radiological significance of such events is negligible.

The results indicate that the representative truck and rail casks can be exposed to a regulatory fire (1475°F, engulfing, etc.) for over 1 hour before the 500°F temperature (T_1) limit is reached. This fire duration is approximately twice as long as that specified in the regulations for the accident test conditions; hence, the representative cask designs have considerable margin with respect to the fire duration. This margin is due to the high heat capacity and thermal resistance inherent in the casks. The massiveness of spent fuel casks due to shielding and mechanical strength contributes significantly to the thermal response characteristics.



*Heat load factor = multiple of heat load required to achieve cask temperature equal to these achieved in an engulfing fire

Figure 6-17 Heat load factor for real fire versus location of representative rail cask.

In reality, many currently licensed casks use components and seals that can reliably function at temperatures exceeding those associated with a 500^oF (T_1) lead mid-thickness temperature for long periods of time without being damaged. Therefore, the actual percentage of highway and railway accidents that are within the thermal loading envelope of the accident test conditions is significantly higher than those documented in this study. The radiological hazards for these events are expected to be negligible.

6.4 Accident Screening Analysis

Section 5.0 provides the detailed probabilistic calculations performed in the accident screening analysis. From that analysis, approximately 99.4% of both highway and railway accidents leads to cask responses within the R(1,1) response region. At this level of damage, no radiological hazards of significance are expected; therefore, all are within the stated regulatory limits for radioactive releases and direct exposures. These results are discussed in detail in Subsection 9.2.1.

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7.0 SECOND-STAGE SCREENING ANALYSIS

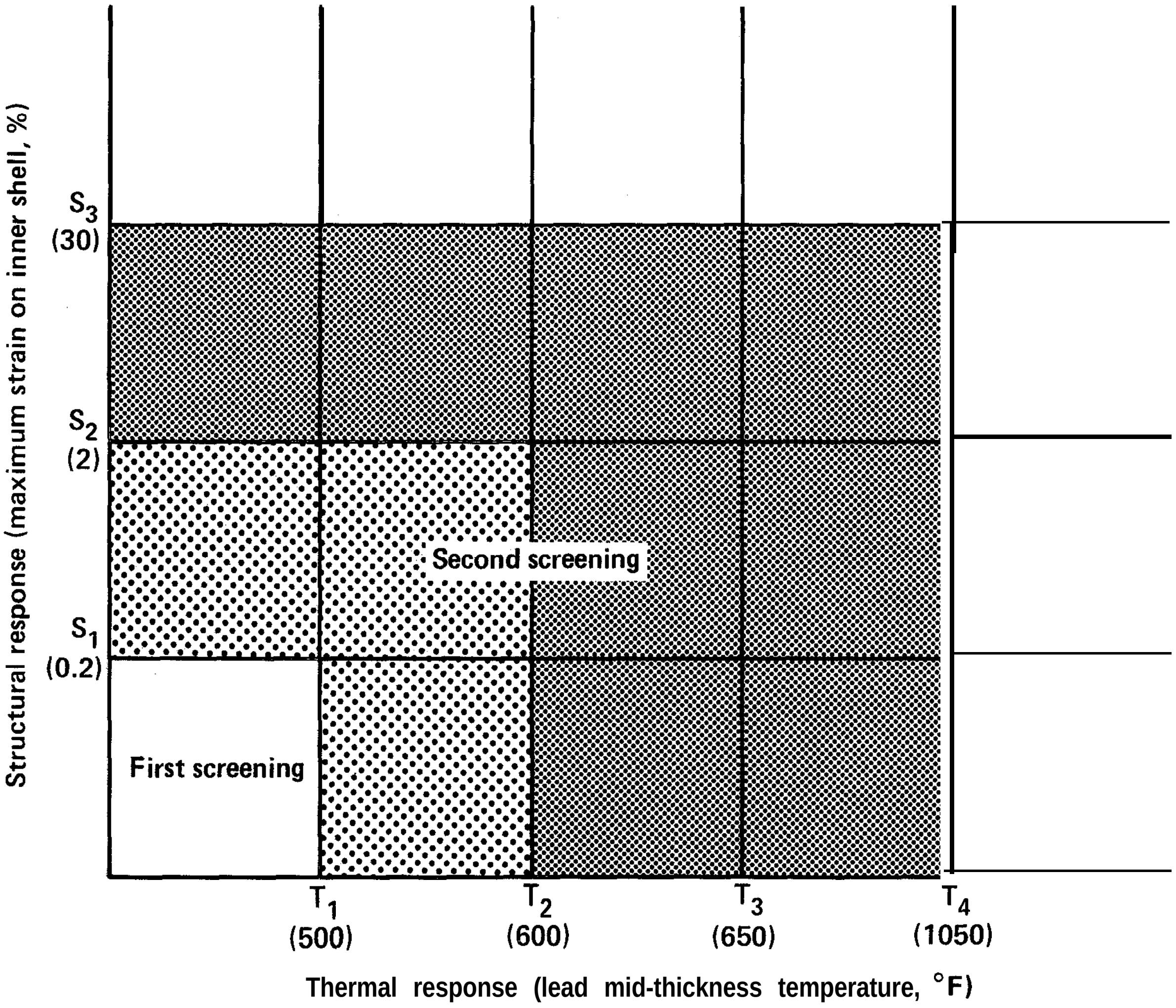
7.1 Introduction

The first-stage screening analyses identify classes of accidents in which the responses generated by the mechanical and thermal loadings are within the R(1,1) response region. At levels of response within the R(1,1) region, the accident event would not be expected to have any radiological significance. Approximately 99.4% of highway and railway accidents are expected to cause cask response. states within the R(1,1) region.

The residual 0.6% of highway and railway accidents which could cause cask responses outside the R(1,1) region are addressed in this section. The intent of the second-stage screening is to determine what fractions of these residual accidents can be categorized- into regions bounded by 30% strain (S_3) in the inner cask containment shell and by a lead mid-thickness temperature of 1050^oF (T_4). These regions are shown in Fig. 7-l.

The light stippled area in Fig. 7-1, which covers regions R(1,2),R(2,1), and R(2,2), represents cask responses between the 0.2% (S_1) and 2% (S_2) strain levels and between the 500^oF (T_1) and 600^oF (T2) temperature levels. These cask responses exceed the responses that would be generated if a shipping cask were subjected to the 10 CFR 71 accident test conditions.[1] Responses in this light stippled area can result in minor damage to the cask and could result in small radioactive releases or small increases in the direct radiation levels external to the cask. The radiological hazards associated with these cask responses could approach or slightly exceed the regulatory limits specified in 10 CFR 71 for transportation accidents.

The remaining eight regions, beyond the 2% strain (S_2) and 600^oF temperature (T2) levels, represent individual or combined cask responses between the 2% (S_2) and 30% (S_3) strain levels and between the 600^oF (T_2) and 1050^oF (T_4) temperature levels. For clarity, they are darkly shaded in Fig. 7-l. These responses are significantly greater than the responses expected after exposing the representative casks to the accident test conditions. Responses within the darkly shaded area in Fig. 7-l can result in



0 First-stage screening analysis radiological hazards are negligible and less than 10 CFR 71 limits.

0 Second-stage screening analysis radiological hazards can be less than, equal to, or greater than 10 CFR 71 limits.

- Light stippled area - minor damage to cask, with consequent radiological hazards approaching or slightly exceeding 10 CFR 71 limits.

0 - Dark shaded area - more substantial cask damage, with radiological hazards probably exceeding 10 CFR 71 limits.

Figure 7-1 Second-stage screening analysis relationship with response regions.

significant permanent deformation of the cask structure and melting of the lead shielding. Any radioactive material releases or increase in the direct radiation levels that could result from these cask responses are probably greater than the regulatory limits specified in 10 CFR 71 for transportation accidents.

The second-stage screening analysis involves calculations similar to those performed in the first-stage screening. The major difference between the two screening evaluations involves the calculational methods used. Nonlinear small-deformation analysis methods are needed to analyze the cask structure for deformations having strain levels within the 2% strain (S2) limit. For strain levels beyond the 2% (S_2) limit, nonlinear, large deformation methods are needed. Thermal analysis methods account for the melting of the lead shield in the 600^oF (T_2) to 1050^oF (T_4) temperature range.

Section 7.2 discusses the structural response of the representative casks to mechanical loads; Section 7.3 addresses response to thermal loads. In Section 7.4, the results of both structural and thermal response are combined to estimate the fraction of accidents that fall within each of the response regions.

7.2 Structural Response Analysis

The classes of accidents requiring structural analysis in the second-stage screening typically involve impacts with massive objects or hard surfaces. In these accidents, dynamic forces greater than 400,000 pounds can be generated. The computer codes selected to perform the required analysis include two established codes called DYNA 2-D/3-D and NIKE 2-D/3-D; the 2-D/3-D designation indicating that either two- or three-dimensional modeling can be performed.[2,3] Two-dimensional calculations are much simpler and faster to run and are used whenever possible. The applicability of the 2-D modeling is verified through the performance of sensitivity studies which compared results of 2-D and 3-D modeling. The calculation methods and assumptions used in the 2-D modeling are discussed in further detail in Appendix E. The most significant aspects include the following:

1. For cask orientations between sidewise and endwise in the range of $0^0 < \beta < 90^0$, the structural strain responses for the representative casks impacting solid surfaces are linearly interpolated from the results of sidewise, $\beta=0^0$, and endwise, $\beta=90^0$, impacts.

2. Two-dimensional plane strain analyses without impact limiters or end enclosures are performed for high velocity sidewise impacts, $\beta=0^0$, on hard rock, soft rock, and soil surfaces, This elimination of impact limiters overestimates strain responses of the representative casks, particularly for impact velocities less than 60 mph and for impacts on soft surfaces such as soil. The 2-D method is benchmarked with a 3-D impact analysis that modeled the representative truck cask with the inclusion of the impact limiters and end closures.

3. The strain responses of the representative casks impacting real surfaces are estimated using the equivalent damage technique discussed in Section 6.2 and in Appendix E.

The structural response analysis of highway accidents is in Subsection 7.2.1. Highway accident scenarios, in which the first-stage screening indicates the possibility of cask response outside the R(1,1) region, are evaluated. The fraction of these accidents causing responses within the 0.2% (S_1) to 2% (S_2) and 2% (S_3) to 30% (S_3) strain levels on the inner shell of the representative truck cask is determined. Subsection 7.2.2 describes a similar structural response analysis performed for the railway accidents. In Subsection 7.2.3 the overall structural analysis results are discussed.

7.2.1 Cask Response Analysis for Highway Accidents

The representative truck cask described in Section 3.5 is used in the second stage screening analysis for highway accidents. Appendix E discusses the computer models of the cask, material properties, and the detailed structural evaluations used in the response analysis.

The highway accident scenarios involve impacts by train sills and impacts occurring as a result of a truck running off a bridge, over an embankment, into a slope, or into a massive concrete structure.

In this evaluation, the maximum strain at the inner wall of the representative truck cask is calculated as a function of the impact velocity for both endwise and sidewise impacts with real surfaces.

7.2.1.1 Endwise Impacts

Since the representative truck cask is axi-symmetric along its length, a 2-D cask model with impact limiters is used to evaluate the response of the representative truck cask for endwise impacts on an unyielding surface. Figure 7-2 shows the strain response for the representative truck cask impacting an unyielding surface at 45 mph. The maximum strain of 3.63% occurs on the inner shell of the cask at the bottom junction with the end-cap, near the point of impact. The lead slumps to the impacted end of the cask, causing a 4-inch gap in the lead shield at the opposite end.

The cask impact calculations are performed, assuming impacts on an unyielding surface, over a range of velocities from 30 to 90 mph. As discussed in Appendix E, the energy absorption effects of crushing the transport truck cab are included in the analysis. The resultant impact force, maximum plastic strain at the inner shell of the cask, and the amount of lead slump are plotted as functions of impact velocity in Fig. 7-3. The 2% strain (S_2) level occurs when a cask impacts an unyielding surface at a velocity of 46 mph. At this velocity the impact force is 80 g, and the lead slump is about 3 inches. The 30% strain (S_3) level occurs when a cask impacts an unyielding surface at a velocity of 76 mph. The resultant impact force is 300 g and the lead slump is 16 inches. In both cases, the maximum strains occur because of lead slump at the bottom of the cask on the inner shell.

The equivalent damage technique, discussed in Section 6.2 and Appendix E, is used to estimate the cask response for endwise impacts on real surfaces. A rigid body with the outer dimensions and weight of the truck cask impacts varying surfaces at velocities up to 120 mph. The resultant interface forces

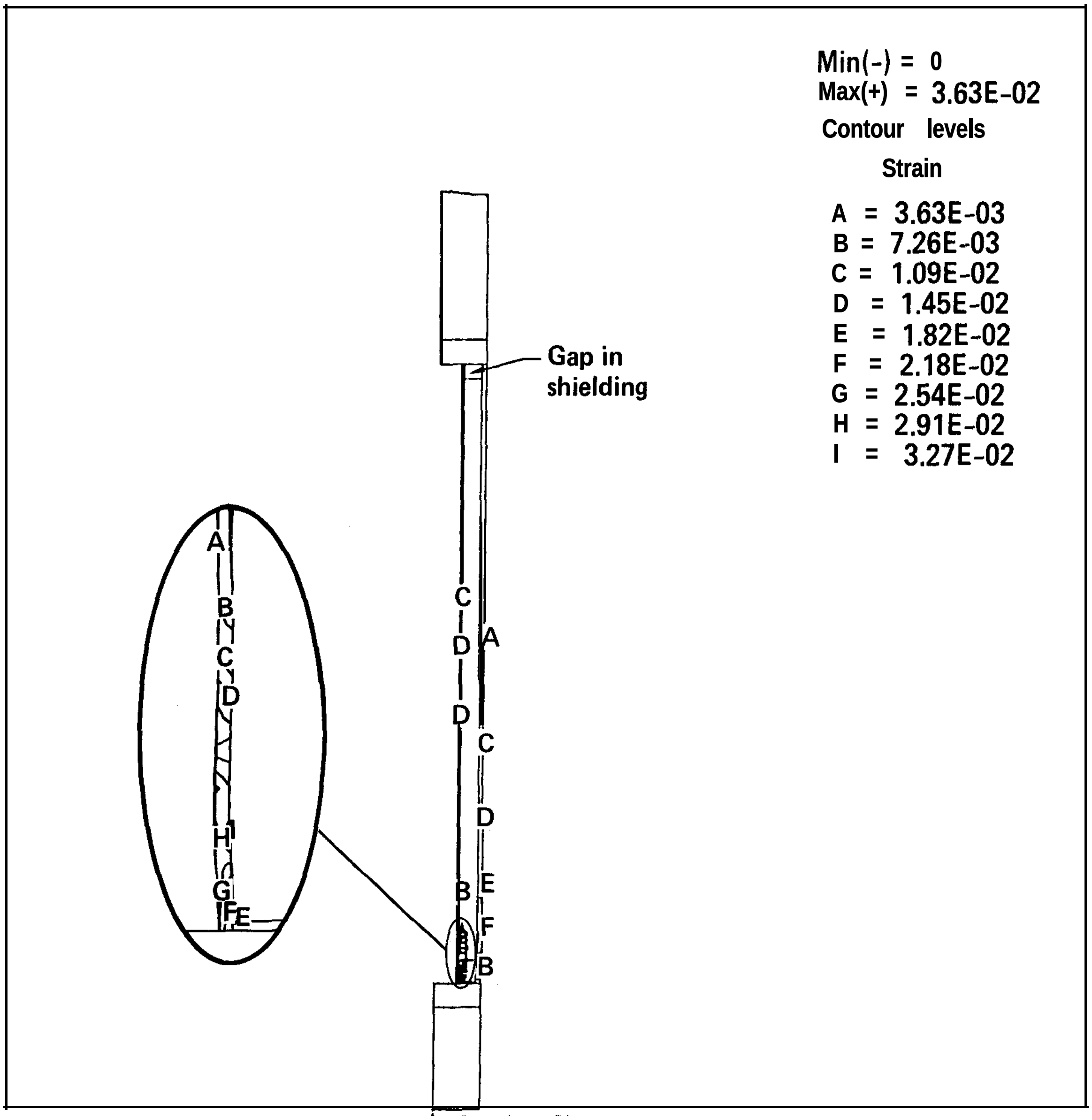


Figure 7-2 Example showing strain response of the representative truck cask for 45 mph endwise impact on an unyielding surface (Z-D model with impact limiters) without any truck cab crushing included.

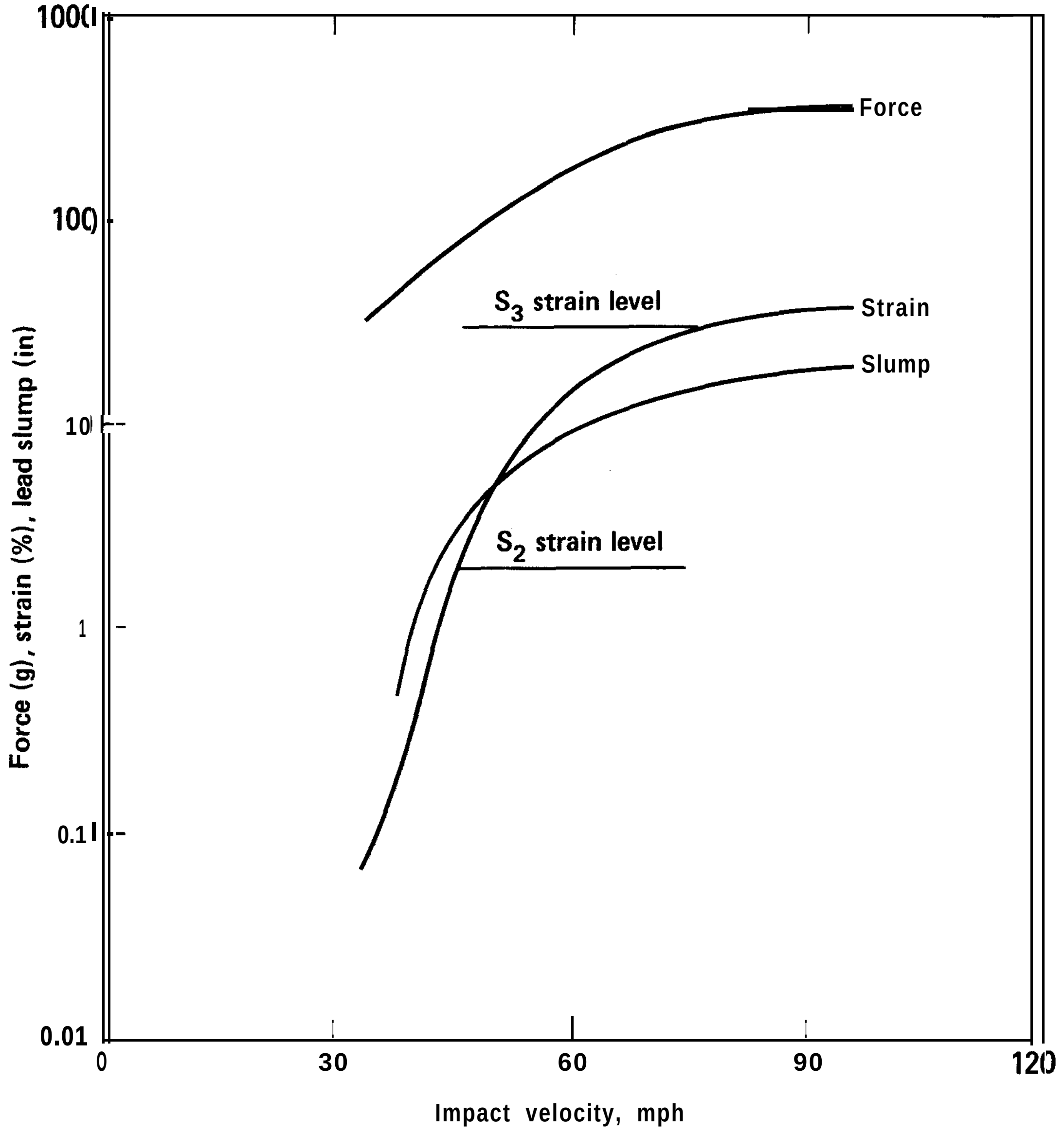


Figure 7-3 Response of the representative truck cask to endwise impacts on an unyielding surface (Z-D model with impact limiters and cab crush).

were calculated in the first-stage screening and are plotted in Fig. 6-7. Using the equivalent damage technique, the 2% strain (S_2) level is reached at impact velocities of 46 mph for impacts on hard and soft rocks but is never reached for impacts on soil. The 30% strain (S_3) level is reached only for impacts on hard rocks at impact velocities exceeding 76 mph.

7.2.1.2 Sidewise Impacts

An approximate Z-D plane strain model is used to calculate the response for high-velocity sidewise impacts on soil, soft rock, and hard rock. Figure 7-4 shows the strain response for the representative truck cask without an impact limiter impacting tillable soil at 60 mph. The maximum strain of 8.47% occurs at the inner shell. During impact, the cask inner diameter decreases by 50% in the impact direction and collapses onto any spent fuel being transported.

In Fig. 7-5, the maximum plastic strain at the inner wall is plotted as a function of impact velocity for impacts on hard rock, soft rock, and tillable soil. In the approximate Z-D model, the strains calculated for a specific impact velocity are essentially the same for sidewise impacts regardless of the surface impacted. The 2% strain (S_2) level occurs at a velocity of 51 mph for impacts on all of the surfaces considered. The 30% strain (S_3) level does not occur because the representative cask walls collapse together or onto the spent fuel contents before the limit is reached.

7.2.1.3 Impact Response Summary

Table 7.1 summarizes the impact velocities at the 2% (S_2) and 30% (S_3) strain levels for sidewise, $\beta = 0^{\circ}$, and endwise, $\beta = 90^{\circ}$, impacts on hard rock, soft rock, and soil surfaces. Impacts of the cask on water and by a train sill are also included. In general, the endwise impacts result in higher strains to the cask than sidewise impacts for the same impact conditions on surfaces. The cask attains the 30% strain (S_3) level only at high-velocity endwise impacts on hard rock.

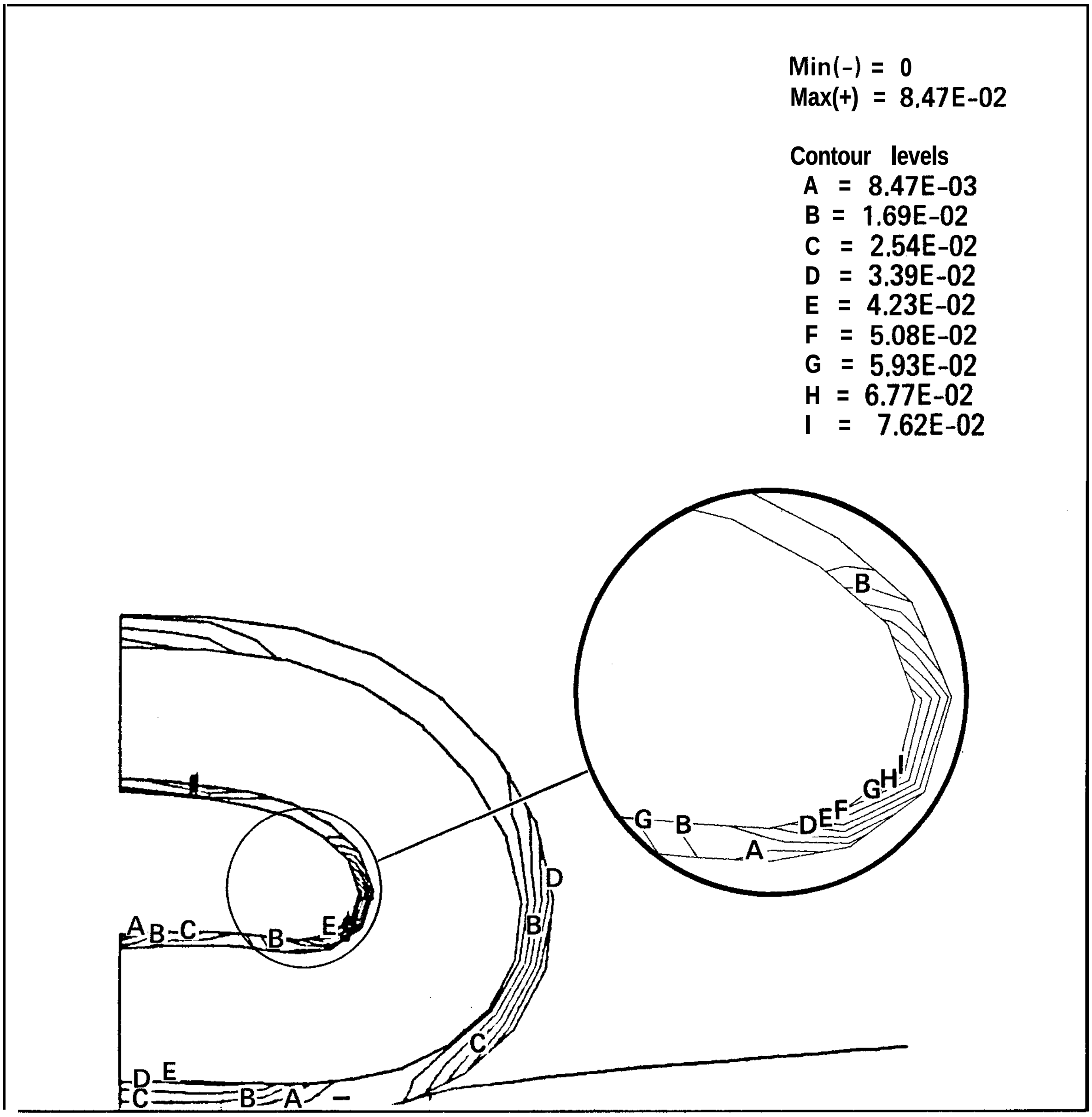


Figure 7-4 Example showing strain response of the representative truck cask for 60 mph sidewise impact on soil (Z-D model without impact limiters) with strain exceeding the 2% (S_2) limit;

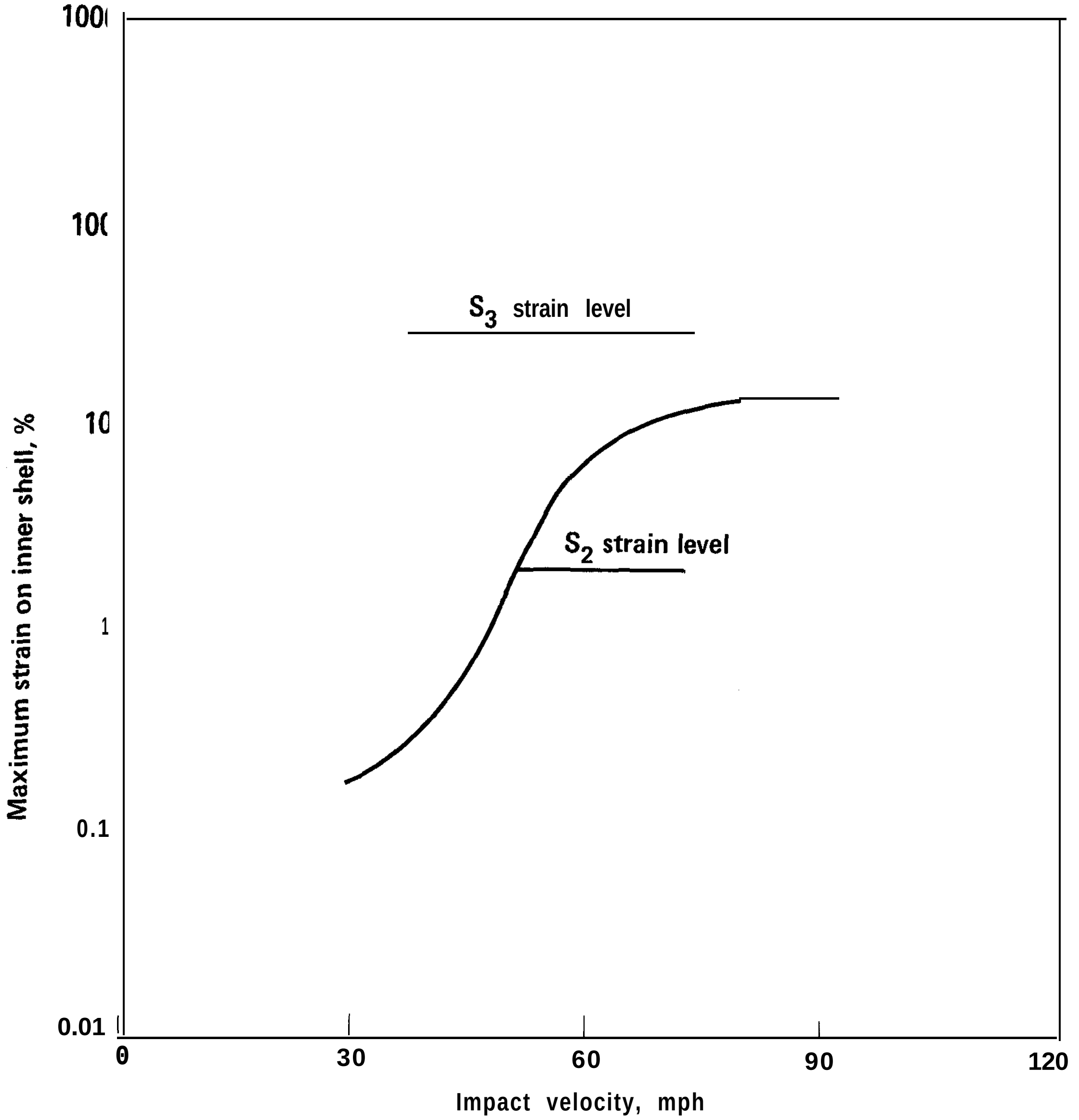


Figure 7-5 Response of the representative truck cask to sidewise impacts on various surfaces.

Table 7.1
Impact Velocities Required to Attain 2% (S_2) and 30% (S_3) Strain Levels for Objects Impacted in Highway Accidents

	Impact Velocity [a] at 2% Strain (S_2) (mph)			Impact Velocity [a] at 30% Strain (S_3) (mph)		
	Cask Orientation Angle (°)			Cask Orientation Angle (°)		
Object Impacted	0	45	90	0	45	90
Hard Rock	51	49 [b]	46	>150	113 [b]	76
Soft Rock	51	49 [b]	46	>150	>150 [b]	150
Tillable Soil	51	101 [b]	>150	>150	>150 [b]	>150
Water	59	>150	64	>150	>150	>150
Train Sill	20	27	>150	>150	>150	>150

[a] Impact velocity of >150 mph means that the strain level is not reached.

[b] Impact velocities at these orientation angles are linearly interpolated between the two bounding values.

7.2.2 Cask Response Analysis for Railway Accidents

The representative rail cask described in Section 3.5 is used in the railway accident response analysis. Appendix E discusses the computer models of the cask, the material properties, and the detailed structural evaluations use in the cask response analysis.

The railway accident scenarios of interest are those involving falls from bridges; drops over embankments; 'and impacts into slopes, train couplers, or massive concrete structures. Again, the maximum strain at the inner wall of the representative rail cask is calculated as a function of the impact velocity for both endwise and sidewise impacts with real surfaces.

7.2.2.1 Endwise Impacts

As was done in the truck cask analysis, a Z-D model is used to evaluate the response of the representative rail cask for endwise impacts on an unyielding surface. The cask impact calculations cover a range of velocities from 30 to 90 mph. Figure 7-6 shows the resultant impact force, maximum plastic strain at the inner shell of the cask, and the amount of lead slump as functions of impact velocity. The 2% strain (S_2) level occurs when a cask impacts an unyielding surface at a velocity of 48 mph. At this velocity the impact force is 102 g, and the lead slump is 6 inches. The 30% strain (S_3) level occurs when a cask impacts an unyielding surface at a velocity of 105 mph. The resultant impact force at this velocity is 500 g and the lead slump is 28 inches. In both cases the maximum strain occurs at the bottom of the cask on the inner shell.

The equivalent damage technique is used to estimate the cask response for endwise impacts on real surfaces. A rigid body with the outer dimensions and weight of the rail cask impacts various surfaces at velocities up to 120 mph. The resultant interface forces for these impacts are calculated in the first-stage screening and are plotted in Fig. 6-10. Using the equivalent damage technique, the 2% strain (S_2) level is reached at impact velocities of 48 mph for impacts on hard and soft rocks, and 65 mph for impacts on soil. The 30% strain (S_3) level is reached only for impacts on hard and soft rocks at an impact velocity of 105 mph.

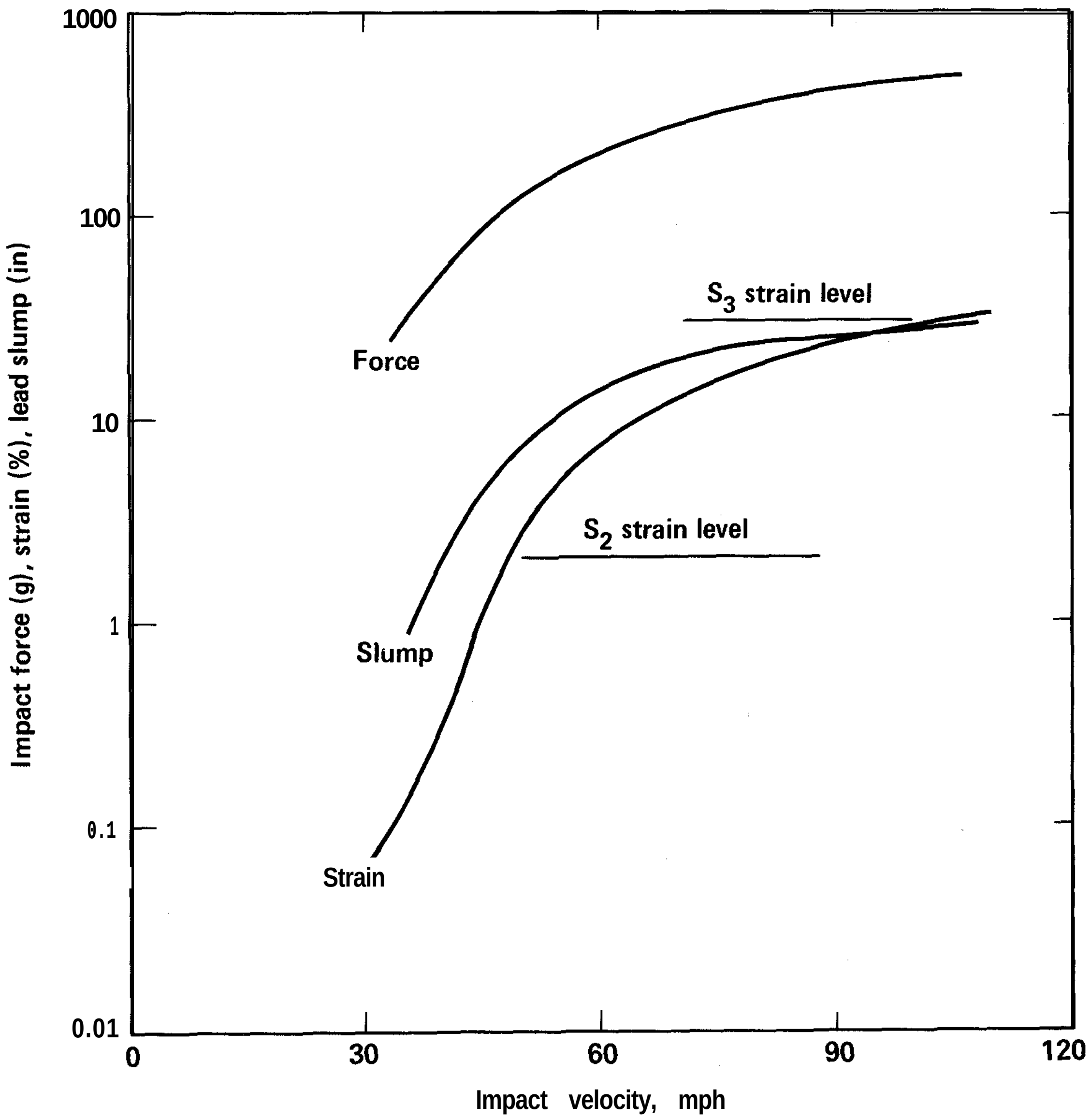


Figure 7-6 Response of the representative rail cask to endwise impacts on an unyielding surface (Z-D model with impact limiters and railcar crush).

7.2.2.2 Sidewise Impacts

As done in the truck cask, a Z-D model of the rail cask is used to calculate the response for high-velocity sidewise impacts on soil, soft rock, and hard rock. In Fig. 7-7, the maximum plastic strain at the inner wall is plotted as a function of impact velocity. The 2% strain (S_2) level occurs at a velocity of 72 mph for impacts on hard and soft rock and on soil. The 30% strain (S_3) level can never occur because the representative cask walls collapse together or onto the spent fuel contents before the limit is reached.

7.2.2.3 Impact Response Summary

Table 7.2 summarizes the impact velocities at the 2% (S_2) and 30% (S3) strain level for sidewise, $\beta = 0^o$, and endwise, $\beta = 90^o$, impacts on hard rock, soft rock, and soil surfaces. Impacts of the cask on water and by a train sill are also included. In general, the endwise impacts result in higher strains to the cask than sidewise impacts for the same impact conditions.

7.2.3 Discussion of Structural Analysis Results

This section has thus far addressed highway and railway accidents that can generate cask responses within the 2% (S_2) and 30% (S_3) strain levels. Cask structural responses at these levels result in permanent deformations to the cask and potential radioactive material releases or increases in direct radiation exposure levels which could approach or exceed the limits specified in 10 CFR 71.

The dynamic response of the cask is calculated using the DYNA and NIKE families of elastic-plastic finite element computer codes.[2,3] These codes were developed at the Lawrence Livermore National Laboratory (LLNL) around 1979, and their predicted results were extensively benchmarked. Appendix H, for example, discusses the capability of these computer codes to calculate the dynamic responses of a cylinder impacting a rail, a nose cone impacting a rigid wall, and a rod impacting a rigid wall obliquely.

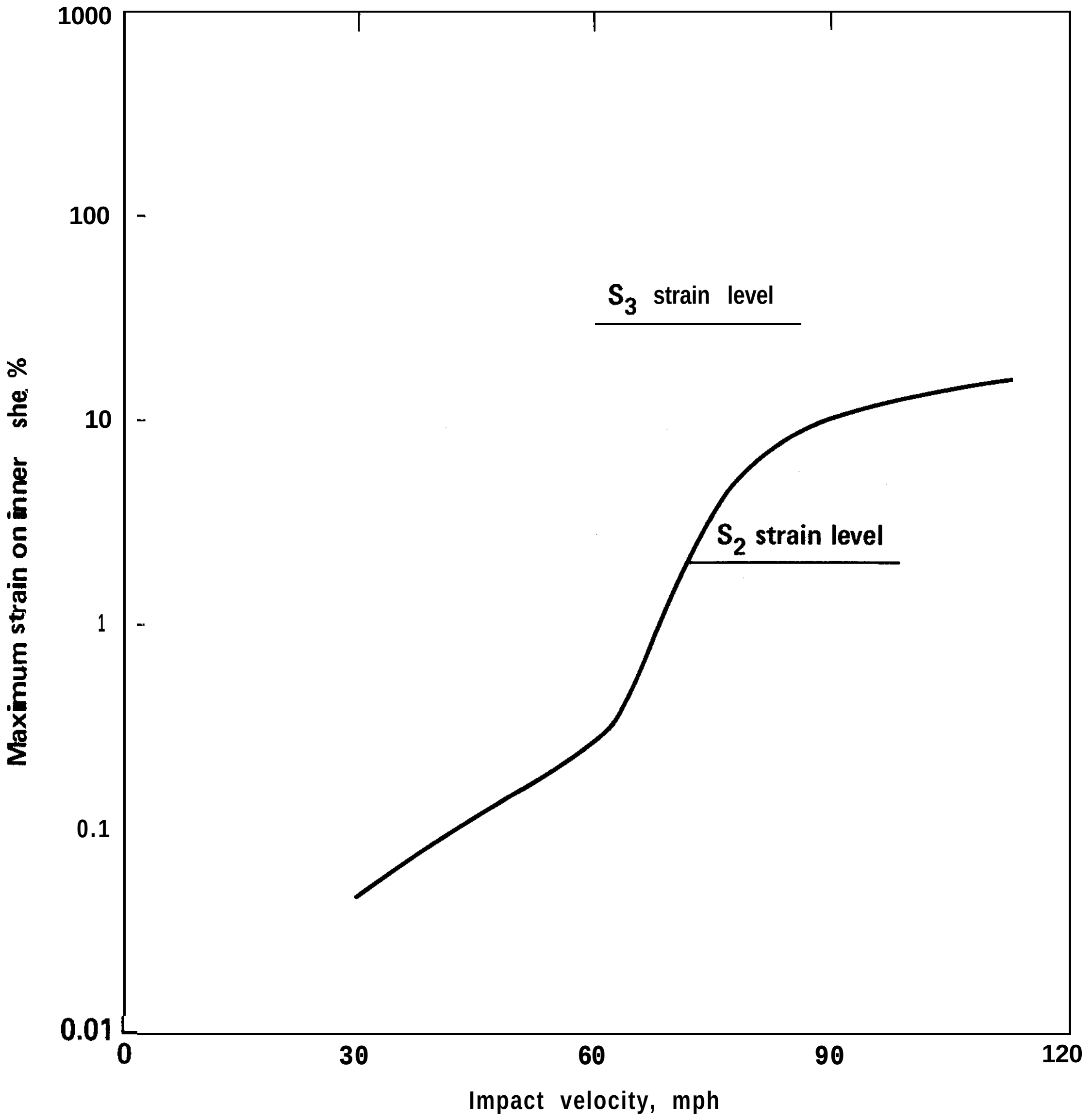


Figure 7-7 Response of the representative rail cask to sidewise impacts on various surfaces.

Table 7.2
Impact Velocities Required to Attain 2% (S_2) and 30% (S3) Strain Levels for Objects Impacted in Railway Accidents

	Impact Velocity [a] for 2% Strain (mph)			Impact Velocity [a] for 30% Strain (mph)		
	Cask Orientation Angle (0)			Cask Orientation Angle (0)		
Object Impacted	(T	- - - +	3 -	0	& - -	9 0
Hard Rock	72	60 [b]	48	150	128 [b]	105
Soft Rock	72	60 [b]	48	150	128 [b]	105
Tillable Soil	72	69 [b]	65	150	150 [b]	150
Water		150	60	150	150	150
Train Sill	27	49	150	150	150	150

[a] Impact velocity of 150 mph means that the strain level is not reached.

[b] Impact velocities at these orientation angles are linearly interpolated between the two bounding values.

These benchmark cases demonstrate the capabilities of the codes to calculate the dynamic response of objects which, when subjected to impact, can experience large permanent deformations. In all three cases, the computer predictions were within a few percent of the deformations measured in the tests.

Benchmark tests of DYNA 3-D have also been performed in the United Kingdom. Excellent agreement was obtained in predicting the dynamic response of a missile impacting a pipe.[4] DYNA 3-D was also used to predict the high deformation characteristics and response of a metal fin on the MAGNOX spent fuel cask when subjected to a 30-foot drop onto an unyielding surface.[5] Again there was a good comparison between the test results and the computer predictions.

The Sandia National Laboratory (SNL) used scale model tests and a computer code similar to DYNA Z-D to predict the dynamic response and deformations of full-scale casks used in a series of crash tests. The full-scale tests included a 25-ton truck cask being struck by a 100-ton locomotive at 80 mph.[6] Following the high-velocity impact, the cask was dented at the points of impact on the side, was slightly bowed along the length, and had a small leak at the closure. In another test, a similar truck cask was carried at 80 mph on a truck which crashed into a huge unyielding concrete abutment.-/ The endwise impact resulted in some lead slump and a small leak at the closure. The results of both of these tests were in good agreement with the computer predictions.

These benchmark tests of the computer codes support their use in conservatively predicting the damage to a spent fuel cask which is subjected to severe accident conditions. In many cases in this study, conservative modeling assumptions are made to simplify the cask response evaluation over a wide range of accident conditions. Examples include the Z-D modeling of 3-D sidewise impacts, the use of elastic-plastic soil modeling, the use of the equivalent damage technique for estimating strain, and the assumption of no bonding between the lead shield and the inner shell of the cask. All these assumptions result in overpredicting the cask damage response to real accident conditions. In addition, the representative cask is structurally weaker than current casks. Again, for the same impact conditions, damage to the representative casks will be greater than that which would be incurred by real casks.

7.3 Thermal Response Analysis

Many of the accident scenarios involving fire led to a cask response well within the R(1,1) region associated with the first-stage screening. This observation is true for both truck and rail casks, but more prevalent for truck casks.

The accidents of interest in this section involve fires of approximately 1-hour duration and longer, These fire accidents have three loading parameters that can affect the response of a spent fuel cask: fire duration, flame temperature, and fire location. Longer fire durations and higher flame temperatures increase the thermal loads to the cask and increase its temperature responses. Also, the closer the cask is to the fire, the better the thermal interaction and the higher the thermal load. In the worst case, the cask is submerged or engulfed by the fire.

The thermal screening analysis in this section compares the truck and rail cask responses to the three temperature response levels of 600°F (T_2), 650°F (T_3), and 1050°F (T_4) at the middle of the lead shield thickness. Since lead melts at 621°F, the calculation of the responses between 600°F (T_2) and 650°F (T_3) has to include the melting of the lead shield. The computer code TACO 2-O used in the first-stage screening has the capability of handling lead melt. TACO 2-D is used with the same one-dimensional (1-D) thermal models to perform the second-stage screening.[8] In other words, the thermal analysis is a continuation of the analysis performed for the first-stage screening, but includes consideration of lead melt.

The calculational method relies on the concept that the time to reach a specific cask temperature is approximately proportional to the incident heat flux on the cask caused by the fire. A fire that causes a heat flux twice the heat flux of a reference fire can heat a cask to a specified temperature in one-half the time it takes the reference fire. Conversely, a fire that causes one-half the heat flux takes twice as long to heat the cask in comparison to a reference fire. For details on the calculational method, refer to Section 6.3.

The thermal response analysis of highway fire accidents is provided in Subsection 7.3.1. Subsection 7.3.2 describes a similar response analysis performed for the railway fire accidents. In Subsection 7.3.3, the overall thermal screening results are discussed.

7.3.1 Cask Response Analysis for Highway Fire Accidents

The representative truck cask described in Section 3.5 is used in the highway fire accident response analysis. Appendix F discusses the computer analysis model, the cask material properties, and the detailed thermal calculations. All highway accident scenarios are evaluated for cask responses to fire because in all scenarios, possibilities exist that a fire can occur and last longer than 1 hour.

The temperature response of the representative truck cask is calculated for a hypothetical engulfing fire with a flame temperature of $1475^{O}F$ and flame emissivity of 0.9. This hypothetical fire approximates a real engulfing fire with a $1700^{O}F$ flame temperature. The temperature at the middle of the lead shield thickness is plotted in Fig. 7-8 as a function of time. The lead mid-thickness temperature reaches $600^{O}F$ (T_2) in 1.35 hours for the specified heat flux conditions. The total heat absorbed by the cask in reaching the $600^{O}F$ temperature (T_2) level is approximately 6,000 Btu/ft^2 which results in an average thermal flux of approximately 4,450 $Btu/hr\text{-}ft^2$. As the lead mid-thickness temperature increases beyond the $600^{O}F$ (T_2) level, the lead at the outer shell starts to melt. The lead melts at the inner shell in 2.1 hours as the mid-thickness temperature reaches $650^{O}F$ (T_3). The $1050^{O}F$ temperature (T_4) level is reached in 3.3 hours.

These temperature response and heat flux results from the hypothetical fire are used to evaluate real fires. For an engulfing fire, the heat flux from the fire onto the surface of the truck cask depends on radiation heat

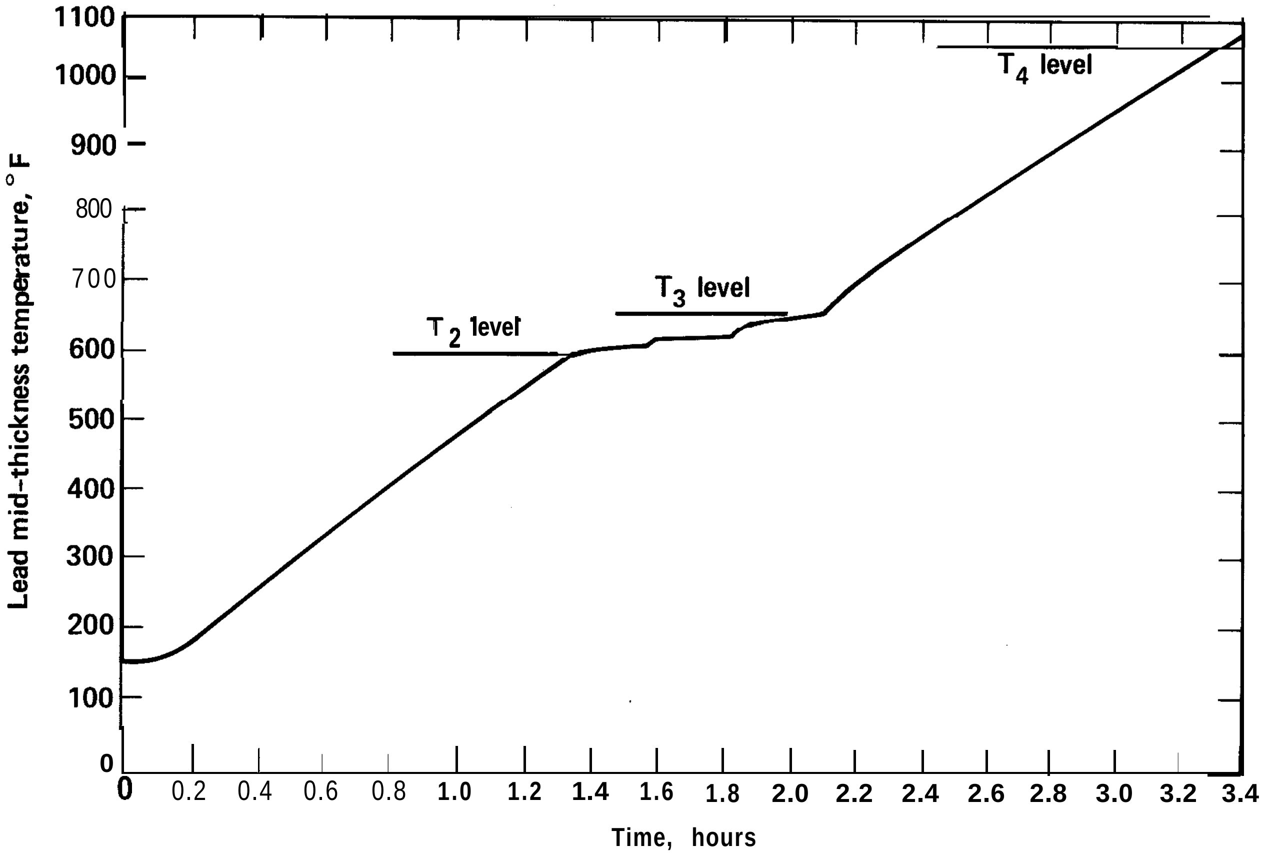


Figure 7-8 Representative truck cask temperature response to a hypothetical 1475°F (equivalent to a real 1700°F) fire versus fire duration.

becoming submerged in water is estimated to be 0.00000078%, given an accident. Using the accident and rail shipment rates in this study, this type of accident is estimated to occur approximately once every ten million years.

9.3.3 Uncertainty in Probability Models

There is uncertainty associated with the probability distributions used in this study. However, two points should be emphasized. First, although direct experience with events involving the transport of casks would be the best source of information, very little, if any, such information is available. Thus, it is necessary to use data derived from similar types of experiences --results which can be considered to be a sample of what potentially will be experienced in the transport of spent fuel casks. Second, similar types of probabilistic analyses have been done based on sparse data similar to that used in this study. The important point for those other studies, and for this study as well, is the need to recognize that the uncertainty exists and to consider this uncertainty in the use of the results.

The estimated probabilities and probability distributions used in the probabilistic analyses are based on (1) accident statistics, (2) surveys of physical structures/features, (3) past analyses and models, and (4) engineering judgment, when no data is available.

9.3.3.1 Accident Statistics

The estimated accident rate for highway accidents is based on the number of accidents experienced by trucks transporting petroleum products during 1973-1981. The extent to which the past experience of trucks transporting petroleum products can be considered to be a random sample of the future experiences of trucks transporting fuel casks determines the quality of the estimate of the highway accident rate used in the analysis,

Similarly, the distributions of truck and train' velocities in an accident are based on statistics compiled from actual accidents. The train velocities are derived from recorders in the locomotives, and are likely to represent a good sample. That velocity is directly attributed to the cask upon impact, but does not include braking effects. Truck velocities are based on estimates by law enforcement officers in their investigation of accidents. The subset of accidents used in this study is based only on data accumulated in California. These accidents involved injury or fatality events that occur at higher velocities than non-injury accidents. It is assumed that the accident report data from 1973-1981 represent a sample of future incidents involving cask transports. Also, the experiences in North Carolina are used to empirically adjust for breaking. Overall, the distributions of train and truck velocities used in this study are conservative.

9.3.3.2 Surveys of Structures and Features

The hardness of earth surfaces adjacent to highways can vary over a wide range. This variability can have a significant effect on the loadings that could be imposed on a cask or any other impacting object, The water and land (hard rock, soft rock, and soil) distribution along proposed spent fuel shipment routes between the east coast and west coast is initially estimated using agricultural soil survey data and geological highway maps for the United States. The initial distribution indicates the types of surfaces which can be impacted along highways in the various regions of the United States. The initial distribution is adjusted to an expected highway distribution by performing highway surveys along representative portions of Federal Interstates 5 and 80 in California. Also, these highway surveys are used to estimate the distributions of bridge heights and column sizes along Federal Interstates.

Improved distribution estimates could be made if the highway surveys were actually performed along proposed spent fuel routes. However, for evaluating the risk for cross-country transportation of spent fuel, the representative distributions are reasonable.

9.3.3.3 Past Analysis and Models

Information on the occurrence of fires is very limited. Thus the thermal evaluations rely on the models developed in a previous analysis of severe accidents[7]. As mathematical models, the flame temperature and fire duration distributions are only approximations of reality. Little or no information has been compiled which directly models the fire accident environment. The fire parameters, duration, temperature, and location, jointly affect the thermal loading on the cask and hence its response.

9.3.3.4 Engineering Judgment

Finally, engineering judgment is used to model the distributions of some accident parameters--impact angle and fire location. Distribution on these important parameters could not be found in actual data. For instance, a uniform distribution is assumed for impact angle and a linear model for fire location. In general, where judgment is used, conservative assumptions are made.

9.3.4 Overall Statement of Uncertainty

As discussed, there are numerous uncertainties associated with the analysis of the risks from transport of spent nuclear fuel. Related highway and railway accident data is limited, and what is reported is often insufficient or not applicable to developing the appropriate distributions and models necessary to estimate risk. Similarly, mathematical models of the fire environment in an accident and the structural and thermal responses of a cask given the corresponding accident loadings are limited in their ability to approximate the actual physical processes that occur during an accident. Thus, the estimated probabilities and risks have uncertainty associated with them.

However, recognizing the 'limited data and information on past accidents, the limitations of using mathematical models to model complex physical phenomena, and the limitations on the resources and time to do this analysis, it is felt that a reasonably conservative estimate of risk is provided.

9.4 Conclusions

The focus of this report is on the integrity of casks used for U.S. shipments of commercially generated spent fuel, specifically on the level of safety provided in the event of a transportation accident. Since all shipping casks are designed to meet an existing set of regulatory standards, the report evaluates the level of safety being provided by current regulations.

The response of representative spent fuel casks are assessed under a range of transportation accident conditions. The accident conditions are derived from historical accident data applicable to truck and rail shipments. The responses of the casks are categorized by a two-stage screening process and compared with two benchmarks: 10 CFR 71 regulations, and NUREG-0170.

The first benchmark is chosen to evaluate cask responses to accident loading conditions which fall within the 10 CFR 71 accident test conditions. As discussed in Subsection 9.2.1, approximately 99.4% of the truck accidents and 98.7% of the rail accidents have both mechanical and thermal loading conditions less than those implied by 10 CFR 71 regulations. The 10 CFR 71 benchmark is also chosen to represent a level of radiological hazard currently reflected in existing regulations. This benchmark specifies limits for both radioactive material releases and the magnitude of the radiation level external to a cask. The limits are chosen to provide high assurance that public radiation exposures would be less than permissible annual limits established for workers in occupations involving the use of radioactive materials. When considering real cask capabilities to withstand thermal loading conditions beyond the regulatory ones, approximately 99.4% of the truck and rail accidents would result in negligible radiological hazards which are less than those implied by 10 CFR 71 regulations. As discussed in Subsection 9.2.2, an additional 0.4% of both highway accidents and railway accidents could result in radiological hazards near the regulatory limits.

The second benchmark value is chosen to provide a risk perspective; that is, a benchmark which includes probabilistic consideration of all possible levels of public radiological hazard. The probabilistic consideration was originally presented in NUREG-0170, an environmental impact statement which considered radiological risk from all shipments of radioactive material in the

U.S., including spent fuel. The significance of this particular document is that based, in part, on the overall assessment of risk which it provided, the NRC made a judgment on the adequacy of its transportation regulations. The judgment was made that the regulations were adequate and not in need of immediate change.

The benchmark taken from NUREG-0170 is the risk calculated specifically for spent fuel shipments. The evaluations in Subsection 9.2.3 indicate that the risks from spent fuel shipments derived in this study, are less than those previously estimated in the NUREG-0170 document. The evaluations in NUREG-0170 indicate that the expected radiological consequences from the shipment of 3000 metric tons of spent fuel per year is less than 1 latent cancer fatality every 2300 years.

The results of this study depend primarily on the quality of the cask response models, the radiation release models, and the probability models and distributions used in the analysis. Models for cask responses, radioactive releases, and distributions for the accident parameters are new developments based on current computer codes, limited test data on radioactive releases, and limited historical accident data. The results of this study apply to spent fuel casks which can be licensed by the NRC and are designed, manufactured, operated, and maintained in accordance with national codes and standards (or equivalent) which have adequate margins of safety embedded in them.

If the objective of this study is to precisely define spent fuel transportation risks, many improvements need to be made to these models to calculate the probability and radioactive release estimates and to quantify the uncertainties in the estimates. For example, tests could be performed to benchmark the DYNA/NIKE computer codes for predicting lead slump for a variety of realistic boundary conditions which would provide nominal values with uncertainty bounds. Similarly, more sophisticated modeling of rock surfaces, which includes cracking, could be developed and benchmarked for improving the prediction of cask responses to a variety of rock properties and impact conditions. Finally, the probability distributions for all the accident parameters, e.g., velocity, fire duration, impact angle, could be improved with further research, data analysis and sensitivity studies. Human factors which affect the cask design, manufacture, operation, and maintenance could also be considered because they affect the cask response and contribute to the overall risk in transporting spent fuel.

None of these improvements are being considered at this point for two reasons: (1) the objective of this study is to estimate the level of safety provided to the shipment of spent fuel using casks licensed to current regulatory standards (a conservatively estimated measure of safety), and (2) the radiological risk in current and future commercial spent fuel shipments is a small component of the total risks applicable for all radioactive material shipments.

The attempt is made in this study to use realistic, yet conservative when appropriate, models and probabilistic distributions. Thus, the estimates derived from the analysis are usable to achieve the study's objective.

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This report describes a study performed by the Lawrence Livermore National Laboratory to evaluate the level of safety provided under severe accident conditions during the shipment of spent fuel from nuclear power reactors. The evaluation is performed using data from real accident histories and using representative truck and rail cask models that likely meet 10 CFR 71 regulations. The responses of the representative casks are calculated for structural and thermal loads generated by severe highway and railway accident conditions. The cask responses are compared with those responses calculated for the 10 CFR 71 hypothetical accident conditions. By comparing the responses it is determined that most highway and railway accident conditions fall within the 10 CFR 71 hypothetical accident conditions. For those accidents that have higher responses, the probabilities and potential radiation exposures of the accidents are compared with those Pdentified by the assessments made in the "Final Environmental Statement on the Transportation of Radioactive Material by Air and other Modes," NUREG-0170. Based on this comparison, it is concluded that the radiological risks from spent fuel under severe highway and railway accident conditions as derived in this study are less than risks previously estimated in the NUREG-0170 document,

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