SPENT NUCLEAR FUEL TRANSPORTATION PACKAGE PERFORMANCE STUDY ISSUES REPORT

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The opinions expressed in this document do not necessarily reflect those of the U.S. Nuclear Regulatory Commission

EXECUTIVE SUMMARY

This report presents the results of the scoping phase of the Package Performance Study which Sandia National Laboratories (SNL) is performing for U.S. Nuclear Regulatory Commission (NRC). The report presents SNL's assessment of the research that could be undertaken to address stakeholder concerns about the safety performance of spent fuel and spent fuel packages during unlikely but severe transportation accidents and thereby increase public confidence in the safety of spent fuel shipments.

The Package Performance Study will reexamine the level of protection provided by NRC certified spent fuel transportation package designs under severe accident conditions. The study will update the methods and results of a 1987 study of package performance under severe accident conditions, commonly referred to as the Modal Study (NUREG/CR-4829), and the extensions of those methods used in a recently completed study (NUREG/CR-6672), which estimated the risks of transporting spent fuel by truck and rail.

This report considers the issues and concerns that were raised at four public meetings and by questions and comments submitted to the NRC as a result of those meetings. The report considers issues and concerns in five topic areas:

- Package Performance During Collisions,
- Package Performance During Fires,
- Spent Nuclear Fuel Behavior during Accidents,
- Highway and Railway Accident Conditions and Probabilities, and
- Other Transportation Safety Issues.

In each topic area, each issue or concern is discussed and resolution options are proposed, costed, and assigned a rating that reflects the importance of the technical results that would be developed by the resolution option and the degree to which those results would contribute to increased public confidence in spent fuel transportation safety.

The review and assessment of stakeholder concerns about spent fuel package performance are summarized in Table E-1, and the four principle issues that SNL believes should be studied are:

- validation of finite element package collision damage predictions by comparison to test results,
- validation of thermal analysis predictions of package heating rates in fires by comparison to test results,
- determination of fuel pellet, fuel rod, and fuel assembly response to severe impact environments by tests and computations, and
- reconstruction of the truck and train accident event trees developed by the Modal Study.

NRC and SNL are sharing this report with the public prior to two public meetings that will be held later this summer to ensure that issues raised at the four meetings held in 1999, or in written submissions to the NRC, have been included and appropriately characterized in this report, and to obtain feedback on SNL's assessment of the issues raised, the resolution options suggested by SNL, and SNL's ratings of these resolution options.

Table E-1 Summary of the Issues Raised at the Four Public Meetings

Resolution Option [section where discussed]	Sandia's Rating	Estimated Cost	Recommended Options
Purchase of full scale rail cask [2.9]	A	Very High	X
Full scale rail cask rocket sled collision test [2.9]	A	High	X
Design and construction of 1/3 scale rail cask [2.9]	B	High	
1/3 scale rail cask cable pulldown collision test [2.9]	B	High	
Validation of scale model testing [2.8]			
If a scale model cask is tested	A	Low	
If a real full-scale cask is tested	C	Low	
Finite element modeling of either cask collision test [2.4]	A	Medium	X
Dual-purpose casks (effect cansister, storage) [2.7]	A	Medium	X
Impact response of pellets, rods, and fuel assemblies [4.3]	A	Medium	X
Calorimeter pool fire test [3.1]	A	High	X
3D thermal modeling of pool fire test [3.1]	A	High	X
Cask pool fire test [3.1]			
Undamaged cask	A	Medium	
Damaged cask	B	Medium	
Fuel types [3.1]	B	Medium	
Event tree structures and branch point probabilities [5.2.4.5]	A	Medium	X
Occurrence frequencies of route wayside parameters [5.3.4.2]	A	Medium	X
Specific historic severe accidents [5.3.4.6]	A	Low	X
Speed and fire duration distributions [5.3.4.4]	B	Low	
Human error probabilities [5.3.4.3]	B	Low	
Specific routes [5.2.4.2]	B	Low	
Sensitivity study [6.3.1]	B	Low	
Collisions with non-planar objects [2.2]			
By finite element analysis	B	Medium	
Using NTP and Eiffort results	C	Low	
Impacts onto yielding targets [2.5]			
Analysis by finite element calculations			
Using deformable test cask	B	High	
Using rigid test cask	B	Medium	
Analysis by engineering calculations	C	Low	
Analysis using empirical data	D	Low	
Crushing environments [2.3]	B	Medium	
Characteristics of collision accidents (orientation, impact angle) [2.1]	B	Medium	
Finite element calculations to examine effects of human errors [2.6]			
Using models developed for the Package Performance Study	B	Low	
Using NUREG/CR-6672 models	C	Low	
Differences between truck and rail fires [3.2.3.2]	C	Low	
Torch fires [3.2.3.1]	C	Low	
First responder fire accident actions [3.4.3.1]	C	Low	
Cask damage from explosions [3.4.3.2]	D	Medium	
Accident test sequence [3.3]	D	Low	
Dependence of accident rates on accident conditions [5.2.4.1]	C	Low	
Correlations among accident risk parameters [5.3.4.1]	C	Low	

Full uncertainty study [6.3.2]	**D**	**High**	
Accident rate uncertainties [5.2.4.4]	**D**	**Medium**	

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1. INTRODUCTION

This report presents the results of the scoping phase of the Package Performance Study (PPS) which Sandia National Laboratories (SNL) is performing on behalf of the U.S. Nuclear Regulatory Commission (NRC). The report presents SNL's assessment of the research that could be undertaken to demonstrate the safety performance of spent fuel and spent fuel packages during unlikely but severe transportation accidents and to increase public confidence in the safety of spent fuel shipments. The report is being distributed for comment to interested parties before NRC makes any decisions about the actual issues to be examined by experiments or analysis during succeeding phases of the study. Succeeding program phases will develop test and analysis protocols, perform these tests and analyses, and document their results.

1.1 Background

The overall purpose of the Package Performance Study is to update the NRC's evaluation of the level of protection provided by NRC certified spent fuel transportation package designs under severe accident conditions. The study is expected to provide additional confirmation of results developed by previous NRC studies of spent fuel package performance and the risks associated with shipping spent fuel in NRC certified spent fuel casks. NRC will use the results of this study to continue NRC's ongoing evaluation of the risks of spent fuel transportation and the level of safety provided by NRC's approach to the regulation of spent fuel transportation.

NRC previously studied spent fuel package performance during accident conditions in the 1980s. The results of that study, which is usually called the Modal Study, were published in NUREG/CR-4829 [1] and summarized in NUREG/BR-0111 [2]. Recently SNL used extensions of the methods of analysis developed by the Modal Study to reexamine spent fuel truck and rail transportation risks for the NRC. The results of this study were published in NUREG/CR-6672 [3].

The risks associated with the transportation of highly radioactive spent nuclear fuel from nuclear power plants to an interim storage facility or to an underground permanent repository are important to both the NRC and the public because the number of spent fuel shipments is expected to increase significantly if these facilities begin operating. To date, about 1300 shipments of spent nuclear fuel have been made in NRC-certified packages without the release of radioactivity from the spent fuel package to the environment. Despite this exceptional safety record and the finding by previous NRC studies that spent nuclear fuel can be shipped safely, some stakeholders may still have questions or concerns regarding the performance of spent fuel packages during highly unlikely accidents that are much more severe than any of the accidents that have occurred during past spent fuel shipments. For example, several groups have suggested that neither NRC's cask standards nor the Modal Study adequately demonstrate that NRC-certified spent fuel packages will provide adequate safety during unusually severe transportation accidents. One goal of the Package Performance Study is to respond to those concerns by performing studies that will enhance public confidence in package performance.

NRC has funded SNL to perform the scoping phase of the Package Performance Study. This scoping phase has several objectives: (1) examination of the need to revisit the conclusions of the 1987 Modal Study, to evaluate their continued validity, and to extend the methods used to develop those conclusions, (2) identification of studies needed to confirm the risk results documented in

NUREG/CR-6672, and (3) increasing public confidence in the safety of spent fuel transportation.

Presently, the NRC is actively seeking suggestions and comments about the design of the Package Performance Study. Suggestions and comments were initially sought by holding four public meetings, the first in Bethesda MD on 17 November 1999, the second and third in Henderson NV on 8 December 1999, and the fourth in Pahrump NV on 9 December 1999. At each of these meetings, stakeholders from affected organizations and citizens discussed their concerns about the transportation of spent fuel. To further facilitate public participation in this project, an interactive project website (http://ttd.sandia.gov/nrc/modal.htm) was established in the fall of 1999.

To ensure that public concerns are affectively identified and understood, and that the design of the Package Performance Study allows these concerns to be addressed, public interactions will be an ongoing process throughout this project. For example, a second series of public meetings and workshops, to discuss this report and NUREG/CR-6672, is planned for late summer of 2000.

This report considers the issues and concerns that were raised at the public meetings and by questions and comments submitted to the project web site. The report also considers issues and concerns raised by letters and reports submitted to the NRC by meeting attendees and includes perspectives from SNL's review of literature relating to the safety of spent fuel shipments. SNL has grouped the issues into topical categories, discussed the issues that relate to each category, and proposed at least one resolution option for each issue. Additionally, SNL has attempted to characterize each issue in terms of its safety significance and contribution to enhancing public confidence in the safety of spent fuel transportation. SNL developed resolution options only for issues that pertain to the performance of spent fuel and spent fuel packages when subjected to severe accident conditions. Resolution options were not developed for issues that did not relate to fuel or package performance; for example, resolution options were not suggested for post-accident recovery issues. The fact that a resolution option is not proposed for an issue raised in this report does not mean that the issue is viewed as unimportant by the NRC. Conversely, the fact that a resolution option is proposed for an issue does not guarantee that the issue will be examined during the course of the Package Performance Study.

NRC and SNL are sharing this report with the public before the workshops to be held during the summer of 2000 for several reasons. First, we want to ensure that comments made at the 1999 public workshops, made in letters, or made through the website, have been included and appropriately characterized in this report. Second, we want to obtain feedback on SNL's assessment of the issues raised, the resolution options suggested by SNL, and SNL's ratings of these solution options. Third, we want feedback on additional issues, such as comments related to the NUREG/CR-6672 study, that could be addressed during future phases of the Package Performance Study. After reviewing these comments and analyzing the issues and resolution options discussed in this report, NRC will decide which issues and resolution options will be examined by the Package Performance Study

Please plan to offer your comments at the public meetings that will be held in Las Vegas and Pahrump NV and Rockville MD later this summer or send your comments to one of the following contacts before September 29, 2000. Comments in electronic form are preferred, but not required.

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1.2 Report Structure

This report considers concerns in five topic areas:

- Container Performance During Collisions,
- Container Performance During Fires,
- Spent Nuclear Fuel Behavior during Accidents, and
- Highway and Railway Accident Conditions and Probabilities,
- Other Transportation Safety Issues.

The report sections that deal with each of the five topic areas are organized as follows. First, the concerns and issues raised at the public meetings, in documents submitted to the NRC as a result of these meetings, or in previous transportation risk studies are summarized. Second, the technical concerns raised by each issue are discussed. Third, ways to resolve each issue by performing studies, calculations, and/or experiments are proposed, the cost of each resolution option is estimated, and each option is assigned a rating that reflects the importance of the technical results that would be developed by the resolution option and the degree to which those results would contribute to increased public confidence in spent fuel transportation safety.

The following table describes the cost indicators and the ratings assigned to the resolution options.

Cost	Range	Rating	Definition
Low	<$100 K	**A**	Resolves a very important technical shortcoming or confirms the adequacy of a very important analysis method
Medium	$100 to 249K	**B**	Resolves an important technical shortcoming or confirms the adequacy of an important analysis method
High	$250 to 1000K	**C**	Resolves a secondary technical shortcoming or confirms the adequacy of secondary analysis methods
Very High	>$1000 K	**D**	Not viewed as significant or answer already essentially known

Finally, the assessments, interpretations, recommendations, and conclusions presented in this report with regard to any issue are based on the knowledge and judgements of Sandia transportation experts and thus do not necessarily reflect the views of the NRC with regard to the particular issue.

2. CONTAINER PERFORMANCE DURING COLLISIONS

2.1 Characteristics of Collision Accidents

2.1.1 Comments and Issues Raised

The following indented paragraphs summarize the comments about collision accident characteristics that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

The speeds at which collision accidents might occur were discussed. Examination of collisions that occur at speeds that exceed the regulatory impact test velocity of 30 mph was strongly recommended. Examination of truck collision accidents with speeds of 70 to 75 mph and train accidents with speeds of 85 to 90 mph was recommended. It was noted that if the impact surface was unyielding, then these speeds might need to be modified.

It was noted that the orientation of the cask upon impact is important. It was suggested that sideways cask impacts onto hard targets shaped so that they fit between the cask impact limiters should be investigated.

The effects of using dedicated trains on rail accident severities was discussed. It was noted that dedicated trains can apply their brakes more quickly than regular freight trains, that "strain coupling" probably prevents cars in the consist (mixture of cars in the train) of the dedicated train from running into each other, and that dedicated train derailment accidents will be less likely if buffer cars are weighted similarly to the other cars in the dedicated train consist.

Study of rail accidents where one train collides with a second train was recommended.

Sandia believes that these comments raise the following technical issues:

(1) Accident speeds greater than the certification test speed need to be examined. In particular, the distribution of accident speeds needs to be developed since many commentors believe high-speed collision are likely to significantly damage a cask.

(2) Impact damage will depend strongly on the hardness of the impact surface and the cask impact orientation relative to the accident velocity vector.

(3) For rail accidents, the effect of consist on accident types and severity should be examined.

2.1.2 Sandia's Discussion of These Issues

The severity of any accident on the event tree depends on several parameters that are not part of the event tree. These parameters include the cask speed and orientation at impact, the angle between the velocity vector and the surface, the orientation of the cask, and the characteristics of the impacted object/surface. In a risk assessment the distributions for each of these parameters must be determined, and each distribution can vary with accident type. Also, the effect of each of these parameters must be determined. For some of the parameters, the effect of its variation depends on other parameters. For example, the angle of the velocity vector to the surface will have a different effect for impacts onto relatively hard surfaces where indentation of the surface is small than it will for relatively soft surfaces where the indentation is large. The characteristics of the impacted object/surface also determine if the accident can result in a puncture environment. Past risk assessments have developed distributions for impact angle and cask orientation based upon engineering judgment. For many of the event tree paths, the cask orientation is influenced by the fact that, during normal transportation, the velocity vector of the transport vehicle is aligned with the axis of the cask. The rotational inertia of the cask will tend to maintain this orientation during an accident. However, it is possible for lateral forces to cause the cask to rotate during the progression of the accident, so that the velocity vector is no longer aligned with the cask axis. Impact angle is influenced by the fact that the original velocity vector of the cask at the time of accident initiation will lie parallel to the wayside accident surface. Therefore, most cask surface impacts will occur at relatively shallow or glancing angles.

2.1.3 Issue Resolution Options

For many accident types the initiating speed is significantly greater than the impact speed, as the transport vehicle will often slow down during the progression of the accident. A method should be developed to estimate impact velocity from initial accident velocity and accident characteristics. For accidents that involve falling off a bridge or going down a slope, the bridge or slope height distributions determine the impact velocity. Surveys along selected transportation corridors should be conducted to develop these distributions.

It is possible for future risk assessments to use distributions of cask orientations and impact angles based upon engineering judgment, but if they are to be technically and publicly defensible, a more rigorous method for developing the distributions is needed. It is possible to develop for each transportation mode a kinematic model that predicts how the velocity vector and orientation of the cask change as an accident progresses. Distributions of cask orientations upon impact could also be developed using Monte Carlo sampling techniques or by surveys of accident data and route characteristics.

Sandia Rating **B**

Estimated Cost **Medium**

2.2 Collisions with/by Non-Planar Objects

2.2.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about collisions with non-planar objects that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

It was noted that impacts with objects that fit between the cask's impact limiters may damage a cask severely. It was recommended that mid-cask wraparound be considered – especially the effects of these collisions on bolts and closures. It was also suggested that impacts with vehicle structural frames and couplers be studied.

These comments raise the following issue:

The NRC regulatory impact test involves impact onto a flat essentially rigid target. All previous risk assessments have focussed on impacts with flat targets. Cask designers incorporate impact limiters on the ends of the cask that can be bypassed by impacts with non-flat targets, especially objects such as boulders, columns, the corners of abutments, and other casks.

2.2.2 Sandia's Discussion of These Issues

Accident classes where impacts between the impact limiters are likely to occur are rail-car pile-ups when several casks are being shipped at once and landslides where a large boulder can strike the center of the cask. Cask designers incorporate impact limiters on the ends of the cask that can be bypassed by impacts with non-flat targets. Examples of non-flat targets include, but are not limited to, bridge supports, tunnel faces, some rock out-croppings, transportation vehicle frames, train couplers, and other casks. To a certain extent issues concerning impacts with non-flat surfaces arise from indiscriminant application of the definition for failure used in the Modal Study (strains higher than 0.2% in the inner shell of the steel-lead-steel wall implied a 100% cask-to-environment release) [1]. It is possible for impacts that bypass the impact limiters to produce inner shell strains greater than 0.2% at a velocity that is lower than the velocity required to produce this strain level for impact onto a flat target (the regulatory puncture test is an example of this). However, because the middle of the cask does not contain any containment penetrations, plastic deformation in the middle of the cask is less likely to lead to release of radioactive material than plastic deformation near the closure of the cask. Because the closure of the cask is protected by the impact limiter, collision with a non-planar object near the closure will involve the impact limiter, and therefore is not significantly different than impact onto a large flat surface which always involves the impact limiter regardless of the cask orientation at impact. Analyses by Eiffort et al. [4] of cask-to-cask collisions that show very low strains in the closure region, but relatively high strains in the middle of the cask are a starting point to address these concerns.

2.2.3 Issue Resolution Options

The DOE National Transportation Program will initiate a study that includes impacts onto non-planar objects during FY01. Information from that study and the results of the analyses by Eiffort et al. [4] can be used as references in this study to develop a position on the risk associated with impacts against non-planar objects.

Sandia Rating **C**

Estimated Cost **Low**

Finite element analyses of impacts involving non-planar targets and impacting bodies can show if this type of impact is more or less likely to lead to cask release than impacts onto flat surfaces. The most probable non-planar objects that could lead to cask damage are other casks, large concrete bridge supports, or locomotives.

Sandia Rating **B**

Estimated Cost **Medium**

2.3 Crushing Environments

2.3.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about crushing accident environments that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **The possibility that during some accidents a massive heavy object, for example a section of a bridge, may fall on the cask subjecting it to a crush load was raised by several commentors. It was suggested that, for crush accidents, the impact cross-section should be described and a bounding approach should be used. It was recommended that rail derailment accidents where there is more than one cask on a train should be examined, because these accidents may lead to cask-to-cask collisions.**

These comments raise the following issue:

> 10 CFR Part 71 does not have a dynamic crush test for spent fuel casks. This leads to public uncertainty of the ability of casks to withstand crushing events, as it may be difficult to relate the inertial crush environment from the impact test to a static or dynamic crush environment. Because many accidents, such as cask-to-cask collisions during rail accidents, may lead to dynamic crush environments, the response of casks to crush environments should be investigated.

2.3.2 Sandia's Discussion of These Issues

Spent fuel casks are required to pass an impact test that exposes the cask to large inertial crush forces. For objects as large as spent fuel casks the inertial crush force from the regulatory impact is much higher than the dynamic or static crush forces that the casks are likely to experience during any accident. The concern about crushing environments is usually for casks being crushed by objects that contact them between the impact limiters. Accident scenarios that can develop crushing forces include railcar pileups, landslides, and the collapse of sections of bridges or elevated highways onto a cask.

2.3.3 Issue Resolution Options

Initially, the magnitude of the problem should be determined. Are there possible crush environments that result in forces larger than the inertial crush forces from the regulatory impact test? Sandia believes the answer to this question is probably no, but if it is yes, with what frequency do they occur? Do these environments lead to crush forces that are larger than the inertial crush forces experienced in the extra-regulatory analyses performed for risk assessments? The answers to these questions in conjunction with the resolution of the previous issue will determine if any additional work is needed to resolve this issue.

Sandia Rating	**B**	
Estimated Cost	**Low**	**to determine the magnitude of the problem**
Estimated Cost	**Medium**	**for analyses if they are needed**

2.4 Finite Element Modeling

2.4.1 Comments and Issues Raised

The following indented paragraphs summarize the comments about finite element modeling that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Commentors stated that finite element cask models should implement a discrete way to look at bolts and allow damage to several bolts and the effect of improper cask closure on closure damage to be examined.**
>
> **The AAR review [5] of the original Modal Study [1] and comments made at public meetings held during past spent fuel shipping campaigns raise additional concerns about the modeling of cask impacts. Most of the additional concerns focus on specific examples of the way packages have been modeled in previous risk assessments. Specifically, in the Modal Study there was no attempt to model the spent fuel contents of the packages, but instead the mass of the contents was added to the mass of the inner shell of the steel-lead-steel casks studied. In NUREG/CR-6672 [3] the contents of the cask were modeled as a lumped homogenized mass, rather than as discrete structures. Neither of these two approaches can be used to deterministically predict the behavior of the spent fuel assemblies. Both studies therefore used other parameters to predict the behavior of the spent fuel contents during collisions.**

These comments raise the following issues:

> The degree of detail implemented in finite element cask models strongly affects the precision of finite element predictions of cask damage during severe impacts, especially damage to the cask closure.

> Indirect determination of spent fuel response to impact forces increases the level of uncertainty in estimates of fuel damage. Approximate modeling of the contents of the cask only provides a general understanding of the way the contents may apply loads to the cask body and closure lid.

2.4.2 Sandia's Discussion of These Issues

Both the Modal Study [1] and NUREG/CR-6672 [3] used finite element modeling to investigate the behavior of casks to a wide variety of accident environments. The wide range of impact velocities investigated in these studies required the analyses to use simplified models compared to the current capabilities of finite element modeling. More detailed analyses are typically performed for cask certification, and far more detailed analyses are possible with the massively parallel computers now available. The finite element models in the Modal Study did not include the closure and the contents. The finite element models in NUREG/CR-6672 included both closures and contents, but did not include the fine details of both of these areas. The models used in the previous studies were sufficient to capture the general behavior of the casks, but not the behavior of cask sub-systems (e.g., closure bolts, penetrations, fuel assemblies).

2.4.3 Issue Resolution Options

A very detailed finite element model of one or two casks could be used to determine the adequacy of the models used in previous studies. If the generic designs from NUREG/CR-6672 [3] are used for a starting point for the detailed model, the comparison can be made directly. If another generic or cask specific design is used for the detailed model, a less detailed model that is similar in detail to the ones used in the NUREG/CR-6672 could also be used to support the comparison. The detailed model should start at the level of individual fuel pins. The modeling can be performed in stages, with the first stage being to perform an analysis of a single fuel pin to determine how the pin responds to forces applied to it. The results from the fuel pin model would then be used in a model of a complete fuel assembly. The results of the assembly model would be used in a model of the entire basket. The results of the basket model would be used to determine the properties of the contents in an overall cask model. The results of the full model could then be compared to the results of the models used in NUREG/CR-6672 and/or to the results of physical tests.

Sandia Rating **A**

Estimated Cost **Medium - not including benchmark tests (see testing purpose)**

2.5 Impacts onto Yielding Targets

2.5.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about yielding targets that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

Cask damage during collisions depends both on impact speed and on the hardness of the impact surface. The damage done by high-speed impacts onto yielding targets needs to be examined.

These comments raise the following issue:

The effect of surface hardness on cask damage during impacts onto yielding surfaces should be developed by review of test data and/or performing engineering or finite element calculations for impacts onto yielding targets.

2.5.2 Sandia's Discussion of These Issues

There is an infinite range of possible targets that can be involved in a cask collision. Determination of the response of a cask to an impact onto all targets at all possible velocities, impact orientations, and impact angles is not feasible. For risk assessments, the general approach is to divide the set of possible targets into groups and determine the response to impacts onto a single target within each group.

2.5.3 Issue Resolution Options

Several methods are available to determine the cask response to impacts onto each of these representative targets:

(1) **Empirical Data** can be used where tests have been performed. The limited amount of test data available for this approach requires that many extrapolations are necessary. The use of extrapolated empirical data often raises technical questions regarding accuracy. This was the method used in NUREG/CR-6672, and there is very little merit in repeating those calculations.

Sandia Rating	**D**
Estimated Cost	**Low**

(2) **Engineering Calculations** can be conducted using known (or assumed) target properties to develop response characteristics. The civil engineering profession has well established methods for calculating the stiffness of structures such as bridge columns and surfaces such as compacted fill for road-beds and rock faces. Most of these methods are only applicable to statically applied loads, and neglect the inertial effects that are important for cask impacts and would need to be considered.

Sandia Rating	**C**
Estimated Cost	**Low**

(3) **Finite Element Analyses** of specific targets can be performed using either a rigid cask or the deformable cask used in the finite element calculations discussed above. If a rigid cask is used, these analyses will give a force-vs.-penetration curve for the target, and a method for relating the results of the analysis to a lower velocity impact onto an unyielding target must be developed to determine the response of the cask.

Sandia Rating	**B**	
Estimated Cost	**Medium**	**- rigid cask**
Estimated Cost	**High**	**- deformable cask**

2.6 Effects of Human Errors

2.6.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about human errors that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Human error and human performance factors should be considered with respect to cask manufacture and loading. However, human error can't always be singled out from other causes, and human performance in transportation helps as often as it hurts.**

These comments raise the following issue:

> Cask manufacturing or operational errors may increase the likelihood and severity of cask failures during impact accidents.

2.6.2 Sandia's Discussion of These Issues

Some of the possible human errors that should be considered include improper fabrication of the cask (this can be examined by changing the material properties and/or failure thresholds used in finite element calculations), failure to drain the water from the cask (water can be included in the finite element model), failure to torque the closure bolts (bolt pre-stress can be neglected), and improper installation of the impact limiter (analyses can be performed without the impact limiter). Of course, it is not possible to include all sources of human error. However, the impact of likely human errors on cask performance should be examined. Once the magnitude of the effect and its probability of occurrence have been estimated, the significance of human errors can be determined.

2.6.3 Issue Resolution Options

Finite element analyses that include cask defects can be performed. It requires little effort to change the finite element models developed in section 2.4.3 to include imperfections caused by human error. This would allow the importance of the human errors with respect to cask response to be determined.

Sandia Rating **B**

Estimated Cost **Low**

Alternatively, the cask defects can be added to the simpler finite element cask models used in NUREG/CR-6672 and the new analysis results can be compared to those from that study.

Sandia Rating **C**

Estimated Cost **Low**

2.7 Dual-Purpose Casks

2.7.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about dual-purpose casks (casks approved by the NRC for both storage and transportation of spent nuclear fuel) that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Most of the spent fuel to be transported in the future will be carried in dual-purpose casks.**

This comment raises the following issue:

> Dual-purpose casks generally have two containment boundaries. The inner containment boundary is a welded canister and the outer containment boundary is typical of current generation spent fuel casks. The effect of the additional containment boundary on accident consequences should be examined.

2.7.2 Sandia's Discussion of These Issues

The behavior of dual-purpose casks during impact and puncture accidents is significantly different than the behavior of transportation only casks. Dual-purpose casks typically have multiple containment boundaries. The wall cross-section of the inner containment boundary is quite thin, which allows this layer to undergo large deformations without producing strains large enough to cause rupture. Depending on the impact orientation and the loading to the inner containment vessel, the deformation may be primarily in the vessel wall, and not in the closure region. Some dual-purpose casks have welded inner containment vessel closures. This type of closure is much less likely to fail in both structural and thermal accidents. Even if there is a breaching of the inner containment vessel, the release path is more torturous and through multiple compartments, resulting in much lower release fractions for the same hole size.

Dual-purpose casks have generally been used for the dry storage of spent fuel for some period of time before transportation. This leads to greater uncertainties on the condition of the fuel during the transportation phase. Similarly, the dry storage environment could adversely affect other components of the cask, such as the basket.

2.7.3 Issue Resolution Options

The effect that multiple containment boundaries have on the release of radioactive material from casks subjected to severe transportation accidents can be determined by the use of finite element modeling and by performing source-term analyses. An inner containment vessel can be added to the finite element models developed for the other analyses and several of the more severe accident conditions can be evaluated. Based upon a literature review, the material properties in the finite element model could be adjusted so that they approximate conditions of the cask and contents after the dry storage period. It is Sandia's opinion that it is quite likely that the literature review will reveal that there is no degradation of material properties that are important to safety.

Sandia Rating **A**

Estimated Cost **Medium**

2.8 Validation of Scale Model Testing

2.8.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about testing of scale models that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **One-tenth to quarter scale testing is not satisfactory; half-scale testing or other partial-scale testing could be considered. Full-scale physical testing with a real cask should be done. Testing should include wear and tear on the cask because the cask is used repeatedly. Testing is primarily for benchmarking and validating codes. Full-scale testing should be done to benchmark the codes used to predict cask responses in fires and collisions. TRUPACT-II was tested because there was no faith in the codes. WIPP represents the only acceptable transportation campaign, because there was full-scale testing of the TRUPACT-II.**

These comments raise the following issue:

> There is little public confidence in the ability of sub-scale tests to accurately capture the response of spent fuel casks to severe impacts.

2.8.2 Sandia's Discussion of These Issues

Scale model testing has been extensively used in cask certification, engineering tests, and technology development activities in many complex technical areas. Scaling relationships for most of the phenomena associated with cask behavior are well understood and firmly based on the equations of Neutonian physics. There are, however, several problems with conducting scale model tests. Foremost of these is the difficulty in constructing an exact scale model of the cask. Will the scale model materials behave the same as the full scale ones at the scaled strain-rate? Areas of special concern include the impact limiters, welds, neutron and gamma shielding, bolts, and contents. Leak rate does not scale, and it is the most important measure of cask success in a test. It is impossible to test the scale model cask in a scaled gravitational field. Gravitational forces are generally very small relative to inertial forces so this problem is not severe for most cases. It does result in higher rebound heights for scale model test units than for full scale ones, which may have an effect on slapdown impacts.

2.8.3 Issue Resolution Options

The validity of scale model testing can be shown by discussion of the physical principles used in the development of scaling relationships. Examples of other industries that rely on scale model tests can also be given. However, past efforts along these lines have had limited success in achieving public confidence in the soundness of scale model testing. There have even been some cases where scale model testing was compared to full-scale tests (i.e., Magnox flask testing program, [6]). It should not be a goal of this study to validate the use of scale model tests for certification of cask designs, but if scale model tests are used in this program for demonstration and/or benchmarking purposes, a technical review and discussion of scale modeling principles should be conducted.

Sandia Rating	**C if full scale testing is performed for this study**
	A if scale model testing is performed for this study
Estimated Cost	**Low**

2.9 Purpose of Testing

2.9.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about the purpose of cask testing that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Commentors were concerned that the purpose of cask certification tests and extra-regulatory tests should be distinguished. It should be explained that testing to meet regulatory standards is deterministic, but the performance of a cask in the extra-regulatory environment is used probabilistically in risk analysis. Commentors noted that it should be made clear that the work performed for this study is not intended to support the certification of any particular cask, and that any cask that is certified by the NRC must pass all of the certification tests.**
>
> **Commentors noted the study should be clear on what the goal of the test was and why the test scale will yield the desired results. The explicit goal of each test performed should be stated including the testing parameters and exactly what is being tested, the cask and/or its contents. The objectives and purpose of each test should be clear, and questions of the sort "You tested this – why not that?" should be answered. The goal of each test should be to advance level of knowledge or level of confidence.**
>
> **At the meetings it was observed that it is not possible to answer all questions with tests. Most commentors noted that testing only in the belief that testing alleviates concern is not satisfactory, and there will still be concern about casks that have not been tested.**

Testing to destruction is pointless; real conditions should frame the study. Do not conduct a test that shows gross failure. Test results can easily be taken out of context.

2.9.2 Sandia's Discussion of These Issues

Cask testing may be performed for many reasons. A demonstration test such as the crash tests performed by Sandia in the 1970s [7] and the CEGB in the1980s [6] can be used to show the robustness of casks when subjected to severe environments that are readily understood by the public. Tests with extra-regulatory impact velocities can be used to show the margin of safety of current or planned cask designs. Tests can be performed to demonstrate the ability of analytical methods to predict the response of casks to the test environment. Tests can be performed to determine boundary conditions to use in the analytical methods. Tests can be performed to demonstrate the ability of the cask to satisfy the regulatory requirements (certification tests). Tests can be performed to advance the state of knowledge of cask performance. Some tests can be designed to perform two or more of these purposes. When tests are performed, it should be stated beforehand what the purpose of the test is and how the success of the test will be determined.

2.9.3 Issue Resolution Options

The primary purpose of any tests performed for this study should be the validation of finite element predictions. The ability of the finite element method to model structures undergoing large deformations has been demonstrated in many applications. What is somewhat unique about cask behavior during severe impacts is the influence of interfaces between several dissimilar materials with vastly different stiffnesses. In order to examine this problem, the benchmarking collision tests should examine a complete cask system (i.e., contents, shell, closure, and penetrations).

Sandia believes the test should involve sufficiently large deformations to demonstrate that the finite element method is accurately predicting behaviors (closure or penetration failures) that could lead to a release of radioactive material. Therefore, it would be beyond the regulatory tests. A significant amount of finite element modeling, performed during the development of the test protocol, could assure the test is sufficiently severe to exercise the non-linear nature of the finite element code. A secondary purpose of the test can be to show the level of conservatism in current cask designs. A side benefit of this type of test is that the outcome can be used to dramatically demonstrate that casks do not fail catastrophically when subjected to impacts that are significantly beyond the Part 71 tests.

Full scale tests have the advantage of higher public acceptance. They would need to be performed horizontally on a sled track. The impacted target would have a very large mass, but not the mass of the earth, as is the case for drop tests. An added advantage of full-scale testing is the ability to include surrogate fuel assemblies (one or more) in the model and validate the fuel response model together with the finite element model.

Sandia Rating **A**

Estimated Costs

Full-Scale Rail Cask **Very High**

Full-Scale Impact Test **Medium**

Scale model tests have lower public acceptance, but they can be used to validate the risk results from NUREG/CR-6672 [3]. It would not be feasible to include scale model fuel assemblies in the scale model cask. The scale model tests could be performed at either a drop test facility that has been used for past certification tests or as a horizontal impact on a sled track.

Sandia Rating	**B**
Estimated Costs	
Scale-Model Cask	**High**
Scale-Model Impact Test	**High**

3. CONTAINER PERFORMANCE DURING FIRES

Based on public concerns and comments and the Sandia technical assessment, thermal issues have been broken into four categories: the pool fire environment, specific fire accident issues, the accident test sequence, and miscellaneous thermal issues. After summarizing the issues in each area, possible analyses, tests, and experiments intended to resolve or improve the state of knowledge in that area are proposed and evaluated.

3.1 Pool Fire Environment

The present regulatory fire test environment described in 10CFR71 has its origins in the 1950s. Since it was developed, the regulation has served well in that no incidents where a severe fire led to a release of radioactive materials from a spent fuel cask or large quantity package have occurred. During the last 20 years, research and experiments have led to an improved knowledge of the large pool-fire environment. The thermal issues enumerated in the public meetings and stakeholder comments involve both statistical issues such as fire duration and phenomenological issues such as effective fire temperature.

3.1.1 Comments and Issues Raised

The following indented paragraphs summarize the comments about fire accidents and the fire environment that were made at four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Several issues directly related to pool fires were raised at the public meetings. One stakeholder stated that a pool fire test should be at least 100 minutes. Additionally, statements were made that flame temperatures of real materials should be considered, and that fire temperature and duration should be related to real-world conditions and materials. A look at hotter-burning materials and how often and how much of them are shipped was also suggested. The statement was made that fuel oil and LP gas provide 90% of the range of fire temperatures seen during accidents. Investigation of the various parameters that govern the thermal flux to the package and a range of parameters was suggested. Consideration of a damaged neutron shield compartment with the compartment flattened out against the inner container, and investigation of plating out of fission products on cask inner walls were also suggested.**
>
> **Additional comments regarding the original Modal Study were included in an AAR critique issued in 1995 [5]. Issues such as the use of a one-dimensional heat transfer model, and uncertainty in fire duration are flagged as significant issues of concern. One stakeholder [8] expressed concern over fire temperatures used for accident simulations, claiming that flame temperatures over 6000°C may occur during accidents. Another stakeholder [9] requested analysis of a variety of truck and rail casks based on a range of historical accidents. He concluded by suggesting fire duration of up to 8 hours for truck accidents and up to 24 hours for rail accidents be considered. In the historical list of accidents**

provided, several explosions are listed in addition to fires. An industry group [10] expressed general concern that specific objectives of test and analyses be identified, costs estimated, and that extra-regulatory tests and analyses be clearly identified as such. They suggest emphasis on new materials, new analysis techniques, and benchmarking of calculational methods.

These comments raise the following four issues:

(1) What fire durations should be considered for risk-based analyses?

(2) What effective fire temperatures should be considered for risk studies?

(3) Should more detailed computer models of spent fuel casks be used for risk studies?

(4) The cost/benefit ratio of extra-regulatory tests and any rule changes should be examined.

3.1.2 Sandia Discussion of Issue

Fire duration is discussed in Section 5.3 of this report. With regard to the suggestion that flame temperatures of up to 6000°C are possible, temperatures measured during actual pool fires do not approach these extremes. Very high flame temperatures are characteristic of premixed stoiciometric flames where the optimum fuel-oxygen ratio exists in the ignited gas mixture. In pool fires, turbulent mixing of air and fuel leads to inefficient combustion and measured pool fire temperatures ear 1000°C.

The issue of the combustion temperature during accidents with different fuels could be considered as part of this study. Experience with different hydrocarbon fuels indicates that in open pool fires, fire temperatures are quite similar for a variety of fuels. Collecting data on the effect of fuel type on temperatures in open pool fires could be conducted at a moderate cost.

The use of detailed three-dimensional computer models has become routine, and, although time consuming, can be run on standard engineering workstations. Three-dimensional fire models are available and could be used to model transportation accident fires.

Any study of transportation accident fires should be examined to determine if the data that will be developed will justify the costs incurred by the use of complicated procedures or models. When thermal issue resolution options are discussed, cost estimates are provided.

Some additional comments on the nature of the fire environment could be useful in evaluating the comments. Analysis of fire is complicated by the large differences in the relative sizes (length scales) of the physical phenomena that must be considered. Turbulence and combustion phenomena have length scales with size that range from sub-millimeters to several meters. Air and thus oxygen are introduced into large pool fires through a complex turbulent mixing process that controls both the location and the intensity of the combustion. Because the fuel-air mixing is limited, internal fire temperatures are much lower than stoichiometric limits for well-mixed fuel-oxygen flames. The central region of a pool fire is starved of oxygen, and a vapor dome exists immediately above the pool where evaporated fuel does not have sufficient oxygen to burn [11]. These issues lead to questions about the location of test casks in regulatory fires. Recently developed analysis tools can be used to examine these issues more thoroughly than before.

Another strong influence in large open pool fires is the presence of soot particles in the flames. Soot is formed through the inefficient combustion process that is typical of large pool fires and plays an important role in distributing the energy within the fire. These particles radiate thermal energy with the characteristic orange-yellow glow observed in fires. Recent studies indicate that the absorption length for thermal radiation in these sooty flames is much shorter than previously estimated [12]. This information permits new, simplified fire models to be constructed for cask analysis.

Because of the soot, pool fires must be modeled as thermal radiation in a participating medium. Large cold objects in pool fires tend to cool soot particles in the boundary region near the object. In turn, the cooled soot particles absorb and radiate incoming thermal energy, and can prevent part of the thermal radiation from reaching the surface of the object. As a result, heat transfer to objects in a fire can be very different at different points on the surface of the object. The blocking of incident radiation depends on the amount of cooling, and thus on the thermal mass of the object. A consequence is that, for a given surface temperature, large, massive objects can receive lower heat fluxes than small objects with the same shape. Soot-cask interactions can now be modeled [13], and these models can be used to examine how the large pool fire environment affects cask performance.

For risk studies, the thresholds for accidental release of gases and particulates are topics of interest. Casks are designed to pass regulatory tests, but are usually capable of performing their protective function far beyond the regulatory limit. Thus, an understanding of the failure characteristics of spent fuel casks during unusually severe, highly improbable accidents would help to refine the accuracy of risk estimates.

Recently developed computer codes such as the CAFE [13] fire model include a computational-fluid-mechanics-based flow solver that calculates the flow field in the fire and the resulting convective heat transfer. As the hot gases from the fire pass near the cold cask, they are cooled. For large objects, the cooling path is longer, and the soot carried in the gas is cooled further. This leads to blocking of incident thermal radiation as discussed above, but it also indicates that heat transfer to large objects should vary with location on the object. For no-wind conditions, heat transfer near the bottom of the object, where little cooling of the soot has occurred, should be higher than the heat transfer near the top, where the cooling effect of the soot particles near the surface has accumulated during the long, upward flow path. Such effects have also been observed in experimental data [14].

To reduce costs, scale models are often employed in structural testing. In such testing, raising the test height for a drop test can provide a good approximation to the increased gravitational field that should be employed for proper scale model testing. In contrast, for thermal tests, simultaneous scaling of both time and surface heat transfer must be performed. This makes accurate thermal scale model tests more difficult to conduct than structural tests. A simple scaling analysis indicates that for thermal testing of a half-scale cask, a fire one-fourth the duration with twice the total heat flux must be used. Making fires shorter is not a problem, but increasing the surface heat transfer can be difficult, especially for larger casks. Furnaces and radiant heat facilities can be used to increase heat flux to a cask surface, but open pool fires can not be easily modified to provide the correct heat flux.

With proper time and heat flux scaling, temperatures, thermal gradients and resulting thermal stresses can be reproduced in scale model casks, but some features are not easily scalable. For example, if cellular insulation such as polyurethane foam is used, cell size can not be changed for the scale model. For moderate scale changes, this is not a problem, but when cell size becomes large relative to cask dimensions, a decrease in accuracy of the test would be anticipated. In addition, obtaining exact scale models of details such as o-rings and other seals can be difficult. Confidence in leak rate tests performed on scale model casks would also be lower.

3.1.3 Issue Resolution Options

Based on the comments and discussion above, alternatives for resolution of fire environment issues associated with transportation of radioactive materials can be defined. An overall objective would be to incorporate and apply knowledge that has been gained in the decade since the original Modal Study was published in 1987.

The range of temperatures and other environmental effects found in large pool fires and the fire duration required to fail cask seal or spent fuel rod can be best studied through a combination of research, analysis, observation and measurements in such fires.

General objectives of the issue resolution options include the following:

- Address and respond to the thermal issues that were raised at the public meetings
- Summarize and contribute to improved understanding of the fire accident environment
- Confirm and assess the applicability of fire accident models used for risk and regulatory analyses
- Develop and confirm simple fire models for use in risk analyses
- Demonstrate the level of safety inherent existing cask designs through actual fire tests
- Provide input to the overall effort to evaluate the level of risk associated with transport of radioactive materials

3.1.3.1 Analysis Program

At the initial stage of investigation, a survey of recent fire research would be useful in understanding improvements in the state-of-knowledge of large pool fires. The results can be included in a report that summarizes the present state of understanding of the fire accident environment. Stakeholder comments would be addressed in detail, and, where possible, resolved by analysis. Simulations with advanced three-dimensional fire models can be compared to experimental data and cask positions in large fires to confirm both regulatory and extra-regulatory fire conditions. Temperatures critical for risk analysis such as seal degradation temperatures and rod burst temperatures can be summarized for typical modern rail and truck casks. Detailed accident scenarios will be analyzed for inclusion in accident risk assessments. For communication purposes, the CAFE fire model could be used to produce realistic fire graphics that clearly depict fire-cask interactions. This information would then allow pool fire tests to be designed that could verify the predicted fire environments. Major report writing, review and approval for the thermal task, as well as work supporting overall risk assessment analyses, would be included in this task.

Sandia Rating	**A**
Estimated Cost	**High**

3.1.4.2 Pool Fire Environment Test Program

Periodically, advances in analysis methods should be compared to benchmark tests in order to confirm and refine the analysis approach. As part of the proposed study, tests of this nature can be conducted either separately or in conjunction with the needs of other agencies. Where tests examine extra-regulatory conditions, this fact will be clearly delineated in the test plan. For the thermal program, two possible approaches are under consideration. In the first, an actual Type B cask will be instrumented and tested in an open pool fire and data used to demonstrate the safety of the cask as well as obtain experimental data useful in validating analysis methods. In a second approach, a cask-scale inertial calorimeter could be used to gather accurate data on heat transfer to cask-sized objects.

Cask Test Option. For this test option, which would use a real, full-scale, spent fuel cask, an extra-regulatory pool fire test would be conducted. The cask would be instrumented to record temperatures and estimate heat transfer. Instrumentation would consist of interior and exterior thermocouples to determine temperatures and heat fluxes at important locations. Depending on the geometry of the cask chosen, the estimation of heat transfer to the cask surface with the methods of inverse heat conduction may be possible. Because the external geometry of a real cask will be at least somewhat irregular (not a perfect cylinder), precise estimation of the actual heat fluxes to the cask surface during the fire may not be possible. The fire test would be conducted for a time exceeding the 30-minute regulatory fire, measurements of the temperatures of, and heat fluxes to, important components would be measured, and damage to the cask would be assessed. The duration of the test fire would be based on pretest simulations that would determine the times necessary to reach temperatures of interest such as seal degradation temperatures and fuel rod burst rupture temperatures. After conduct of the test, the test results would be compared to the results predicted by the simulations to confirm that the analysis methods used are able to reliably predict the experimental results.

If the cask used in this test is used in a collision test before conduct of the fire test, then installation of instrumentation in the cask could be difficult if the collision damaged the cask significantly (e.g., made opening and reclosing of the cask lid difficult or impossible). If the cask is damaged during collision testing, costs not included in the cost estimate given below for this issue resolution option may be necessary to prepare the cask for fire testing. Finally, if a damaged cask is used, the precision of the thermal simulations of the thermal response of the cask may not be able to be precisely modeled. Thus, this test option is given a rating of B.

Sandia Rating **B (A if an undamaged cask is used)**
Estimated Cost (excluding cost of the cask) **Medium**

Calorimeter Test Option. Precise heat flux data can be obtained using a large inertial calorimeter that has a shape and mass similar to those of typical spent fuel casks. The experimental results would be compared to the predictions of fire analysis codes such as the CAFE [13] code in order to benchmark the predictions of those codes. Large calorimeters can be fabricated from carbon steel plates by vendors with rolling and welding processes. At present, a test of this type with a calorimeter the size of a truck cask is scheduled to be performed during the summer 2000 using DOE funding. Information gathered during this DOE test should be used to support the design and conduct of any resolution option that used a larger calorimeter as a test object. Tests with a larger calorimeter would be useful in determining whether the thermal environments produced by engulfing pool fires are significantly different for truck and rail casks.

Instrumentation for this type of a test is more extensive than for tests with an actual cask because additional thermocouples are required to assess heat transfer to the entire object rather than only temperatures at a limited set of important locations. Instrumentation would consist of interior thermocouples located in a manner to permit estimation of the heat transfer to the entire surface of the calorimeter. The methods of inverse heat conduction would be used to estimate the magnitude and distribution of the surface heat fluxes. Results would be compared to the predictions of pool fire models for rail-cask-sized objects.

A major advantage of this method is that it permits a careful, controlled measurement of the fire environment for cask tests.

Sandia Rating **A**
Estimated Cost (including the calorimeter) **High**

Fire Fuel Type Effects. To confirm the current hypothesis used with extraregulatory accidents and risk studies that open pool fires with hydrocarbon fuels burn with similar temperatures and other characteristics, a series of instrumented large, open pool fires with a variety of fuels could be conducted. Potential fuels would include diesel fuel, kerosene, gasoline, and other flammable hydrocarbons normally transported by truck and rail. Common fire temperature-measurement techniques such as optical pyrometry with Schmidt-Boelter gauges, thermocouple readings (directional flame thermometers and shielded thermocouples), and use of small inertial calorimeters would be used to assess any fuel-to-fuel variations in fires. Performance of these tests would be quite complicated, because assuring that equivalent pool fire conditions, including wind effects, existed during each test would be necessary, so that differences observed could be directly attributed to the fuel type. Although no detailed experimental database for different fuel types in large pool fires exists, experience with hydrocarbon fuel types indicates that temperatures in large pool-fires are very similar regardless of the hydrocarbon fuel used. Therefore, this resolution option is given a rating of B.

Sandia Rating **B**
Estimated Cost **Medium**

3.2 Specific Fire Accident Issues

3.2.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about specific fire accident issues that were made at four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **One stakeholder stated that torch-type fires should be considered, and that the torch test should be at least 30 minutes. Another comment was that the rail environment should produce longer-duration fires and a higher frequency of fires, and that it should be noted that rail-transported tank cars are designed to vent and burn so that they don't explode.**

These comments raised the following issues:

(1) Should torch fire tests be considered?

(2) Should different fire duration and frequency data be used for different transportation modes?

(3) Differences between radioactive cargo shipments and shipments of other hazardous materials should be noted.

3.2.2 Sandia Discussion of the Issue

The frequencies and durations of rail accident fires are discussed in Section 5.3 of this report. Although the pool fire is the basis for qualification of Type B casks, other accident scenarios should be considered during risk analysis. Torch fires are of interest to the offshore oil production industry, and research and analyses on this topic performed to examine oil production torch fires could be directly applied to Type B spent fuel cask analysis. The study proposed below provides an opportunity to summarize the knowledge gained in the oil industry, and outlines methodologies that could be applied to cask analysis.

Data on the response of non-radioactive hazardous materials is available from the results of Department of Transportation (DOT) tests conducted on tank cars and tank trucks. The DOT requires thermal testing of the tank car and tank trucks that are used for transport of hazardous materials. The purpose behind these thermal tests is fundamentally different from the purpose of thermal tests conducted on spent fuel casks. The intent of the DOT tests is to assure that explosions of materials such as propane or the sudden release of large quantities of hazardous cargo such as hydrochloric acid can not occur. Safety relief valves on tanks that carry these materials are intended to prevent explosions by venting the hazardous cargo for the duration of the regulatory 100-minute fire, and for some cargoes, the entire tank volume may be vented through the relief valves. The purpose of the DOT regulatory fire tests for tank insulation is to assure that the insulation surrounding the tank limits total heat input so that the relief valves can release the tank contents in a controlled manner. For spent fuel casks, no such relief function is permitted, and only A_2 quantities of the cargo are allowed to be released after the 30-minute pool fire. The differences in philosophy and approach should be clarified in any study or risk assessment where differences in the response of the containers used to transport non-radioactive hazardous materials and spent fuel are being examined.

3.2.3 Issue Resolution Options

3.2.3.1 Torch Fire Investigation

Whether a torch fire scenario should be considered separately from the open pool fire test can be addressed with a combination of research and existing techniques for analysis. Typical torch fire sources are petroleum and gas pipeline ruptures and safety relief valves on rail tank cars. Through three-dimensional finite-element analysis, the effects of torch-fire boundary conditions on casks can be compared to pool fire conditions. Previous studies of torch-type fires have been studied previously and analysis techniques are already available, so the risk significance of torch fires can be readily evaluated by other programs without special research. Because no new technical information is required for resolution, the rating of this option is C.

Sandia Rating	**C**
Estimated Cost	**Low**

3.2.3.2 Truck and Rail Fire Difference Investigation

Analytical methods and advanced fire models can be used to study potential differences between truck and rail fire accident environments. Three-dimensional models of truck and rail casks can be exposed to regulatory and extra-regulatory fire environments, and differences identified. Duration of such fires is a major factor to consider, and this issue is addressed separately in Section 5.3, Accident Scenarios. For example, if a long duration fire could fail a cask and that scenario is not on the event tree, the event tree analysis would need to be updated. Fire duration results would be included in the simulations supporting the risk analysis. Again, the analytical tools for this type of analysis already exist, and, aside from the duration issue, differences between truck and rail environments are well known. Because risk analyses already include such factors in their accident event trees, this resolution options is given a rating of C.

Sandia Rating	**C**
Estimated Cost	**Low**

3.3 Accident Test Sequence

3.3.1 Comments and Issues Raised

The following indented paragraph summarizes the comment about the accident sequence that was made at one of the four public meetings.

> **One commentor suggested that a new test sequence for package testing should be used: first heat the cask (as in a fire) and then puncture it.**

The comment raises the following issue:

> Are there significant accident scenarios that could lead to a long duration fire prior to a cask puncture or drop so that a modification in the normal regulatory test sequence is warranted?

3.3.2 Sandia Discussion of Issue

The current regulatory test sequence consists of a drop test, followed by a puncture test, followed by a fire. This means that a damaged cask must be able to survive a fire after it has been subjected to substantial impact and puncture loads.

Many accident scenarios are possible and a sequence where a fire leads to failure of a support structure, such as a bridge, could occur, which might subject the cask to an impact or puncture event that followed a fire. The frequency of such occurrences would be studied better by the statistical and historical methods discussed in Section 5.3, Accident Scenarios. If such sequences proved to be of concern, modern thermal and impact analysis tools could be used to estimate the damage that such a sequence might cause to a spent fuel cask. For example, simulations of drop and puncture tests could be completed with the high temperature structural properties used in place of the normal temperature properties that are normally used. First, however, an event tree study would need to indicate that the analysis is needed.

If such accident sequences were shown to be sufficiently probable to be of concern and also were predicted by analysis to cause damage of concern to a spent fuel cask, then a test sequence could be performed where an impact test or a puncture test was performed after the cask was exposed to a regulatory fire test. Such a test would be complicated both to design and to perform. It would be complicated to design, because elevated temperatures greatly decrease the strengths of metals. Thus, the time interval between the fire test and the drop or puncture test would have a very substantial impact on the damage caused by the drop or puncture test.

3.3.3 Issue Resolution Options

Current regulations consider a fixed test sequence consisting of a drop test, a puncture test, and a 30-minute pool fire test. Whether other event sequences pose a significant threat and also are sufficiently probable to be of concern should be determined before revising the standard test sequence is considered. If the risk studies described in Section 5.3, Accident Scenarios, were to find that fires followed by collisions were of concern, then the effect of alternative test sequences could be investigated, first by computations and then if shown to be important by test. However, it is not expected that a revised test sequence would be found to be significant. For this reason, the importance of non-standard test sequences should be first examined by computations and examination by experiments should be performed only if the computations suggest there is a serious problem. Because this sequence of events is expected to be quite improbable, and thus to have little effect on risk, examination of this resolution option by performing computations is given a rating of C.

Sandia Rating **D (examination by computations)**

Estimated Cost	**Low**

3.4 Miscellaneous Thermal Issues

3.4.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about some miscellaneous thermal issues that were made at the four public meetings and in the written documents submitted to the NRC as a result of these meetings:

> **One commentor stated that first responders are there to put out the fire, and wanted to consider complications, such as responders putting water in a cask and inadvertently producing a criticality event. Another comment questioned the conservatism of the Modal Study, and stated that it was not conservative on thermal impacts. The issue of explosions from military munitions and other sources was also raised, and how such explosions could affect radioactive materials shipments.**

These comments raised the following issues:

(1) Are there important actions by first responders that are not currently considered in event trees?

(2) Was the Modal Study analysis of cask response to fires non-conservative?

(3) Should explosions be considered as a significant risk for shipments?

3.4.2 Sandia Discussion of Issues

The likelihood of inappropriate actions (human errors) by first responders is discussed in Section 5.2.4.3, Human Errors. Although some fire response actions by first responders may be of concern, for example, spraying water on a hot cask and thereby subjecting it to thermal shock, inadvertent criticality caused by filling the cask with water is very unlikely because of the design of Type B spent fuel casks does not easily permit them to be filled with water even if collision damage has caused the cask to leak. Moreover, for every certified cask, calculations have been performed that show that criticality conditions are not reached even if the cask is fully loaded with fresh fuel and fully flooded with water that has optimum moderator properties. Catastrophic failures that would both flood the cask interior and alter the fuel geometry thereby producing a criticality configuration are extremely unlikely as could be demonstrated by a simple event tree analysis.

Because the Modal Study inferred seal and fuel rod temperatures from cask midshell lead layer temperatures, the Modal Study estimates of the heating times required to reach thermal seal failure and rod burst rupture temperatures could only be were qualitative. Whether these estimates were non-conservative will be apparent once the pool fire tests and 3-D thermal analyses described in Section 3.1 have been completed and the results used to calculate these heating times for a steel-lead-steel spent fuel cask.

Explosives are not generally regarded as a threat to massive radioactive materials casks such as spent fuel casks. The explosive pressure wave is typically too fast to cause the cask to react, and temperature excursions are small. Testing in Germany [15] with exploding propane tanks confirms this assessment.

3.4.3 Issue Resolution Options

3.4.3.1 First Responder Investigations

An assessment of the possibility that first responders will increase risk through inappropriate actions can be performed. Such a study would include both actions and lack of actions by local first responders and authorities. If this assessment found that some credible responder actions or inactions could significantly affect cask response, the effect of the actions on cask thermal response could be examined by thermal calculations. Because accident scenarios have been examined and such issues already considered, this options is rated C.

Sandia Rating	**C**
Estimated Cost	**Low**

3.4.3.2 Potential for Explosive Damage

Current regulations address fires, but not explosions. The three-dimensional finite-element models of truck and rail casks constructed for the structural analysis tasks could be subjected to a variety of explosive (over-pressure) boundary conditions, and results examined for potential cask compromise. Because previous tests such as the BAM test [15] indicate that casks are not functionally damaged by explosions, this resolution options is given a rating of C.

Sandia Rating	**D**
Estimated Cost	**Medium**

4. SPENT NUCLEAR FUEL BEHAVIOR DURING ACCIDENTS

4.1 Comments and Issues Raised

The following indented paragraphs summarizes the comments about spent nuclear fuel behavior during accidents that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **It was stated that spent fuel release fractions should be determined for fuels other than commercial UO_2 spent fuels. For each fuel examined, development of source terms for short and long cooled fuels and average and high burnup fuels was recommended. One commentor stated that Am-241 and Cl-36 were important radionuclides that should be included in the inventories of the fuels examined.**
>
> **Both meeting comments and written materials submitted to the NRC stated that the effect of fuel assembly construction, impact speed, impact orientation, and cladding brittleness on the damage suffered by fuel assemblies during collision accidents should be investigated. It was strongly recommended that the variation of cladding brittleness with irradiation should be determined.**
>
> **It was recommended that experiments be performed to determine the behavior of spent nuclear fuel under extreme accident conditions. It was further stated that these experiments should examine real spent fuel rods and real spent fuel pellets, should measure the release of fission products as constituents of vapors and particulates, and should determine the size distribution of the particles that might be released during severe accidents.**

These comments raise the following issues:

(1) Radionuclide inventories will vary with fuel type, burnup, and cooling time.

(2) Cladding failure mechanisms and probabilities will depend on cladding embrittlement, which increases with burnup, on fuel assembly design, and also on cask impact speed and orientation (e.g., severe side impacts will slam rods into assembly spacers).

(3) Particle release during collision accidents will be increased by pellet fracturing and decreased by the formation of particle beds and the filtering of particles that must pass through those beds to the location of the rod failure. Large rod failures or circumferential rod breaks may substantially increase particle releases.

(4) Radionuclide release fractions will be quite different for rare gases (e.g., Kr, Xe), condensible vapors (e.g., I_2, CsOH, RuO_4), and particulates (e.g., fuel fines).

4.2 Sandia's Discussion of These Issues

4.2.1 Radionuclide Inventories

On a per assembly basis, high burnup, 3 year cooled fuel, the hottest fuel that might be shipped if an older first generation spent fuel cask were used, has about 4 times the number of curies found in average burnup 10 year cooled fuel, which is the fuel most like the average characteristics of the fuel in the current spent fuel inventory. Fuel assembly inventories and thus cask inventories can be calculated for any particular fuel, fuel burnup, and cooling time using the ORIGEN code [16]. For typical PWR and BWR fuels, the precision of the calculated inventories is more than adequate for use in risk analyses.

Because of the precision of ORIGEN calculations, variations in the amounts of specific radionuclides in the inventory can be reliably calculated for any fuel cooling period and any fuel burnup (the small errors associated with the inventories calculated for very high burnup fuels are not significant for transportation risk analyses). By applying an importance screening technique (e.g., radionuclide importance is proportional to A_2 values) to the results of ORIGEN calculations, the set of about 800 radionuclides normally treated by ORIGEN calculations can be trimmed to a much smaller number of risk dominant radionuclides, thereby answering any questions about the correct set of radionuclides to examine during spent fuel transportation risk calculations.

Because ORIGEN calculations can provide a precise inventory for any spent fuel cask under study, no research in this area is warranted. Conversely, because fuel type, burnup, and cooling period can vary widely, generic spent fuel risk assessments should probably perform risk calculations using inventories and decay heat loads for both bounding and average PWR and BWR spent fuels.

4.2.2 Release Fractions

The failure of spent fuel rods during a severe transportation accident would allow fission products to escape from the rods to the interior of the transportation cask. Fission product transport from failed rods to the cask interior has been reviewed by Sprung et al. [3]. That review suggests the following:

1. Collision accidents that lead to cask impacts at high speed onto hard surfaces, will cause significant fracturing of fuel pellets to occur, which will substantially increase the amount of fuel fines in the spent fuel rods being transported in the cask.
2. Escape of radionuclides from failed rods will occur almost exclusively by gasborne transport of radioactive species along with the rod gases that escape from the pressurized rod upon rod failure due to depressurization, or after depressurization as a result of expansion of the remaining rod gases, if the cask and its contents (the spent fuel rods) are heated by a fire.
3. Transport by diffusion is inconsequential by comparison to gasborne transport caused by rod depressurization or by the thermal expansion of rod gases.
4. Transport of radionuclides as constituents of condensible gases (i.e., vapors, for example, CsI) or non-condensible gases (i.e., noble gases, for example Xe or Kr) are both well defined and can be satisfactorily modeled using simple models (e.g., the ideal gas law) and available data (e.g., vapor pressure data for condensible vapors).
5. Transport of radionuclides as constituents of particles is difficult to model precisely because release of particles from failed rods depends on (a) the fraction of the mass of the spent fuel pellets that is present as particles at the time of the rod failure, (b) the size distribution of the

particles, (c) the degree to which these particles form particle beds in the fuel-cladding gap and in the internal crack network normally present in spent fuel pellets, (d) the degree to which these beds, if they form, filter particles that must pass through them to reach the location of the rod failure, and (e) on the nature of the rod failure (small crack or circumferential tear).

6. The nature of the rod failure (crack or circumferential tear) produced upon cask impact onto a surface at some specific speed and the probability of that failure are strong functions of cladding embrittlement and impact orientation.
7. Rod failure by thermal burst rupture can be adequately treated using the experimental data of Lorenz [17-20] and Burian [21, 22].

The effect of fuel assembly design on the behavior of fuel assemblies during collisions can be examined by performing cask crash tests and modeling those tests as is described in Section 3, Cask Performance during Collisions. Consequently, the technical issues that pertain to release of fission products from failed spent fuel rods, that are not addressed by studies proposed in preceding sections of this report and that need to be studied, all involve the response of spent fuel rods and spent fuel pellets to the severe impacts produced by high-speed collision accidents.

4.3 Issue Resolution Options

Data on the fracturing of embrittled spent fuel rods does not seem to be available. Impact fracturing of spent fuel pellets has been studied by performing Pellini hammer tests. However, the variation with impact energy of the resulting particle size distributions is not known.

A new aerosol generation and sizing test apparatus has recently been brought on line at the Fraunhofer Institute in Germany in which pellets or rods can be impacted onto an unyielding target at known impact speeds and the particles generated, collected, and sized [23]. Discussions with the German scientists who designed and qualified this test apparatus indicate that the impact fracturing of surrogate spent fuel pellets, when free standing and also when contained in sections of fuel cladding, and the collection and sizing of the aerosols produced by the impacts could be performed using this apparatus. If radiation embrittlement of the cladding sections can be simulated by hydriding fresh Zircaloy tubing in an autoclave, then the following physical phenomenon can all be examined experimentally as a function of impact speed and orientation using this test apparatus:

- fracturing of bare pellets not contained in rod sections upon impact onto an unyielding target,
- fracturing of surrogate pellets in strained rod sections upon rod impact onto an unyielding target,
- formation of particle beds in the rod-cladding gap,
- filtering of particles by those beds,
- escape of particles from the failed rod section,
- the nature of the rod section failures, and
- the size distribution of the particles that escape from the failed rod section.

If parallel data on the fracturing of surrogate and radioactive spent fuel pellets can be developed at Sandia by performing Pellini hammer tests, then the combination of the Pellini hammer test data with the data gathered using the Fraunhofer Institute apparatus should allow the impact behavior of spent fuel rods and pellets to be qualitatively delineated. Then, even though assembly, rod, and pellet behavior during impacts will vary with fabrication details, enrichment, reactor power history, fuel age, burnup, and cooling time, the data developed will allow gross rod failure modes, the particle distribution produced by impact fracturing of fuel pellets, the formation of particle beds, and filtering of respirable particles by those beds to be identified.

Because rod failure, pellet fracturing, particle bed formation, and bed filtration of fuel fines strongly influence the release of radioactive particles during severe collisions and are all poorly defined by available data, this study is technically very important. Moreover, study of pellet and rod behavior during severe accidents was recommended at the public meetings.

Sandia Rating **A**

Estimated Cost **Medium**

5. HIGHWAY AND RAILWAY ACCIDENT CONDITIONS AND PROBABILITIES

Issues in this topical area raise questions about shipment routes, accident rates, accident scenarios, and transport modes. Routes are important because, for example, population density and accident rates can be quite different for different routes and also for different portions of a single long route. Accident rates are important because radioactive materials can be released from a spent fuel cask only if the cask is involved in an accident. Accident scenarios are important because they determine the severity of an accident and thus whether it can damage a cask enough to cause it to leak. Transport modes are important because accident rates and accident severities are very different for different modes (e.g., highway, railway) of transport.

5.1 Shipment Routes

5.1.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about shipment routes that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Almost all of the comments made concerned the dependence of accident rates on route characteristics (e.g., rural, suburban, urban) and the fact that the characteristics (e.g., wayside population densities and surfaces) of specific routes can be very different. The use of a Geographic Information System (GIS) to develop route specific information was suggested and discussed at some length. One meeting attendee in a post-meeting written submission named sections of specific interstate highways and mainline rail routes that should be examined (e.g., I-80 from Buffalo NY to Sacramento CA; the BNSF mainline rail route from Kansas City MO to San Bernardino CA). Several meeting participants suggested that the characteristics of highway and railway routes should be developed by GIS analysis of a representative sets of interstate and mainline rail routes. At least one meeting participant stated that it is counterproductive and premature to consider specific routes because they are bound to change, and properly packaged radioactive materials can be shipped along any route.**

Sandia believes that these comments raise the following technical issues:

(1) How should the wide variability of route characteristics along a singe route and among different routes be addressed by risk assessments?

(2) How can GIS methods of analysis be used to examine the characteristics of transportation routes?

5.1.2 Sandia's Discussion of These Issues

Geographic Information Systems allow data that is spatially distributed to be associated with its geographic location. Once this has been done, correlations among the data can be identified. For example, GIS analyses can develop the frequencies of occurrence of urban, suburban, or rural population densities or of various classes of wayside surfaces (e.g., hard rock, water) along a specific route or a representative set of routes; and, if enough data is available, GIS analyses could determine whether accident rates along a specific and lengthy interstate or mainline rail route depended strongly on wayside population density.

Distributions of urban, suburban, and rural population densities along interstate highways and mainline rail routes were developed for NUREG/CR-6672. The population densities that entered the distributions were developed by performing HIGHWAY [24] or INTERLINE [25] routing calculations that examined over 700 different and real interstate highway or mainline rail routes (HIGHWAY and INTERLINE determine the shortest interstate highway or mainline railway route between two locations and the population densities of the urban, suburban, and rural portions of these routes). Because GIS methods of analysis were not used, the variation of population density with other route dependent data (e.g., accident rates) was not examined. GIS analysis was used during the NUREG/CR-6672 study to develop the frequency of occurrence of hard rock surfaces along three interstate highway and mainline rail routes. Similar analyses could be performed for a larger set of routes to test the representativeness of the NUREG/CR-6672 results. GIS methods could be used to develop route data for the specific shipment routes to support analysis of the risks associated with a specific shipping campaigns. As the Package Performance study is a generic study, if GIS analyses are performed, those analyses would examine a representative set of routes for the modes of transport selected by NRC for study during this project.

The dependence of accident rates on route characteristics is discussed further in Section 5.2, Accident Statistics. The development of wayside surface data, to support the identification of important accident scenarios by construction of accident event trees, is discussed further in Section 5.3, Accident Scenarios.

5.1.3 Issue Resolution Options

No issue resolution options are presented here, because all of the issues related to route characteristics are discussed further in subsequent sections.

5.2 Accident Rates

5.2.1 Background

The risks of transporting radioactive materials are usually examined by performing calculations using transportation risk codes such as the RADTRAN code [26, 27]. The RADTRAN code is frequently used by NRC, DOE, and other organizations (e.g., licensees, contractors) to estimate the risks associated with the transport of radioactive materials. Accident rates are one of the more important RADTRAN input variables that support the estimation of accident risks. The 'accident rate' is the chance (usually expressed per kilometer traveled per vehicle) that a vehicle will be involved in an 'accident.' Because of the way accident data is reported, the term 'accident' generally means a fairly severe event, one that causes a person to be killed or hospitalized, property damage that exceeds $50,000, an evacuation, or a major transportation artery to be shut down for more than an hour. Thus, a 'fender-bender' that didn't cause one of these consequences wouldn't be an 'accident' as that term is used here.

NUREG-0170 [28], published in 1977, was NRC's first comprehensive examination of radioactive material transportation risks. That study used a truck accident rate of about 1 accident per million truck kilometers and a rail accident rate of about 0.9 accidents per million rail car kilometers. These values were based on accident data from 1974 and 1975. The Modal Study [1] used a truck accident rate of about 0.4 accidents per million truck kilometers and a rail accident rate of about 0.1 accidents per million rail car kilometers. These values were based on data from 1968 through 1981 for truck accidents and 1976 through 1982 for train accidents. For NUREG/CR-6672, cumulative distributions of truck and rail accident rates were constructed using Department of Transportation Bureau of Motor Carrier Safety (DOT BMCS) data for the years 1984, and 1986 through 1988. For trucks, separate distributions were developed for accidents that occurred in rural and in urban/suburban regions. The rural truck accident distribution had a 50 percentile value of about 0.2 accidents per million truck kilometers and the urban/suburban distribution had a 50 percentile value of about 0.4 per million truck kilometers. The rail accident distribution had a 50 percentile value of about 0.03 accidents per million rail car kilometers independent of wayside population density.

5.2.2 Comments and Issues Raised

The following indented paragraph summarizes the comments about accident rates that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **The appropriateness of different accident databases was discussed. The use of "single point" accident rates, such as the national average values used in NUREG-0170 [28] and in the Modal Study [1], was criticized. It was stated that distributions of accident rates should be used, and that such distributions may be different for urban, suburban, and rural areas, and also different for different seasons of the year. It was noted that the State of Nevada has studied accident rates, finds significant annual variations, and is using a "bounding approach" to accident rates. The Nuclear Energy Institute (NEI) in a letter [10] to the NRC requested that any assessment of accident likelihoods ensure that accident rate data bound the rates in urban, suburban, and rural areas. Use of route-specific accident statistics rather than national averages was suggested. Written comments provided by the State of Nevada [9] requested that accident rates be developed specifically for those portions of the interstate highway and mainline rail systems most likely to be used to transport spent fuel. The incorporation of uncertainties into accident statistics was recommended. It was also noted that, because a train contains many rail cars, train accident rates need to be corrected for train length to obtain rail car accident rates.**

These comments raise four issues:

(1) To what degree should accident rate data be aggregated?

(2) Should accident rates by developed for specific routes?

(3) Should bounding accident rates be used in risk analyses?

(4) How important are the uncertainties associated with accident rates?

5.2.3 Sandia's Discussion of These Issues

5.2.3.1 Aggregation of Accident Rate Data

Accident rates can be very different at different locations and also very different for any specific location during different types of weather or at different times of the day, the week, or the year. Consequently, averaging of accident rate data loses the great variability of real world accident rates. For example, although the use of national average accident rates will yield a reasonable estimate of mean risks at a national level, it will not depict the range of possible accident rates that might apply to shipment over specific routes at specific times.

Average values can be calculated for any set of accident data in a variety of ways. A single average value can be calculated using all of the accidents in the full data set simply by dividing that total number of accidents by the total number of kilometers which were traveled during the number of years when the accidents occurred. Alternatively, as was done by Saricks and Kvitek [29] for truck accidents, truck accident rates can be developed for the rural and non-rural (i.e., rural and urban/suburban) portions of the interstate highway system for each of the 48 states in the continental U.S. This produces 48 rural interstate truck accident rate values and 48 urban/suburban interstate truck accident rate values. For NUREG/CR-6672, this data was used to construct rural and urban/suburban truck accident rate distributions. Then, 200 separate RADTRAN calculations were performed using different accident rates selected by sampling these truck accident rate distributions.

How will the mean result of the 200 RADTRAN calculations that used accident rates selected by sampling the distributions differ from the single rate that could be calculated using the single national average accident rate. Since both results are based on the same set of accident data, the mean result obtained by sampling the distributions and performing 200 separate RADTRAN calculations should be essentially identical to the result that would be obtained by performing a single RADTRAN calculation that used the single national average truck accident rate. What sampling the distributions preserves is a picture of the spread of the possible truck accident risks. Because sampling produces 200 results, that set of results presents a picture of the range of risks that the single calculation is unable to depict.

Accordingly, if a picture of the spread of the individual accident rates in the full data set is desired, then the full set of data should be divided into some number of subsets (subgroups) that contain accident rates that are similar and then average accident rates should be calculated for each of the data subsets. The smaller the number of subsets, the greater the degree of aggregation of the data. Thus, the degree of aggregation of a body of data determines the degree to which the spread of the data is preserved. It also will influence the spread of the consequences and risks that are calculated using the aggregated data. But lessor degrees of aggregation should not significantly change the best estimate of expected risk whether obtained by performing a single calculation and a single national average accident rate or many calculations that use accident rates selected from distributions of subsets of the full set of data.

Although limited aggregation of accident rate data will preserve the range of the risks and consequences calculated using that data, it will not alter the expected (average, mean) result (the average values of the risks or consequences), because, whenever accident rates for less favorable conditions are preserved, so are rates for more favorable conditions. Thus, for example, if accident rates are higher when accidents occur during poor weather on steep, relatively straight, downgrades in the mountains, they will be lower for accidents that occur during good weather on slightly curving roads on relatively level ground. Consequently, whenever a body of accident rate data is used to estimate expected transportation accident risks, greater aggregation of the data will compress the spread of the risk and consequence results calculated using the data but should not significantly alter the expected result. Conversely, if the accident rate data is greatly aggregated, the range of the risks associated with the full unaggregated set of data will not be realistically depicted.

One way to preserve the variability of the full set of accident data is to calculate accident rates for each combination of conditions that will lead to a significantly different rate. For example, accident rates could be constructed for all combinations of principal route characteristics (curvature, grade), wayside population densities (urban, suburban, rural), accident times (time of day, day of the week, season of the year), and types of prevailing weather (snow, ice, rain, sun). If all combinations of these many separate characteristics are examined, then about 200 separated accident rate distributions would be developed. Separate risk calculations could now be performed that used accident rates selected by sampling each of these many different accident rate distributions. This would clearly better depict how the range of risks and consequences would vary with accident rate and the full spectrum of conditions that produce different accident rates. However, a valid representation of the full range of risks and consequences will also be captured by constructing fewer distributions and then sampling from this smaller set of distributions. Using fewer distributions means that the highest and lowest accident rate values will be averaged with other values and thus not preserved. What is lost by sampling from the smaller set of distributions is the tails of the full range of risks and consequences. Thus, accident rate data should be aggregated into a very large set of subgroups only if preservation of the tails of the full distribution of accident rates or the identity of the specific sets of accident conditions needs to be preserved.

5.2.3.2 Specific Routes

In NUREG/CR-6672, risk estimates for four possible real spent fuel shipment routes were compared to the risk estimates developed using 200 generic routes constructed by sampling route parameter distributions using structured Monte Carlo sampling methods. The comparison showed that the risks for the four real routes fell within the range of the risks developed using the 200 generic routes. Additional specific truck and rail spent fuel shipment routes could be examined. Such an examination could strengthen the conclusion reached in NUREG/CR-6672 that the range of the generic route calculations performed for that study encompasses the results for specific real routes. Development of route specific accident rate data could contribute valuable insights when examining a specific shipment. But, since the Package Performance Study is a generic study, extensive examination of specific routes during this study does not seem consistent with the objectives of the study.

5.2.3.3 Bounding Values

Any set of data, for example a set of accident rates, will have an upper bound. The value of the upper bound will be larger than any of the values in the set of data. Use of a bounding accident rate is appropriate if calculation of bounding values of risk or consequences is desired. It is not appropriate for risk analyses where estimation of expected (mean, average) results is the goal.

5.2.3.4 Accident Rate Uncertainties

An accident rate is the ratio of the number of accidents that occurred while some class of vehicles (e.g., semi-tractor trailers) traveled some number of total kilometers to that total number of kilometers. Because of the legal requirements for reporting severe accidents (those where property damage exceeds some specified amount or injuries or deaths occur), it is unlikely that there are significant errors in the reporting of severe truck or train accidents. Because of differences in reporting thresholds, the characteristics of the minor accidents that fall below the reporting threshold will vary somewhat for different reporting agencies.

Accident rates exhibit two types of variability. First, accident rates can take on a wide range of values in the real world. Second, each of these values will have an uncertainty associated with it. Any significant uncertainties in accident rates for trucks or trains will be caused primarily by imprecision in the estimates of the number of kilometers traveled during the years when the tabulated accidents took place, and not imprecision in the number of accidents reported. Since reporting of numbers of kilometers traveled greater than the actual number traveled is not likely (failure to report is more likely than deliberate over-reporting), accident rates are probably slightly conservative and not significantly uncertain. Therefore, so long as the real-world range of accident rates is appropriately captured by the set of accident rate distributions used in the risk assessment, there will be no need to try to estimate the uncertainties associated with the individual data points that enter those distributions because, if estimated, these uncertainties will have ranges substantially smaller than the range (variability) exhibited by any distribution of real-world accident rates.

5.2.4 Issue Resolution Options

5.2.4.1 Dependence of Accident Rates on Accident Conditions (e.g., weather).

The dependence of accident rates on weather conditions, terrain, population density, and time of day, day of the week, and season of the year can be developed. To develop these dependencies, the raw data that underlies both current national and state truck and rail accident statistics and the branch point probabilities on the Modal Study truck and train event trees would need to be minutely reexamined. If conducted on a national scale, such an examination would be a daunting undertaking, because for many states the desired data, if available, would only be available in hardcopy in state or county archives. Therefore, reexamination of the raw data at this level of detail could be extremely labor intensive. If such a reexamination was conducted, the historic accident data could be aggregated into a much larger set of categories than was done in the Modal Study or in NUREG/CR-6672, which would allow the variation of accident parameters with weather, terrain, population density, and time of day, day of the week, and season of the year to be determined.

For some states, California for example, accident data is coded for date, time of day, day of the week, weather, darkness, and object struck. Although the reporting forms and the database allow entries under each of these headings, some of the fields are often blank because the requested data was not available. This means that the dependence of accident rates on these accident characteristics can be developed only for some subset of all accidents in the database. Moreover, if developed, it may not be easy to show that the statistics for the subset are representative of the statistics for the full set of all accidents.

A study could be performed that would examine truck accident data for at least one state (e.g., California) that records route characteristics and prevailing weather and light conditions in an electronic database. By searching the electronic database, the dependence of accident statistics on these accident conditions could be developed for some subset of the accidents in the database. Then, if the representativeness of the subset could be estimated, one could see whether the mean accident rate per kilometer traveled for the subset was close to the mean for all accidents in that database and also whether the more severe sets of accident conditions found in the subset (e.g., accidents that occur during bad weather on steep downgrades in the mountains) would be expected to lead to consequences so large that estimates of mean accident risks would be increased. Note that for this to happen the consequences of unlikely severe accidents (C_{sev}) that occur under unfavorable conditions must increase relative to the consequences associated with occurrence under average conditions (C_{av}) by more than the probability of occurrence (P_{sev}) of the these unlikely severe accidents decreases relative to the probability of occurrence of accidents under average conditions (P_{av}). Mathematically, this means that

$$P_{sev}C_{sev} = Risk_{sev} \approx Risk_{av} = P_{av}C_{av}$$

which can only be true if $P_{av}/P_{sev} \approx C_{sev}/C_{av}$.

Sandia believes that examination of the dependence of accident rates on accident conditions is not likely to significantly alter risk estimates, but might improve the picture of the range of transportation accident severities. Thus, this issue resolution option is given a rating of C.

Sandia Rating **C**
Estimated Cost **Low**

5.2.4.2 Specific Routes

Examination of specific routes is not expected to significantly alter spent fuel transportation risk estimates. Specific spent fuel truck and rail shipment routes beyond those examined in NUREG/CR-6672 could be examined to confirm that specific route results are encompassed by the range of the results developed using generic routes. If performed, this study should focus on those portions of the interstate highway system and the mainline rail system likely to be used to ship spent fuel.

Sandia Rating	**B**
Estimated Cost	**Low**

5.2.4.3 Bounding Accident Rates

Development of a bounding accident rate can be done simply by taking the largest accident rate values in any extensive set of accident rate data (e.g., the ANL longitudinal study [29]) and increasing that largest value by some factor which would be expected to encompass any uncertainties in the data (e.g., a factor of 2). If bounding values are sought for truck shipment accident rates by route segment (urban, suburban, rural), increasing the top values of the distributions for truck accident rates published in NUREG/CR-6672 by the selected factor will provide the needed bounds. Therefore, Sandia does not believe that a study of bounding accident rates needs to be performed.

5.2.4.4 Accident Rate Uncertainties

The uncertainties associated with any specific accident rate can only be developed by scrutiny of the raw data used to develop the accident rate and more importantly of the methods used to collect the underlying data. Doing this would entail trips to the state or county archives where accident rate data is recorded and surveying of the sources of data to identify the errors that might be associated with the raw data. If done for all of the lower 48 states, this would be a time-consuming expensive project that would be expected to show that the uncertainties associated with individual accident rates are not significant when compared to the real-world range (variability) of accident rate data within the lower 48 states. The cost estimate provided here assumes that the study would examine perhaps one highly populated state, one great plains state, and one mountain state. Because this study is not expected to affect spent fuel transportation risk estimates, it is given a rating of C.

Sandia Rating	**D**
Estimated Cost	**Medium**

5.3 Accident Scenarios

5.3.1 Background

Because spent fuel transportation casks are massive robust structures, only a very severe accident can cause a spent fuel cask to leak. Accordingly, to estimate spent fuel transportation accident risks, the fraction of all accidents that are severe enough to cause a spent fuel cask to leak must also be estimated.

Accident rate data examines the occurrence of accidents with severities that exceed some minimum reporting criterion. Because, in general, only very severe accidents can fail a spent fuel cask and only quite minor accidents (e.g., fender-benders) are not included in tabulated accident rate data, tabulated accident rate data reflects primarily accidents that will not cause a spent fuel transportation cask to leak.

Estimates of the fraction of all reported accidents that are severe enough to cause a spent fuel cask to leak are developed by examining accident scenarios, where an accident scenario is any sequence of events that leads to a specific set of accident conditions. For example, the following set of events depicts one possible train accident scenario: a train derailment causes the cask car and a neighboring tank car carrying liquid chemicals to fall off of a high bridge and crash onto hard rock at a speed that fails the seal of the cask lid and punctures the tank car allowing its contents to catch fire. The significance of an accident scenario is that it specifies the accident conditions (impact forces, thermal loads) seen by the cask which allows the scenarios that are severe enough to damage the cask to be identified. After the frequencies of occurrence of the scenarios that lead to significant cask damage have been estimated, summation of these frequencies gives the fraction of all accidents that are able to significantly damage a spent fuel cask.

5.3.2 Comments and Issues Raised

The following indented paragraphs summarize the comments about accident scenarios that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **At the public meetings, examination of weather-related scenarios and cask and fuel loading and unloading accident scenarios was recommended. It was suggested that accident scenarios should reflect emergency response actions (e.g., responders unwilling to put out a fire) and the effects of human errors on accident severity. It was also suggested that the highway and railway route characteristics needed to construct event trees should be developed by GIS analysis of representative sets of truck and rail routes. The availability of rail accident data from the DOT Volpe Center was noted. It was stated that rail wayside conditions are very different from highway wayside conditions; e.g., there are more cuts and gas pipelines frequently share the rail line right-of-way. Development of accident statistics and scenarios for all of the following modes of spent fuel transportation was recommended: legal-weight trucks, rail, heavy-haul truck transport of rail casks, barge shipments, air shipment of NAC legal-weight cask, and dedicated ship transport.**

> **The Nuclear Energy Institute (NEI) in a letter [10] to the NRC asked that extraordinary events not be incorporated into accident scenarios. One meeting comment recommended that accidents with probabilities less than 1 in 10 million per year not be examined.**

> **Written materials authored by Audin, Resnikoff, and Halstead [8, 9, 30, 31, 32] submitted to the NRC following the public meetings suggest:**
>
> - **that the risks posed by human errors and by specific unusually severe historic accidents should be examined,**
> - **that correlations between accident conditions and route characteristics need to be incorporated into spent fuel transportation accident event trees,**
> - **that the probabilities of truck and rail accidents for actual spent fuel shipments might be orders of magnitude higher than the probabilities of general semi-tractor truck and rail accidents,**

- **that accident speeds and accident fire durations are likely to be influenced by route wayside population density,**
- **that severe truck and train accidents are more likely to occur in suburban areas than in rural areas, and**
- **that a large number of unusually severe historic accidents (e.g., the collapse of the Mianus River Bridge on 5 March 1985) be evaluated.**

The Association of American Railroads provided written copies of a review [33] of the Modal Study conducted on its behalf. The AAR review concludes that the following event frequencies may have been significantly underestimated by the Modal Study:

- **Frequency of accidents that lead to significant crush loads**
- **Explosion frequencies**
- **Fire frequencies and durations**
- **Frequency of impacts with massive wayside structures (e.g., columns, abutments)**
- **Frequency of impacts with couplers during pileup accidents**
- **Frequency of impacts with rail car frames during pileup accidents**
- **Frequencies of wayside conditions (e.g., bridges, tunnels, cuts, embankments, flat terrain)**

With regard to wayside conditions, the AAR review [33] states that

> *"Where highways tend to go over hills and down valleys, railroads go around them, or through hills and over valleys. As a consequence, railways frequently follow the path of rivers. In comparison to major interstate highways, one would expect railroads to make deeper and more frequent rock cuts and utilize more frequent and higher bridges to traverse similar terrain... In addition, highways normally have barriers or guard rails to keep highway vehicles from falling into deep cuts. The[re] are no such barriers and guard rails in the rail mode."*

The review also examined the derailment accident speed distribution and the fire duration distribution developed by the Modal Study for train accidents and concluded that derailment accident speeds were likely underestimated and that fire durations may also have been underestimated.

These comments raise ten issues:

(1) Do the structures of the Modal Study event trees need to be modified to reflect the effects of emergency response actions and human errors?

(2) Should correlations between accidents conditions (e.g., prevailing weather) and route characteristics (e.g., wayside population density and surface hardness) be incorporated into the Modal Study event trees?

(3) Should accident scenarios that lead to crush loads be added to the Modal Study event trees?

(4) Should explosion scenarios be added to the Modal Study event trees?

(5) Should the Modal Study event trees incorporate scenarios for loading and unloading accidents?

(6) Should extremely improbable very severe accident scenarios be added to the Modal Study event trees?

(7) Should unusually severe historic accidents be examined or incorporated into the Modal Study event trees?

(8) Do the branch point probabilities on the Modal Study truck and rail accident event trees need to be reevaluated using recent accident data?

(9) Do the Modal Study accident speed and fire duration distributions need to be reevaluated using recent accident data?

(10) Do the Modal Study fire frequencies need to be reevaluated using recent accident data?

The suitability of the structure of the Modal Study event trees is questioned by issues one through seven. Issue eight suggests that the branch point probabilities on these trees are dated and therefore in need of reevaluation. Issues nine and ten suggest that the Modal Study fire frequencies and accident speed and fire duration distributions are dated and therefore in need of reevaluation.

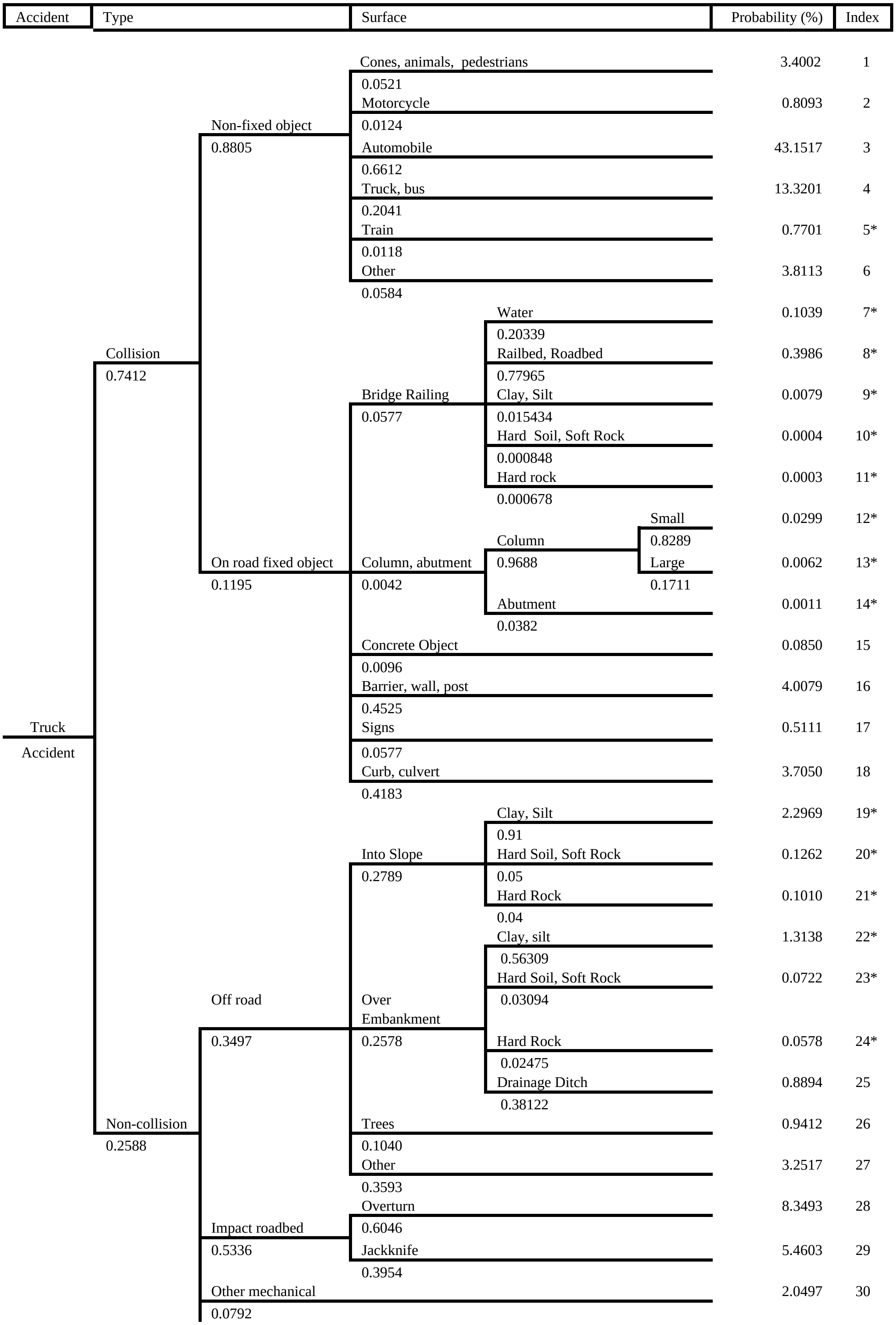
5.3.3 Sandia's Discussion of These Issues

5.3.3.1 Event Trees

In order to examine the tremendous range of possible accidents, risk analyses construct sets of representative accidents that capture the relevant distinguishing characteristics of each accident and also the diversity of all possible accidents. Representative sets of accidents are often developed by constructing accident event trees.

Truck and train accident event trees were constructed to support the Modal Study [1]. Figures 5.1 and 5.2 present the Modal Study truck and rail accident event trees as they were modified for use in the NUREG/CR-6672 study. Inspection of these figures shows that an event tree depicts an accident scenario as a sequence of events and also gives the probability of each event in the sequence. Thus, a path on the event tree constitutes a unique sequence of events and the product of all of the branch point probabilities for the events on a particular path gives the probability of that accident scenario. For example, in the truck accident event tree shown in Figure 5.1, a truck accident that leads to a collision with a pedestrian is depicted by the uppermost branches of the tree, specifically the branches labeled "Collision," "Non-fixed object," and "Cones, animals, pedestrians." Because the probabilities of these branches are 0.7412, 0.8805, and 0.0521, the chance that this accident scenario occurs, given that any truck accident has been initiated, is 3.4002 percent = 100

[(0.7412)(0.8805)(0.0521)], where 3.4002 is called the path (scenario) probability and gives the percent of all truck accidents that follow this path. Since the probability of any accident occurring is not included in this product, the resulting fraction is a conditional probability, that is conditional on the occurrence of a truck accident of any severity and type.


Accident
Type
Surface
Probability (%)
Index
Cones, animals, pedestrians
3.4002
1
0.0521
Motorcycle
0.8093
2
Non-fixed object
0.0124
0.8805
Automobile
43.1517
3
0.6612
Truck, bus
13.3201
4
0.2041
Train
0.7701
5*
0.0118
Other
3.8113
6
0.0584
Water
0.1039
7*
0.20339
Collision
Railbed, Roadbed
0.3986
8*
0.7412
0.77965
Bridge Railing
Clay, Silt
0.0079
9*
0.0577
0.015434
Hard Soil, Soft Rock
0.0004
10*
0.000848
Hard rock
0.0003
11*
0.000678
Small
0.0299
12*
Column
0.8289
On road fixed object
Column, abutment
0.9688
Large
0.0062
13*
0.1195
0.0042
0.1711
Abutment
0.0011
14*
0.0382
Concrete Object
0.0850
15
0.0096
Barrier, wall, post
4.0079
16
0.4525
Truck
Signs
0.5111
17
Accident
0.0577
Curb, culvert
3.7050
18
0.4183
Clay, Silt
2.2969
19*
0.91
Into Slope
Hard Soil, Soft Rock
0.1262
20*
0.2789
0.05
Hard Rock
0.1010
21*
0.04
Clay, silt
1.3138
22*
0.56309
Hard Soil, Soft Rock
0.0722
23*
Off road
Over
0.03094
Embankment
0.3497
0.2578
Hard Rock
0.0578
24*
0.02475
Drainage Ditch
0.8894
25
0.38122
Non-collision
Trees
0.9412
26
0.2588
0.1040
Other
3.2517
27
0.3593
Overturn
8.3493
28
Impact roadbed
0.6046
0.5336
Jackknife
5.4603
29
0.3954
Other mechanical
2.0497
30
0.0792

Fire only 0.9705 31
0.0375

Figure 5.1 Modified Modal Study truck accident event tree.

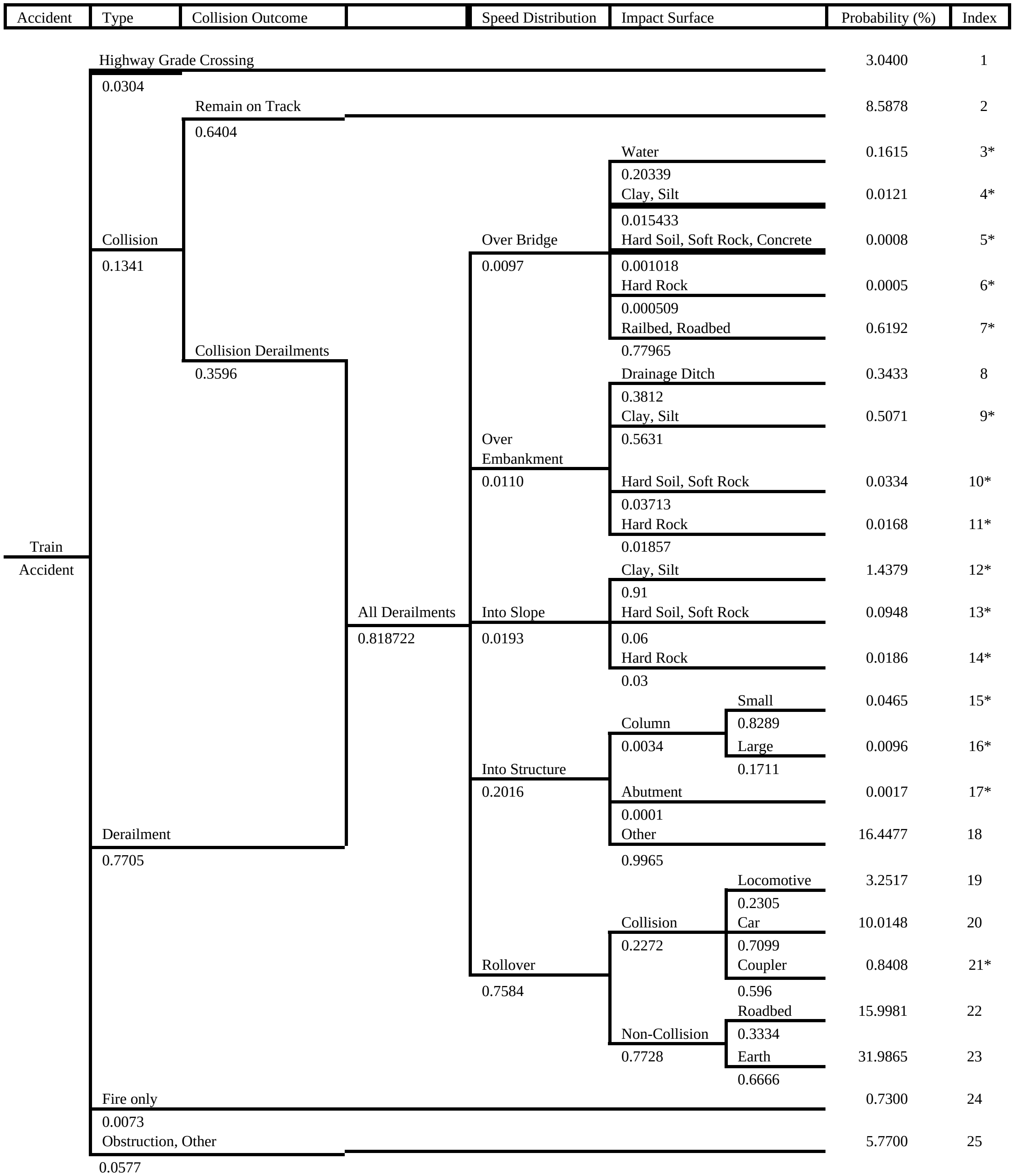


Figure 5.2 Modified Modal Study train accident event tree.

5.3.3.2 Event Tree Branch Point Probabilities

The accident branch point probabilities on the Modal Study event trees were based on truck accident data collected from 1973 through 1983 and train accident data collected from 1975 through 1982 and the branch point probabilities that express the frequencies of occurrence of route characteristics (e.g., the frequencies of occurrence of various wayside surfaces) are based on surveys of California segments of two interstate highways. Because all of this data is now at least 17 years old, it is possible that reconstruction of the Modal Study event trees using more recent data might significantly change the values of the scenario probabilities on those trees.

The risks posed by the transportation of spent fuel by truck and rail were reexamined recently by SNL [3]. The reexamination used the Modal Study event trees to develop representative sets of accidents and accident severity fractions. In the Sandia study (NUREG/CR-6672), the problem posed by the age of the data that underlies the Modal Study event trees was addressed by comparing some of the branch point probabilities and scenario probabilities on these trees to estimates of these parameter values derived from more recent data. Those comparisons suggested that these trees still present a reasonable picture of truck and train accidents and also of the probabilities of occurrence of truck and train accident scenarios (i.e., the tree structures seem reasonable and updating the event tree branch point probabilities would probably not change the scenario probabilities by more than a factor of 2 or 3). However, because of the qualitative and limited nature of the analysis, confirmation of the adequacy of these trees would require reconstructing the trees using recent data.

Because the finite element calculations performed for NUREG/CR-6672 indicated that only high speed collisions with an unusually hard surface were likely to fail a Type B spent fuel cask, Sandia used GIS methods of analysis and U.S. Agriculture Department data to develop new frequencies of occurrence for wayside route surfaces for several multi-state mainline rail and interstate highway transportation routes. This analysis found that hard rock wayside surfaces had higher frequencies of occurrence than those used in the Modal Study. The wayside surface branch point probabilities in Figures 5.1 and 5.2 reflect the results of these GIS analyses.

The AAR review of the Modal Study states that the occurrence frequencies of wayside structures (columns, abutments, other reinforced concrete structures) on the Modal Study rail accident event tree may be significantly in error. Nevertheless, because concrete, even reinforced concrete backed by large amounts of soil (e.g., a bridge abutment), is not a hard surface relative to a Type B spent fuel cask, no attempt was made during the NUREG/CR-6672 study to develop new branch point probabilities for the frequencies of collisions with columns, abutments, and other concrete structures.

The Modal Study rail accident event tree has a path that represents a collision with a coupler. Because cask puncture might be caused by collisions not only with couplers but also with other robust puncture probes (e.g., broken rails), the structure of the Modal Study rail accident event tree may not fully capture the chance that a train accident may lead to the puncture of a spent fuel cask. But tank car puncture data indicates that puncture of tank car shells that are one inch thick is rare. Therefore, puncture of a Type B steel-lead-steel spent fuel cask, which has two steel shells that are each at least one inch thick, is expected to be extremely unlikely.

5.3.3.3 Event Tree Structures

For the Modal Study, a large number of specific historic truck and rail accidents were reviewed in order to develop data about accident velocities, fire durations, and the characteristics of objects struck during collisions. This data was then used to test the reasonableness of the accident velocity and fire duration distributions used in the Modal Study and also of the branch point probabilities for wayside route surfaces on the Modal Study event trees. Estimation of source terms for specific severe historic accidents and calculation of consequences for those accidents was not done.

An accident event tree is an importance sampling scheme that samples the infinite set of real-world accidents thereby constructing a representative set of accidents for analysis. Any event tree can be further elaborated by introducing additional branches. Such elaboration will produce a larger set of representative accidents. Use of this larger accident set will lead to a more detailed depiction of the range of accident risks. However, if the original smaller set of representative accidents was properly constructed, elaboration will not significantly alter the estimates of mean (expected) risk that were obtained using that smaller accident set. Thus, it is not clear a priori that incorporation of event tree branches that express emergency response actions or human errors or additional paths for specific severe historic accidents will improve truck or train spent fuel risk analysis results. Instead, as was done in the Modal Study, when conducting risk analyses, specific accidents should be examined to ensure that the general modeling construct being used (e.g., the event trees and their associated speed and fire duration distributions) encompasses the conditions of these specific accidents and properly reflects their probability of occurrence.

Regional variations in route characteristics (e.g., variation of wayside surface frequencies of occurrence, bridge heights, accident rates, and population densities) and thus correlations between these characteristics can be examined by constructing separate event trees for different regions (e.g., mountain states, great plains states, coastal states), specific routes, and/or route types. The effects of the use of different transport vehicles and operating procedures can also be addressed by constructing separate event trees for each combination of a transport vehicle and a set of operating conditions (e.g., interstate 18-wheel semi-tractor trailers vs heavy haul trucks; regular freight trains running under operating restrictions vs dedicated trains running without operating restrictions, barges, ships, planes). For example, Department of Transportation Volpe Center staff have constructed separate event trees for regular and dedicated trains running with and without speed and passing restrictions on mainline tracks, sidings, and yards. In addition, Volpe Center staff have also developed models that can predict train accident rates on route segments from the characteristics of the segments (e.g., track quality, curvature, grade).

Although the construction of sets of more detailed accident event trees could be done, it is far from clear whether doing so will produce risk estimates that are substantially different from those that would be obtained if the Modal Study event trees were reconstructed with only minimal modifications using more recent accident data. Nevertheless, given that the data used to construct the original Modal Study truck and rail accident event trees, accident speed distributions, accident fire duration distributions, and bridge height distributions is now at least 17 years old, these trees and distributions should surely be reconstructed using more recent accident data and route data that reflects the characteristics of interstate highways and mainline rail routes that span all major regions of the continental United States, not just two interstate highway route segments located in California. After this was done, introducing elaborations (additional tree branches) into dominant event tree pathways on these revised truck and train accident trees, would allow the effects on overall risk estimates of emergency response actions, human errors, and accident scenarios that depict specific severe though improbable historic accidents to be examined.

5.3.3.4 Distributions

Spent fuel transportation risk assessments require data on accident rates (i.e., overall accident rate per km independent of accident severity), accident characteristics (e.g., collision with the exposed face of a hard rock cut), and transportation route characteristics (i.e., route lengths, the heights of bridges on the route, wayside population densities, and wayside surface characteristics). Because accident probabilities and severities depend strongly on these parameters, the variability of these parameters must be examined. Each of these parameters is subject to two types of variability. First, each of these parameters can take on a wide range of values in the real world. Second, each specific value of any of these parameters has an uncertainty associated with it. Thus, each parameter has a real-world distribution of values and each value that enters the real-world distribution has an uncertainty associated with it.

Because the values of these parameters are all developed from real data, the uncertainty distributions associated with specific values of any of these parameters (e.g., the population density of an urban route segment, the fraction of the length of a rural route segment that lies next to bodies of water) are not likely to be broad. Because the real-world distribution of each of these parameters is broad, the uncertainty range associated with individual values in this distribution is unimportant. Therefore, when performing a risk assessment, the development of the distribution of the parameter's values in the real world is far more important than the development or construction of the uncertainty distribution that is associated with any specific value in the real-world distribution.

5.3.3.5 Human Errors

Spent fuel transportation risks could be significantly affected by human errors, for example, the failure to properly secure the cask lid after loading of spent fuel into the cask and driver errors during operation of the cask transport vehicle. Some human errors should be directly accounted for by accident statistics. For example, if semi-tractor trailer and freight train accident statistics are representative of the types and frequencies of the truck and train accidents that might occur during the transport of spent fuel by truck or train, then these accident statistics should already reflect the human errors that might occur when these spent fuel transport vehicles are operated. Conversely, if human errors during the design, construction, and inspection of spent fuel casks are significant and are not encompassed by the range of accident severities and the radioactive releases associated with the more severe accidents in this range, then the range would need to be adjusted to reflect the possibility that human errors could make some severe accidents more probable and/or more severe.

5.3.3.6 Emergency Response

RADTRAN [26, 27] calculations can model the effects of evacuation and decontamination on accident population dose. Specifically, the time when evacuation occurs, the ground contamination level that leads to evacuation, and the ground contamination level that leads to condemnation of property (permanent interdiction) can all be specified through RADTRAN input. Thus, by varying these parameters, the effect of different emergency response actions on consequence and risk estimates could be examined. However, because the NRC has stated that principal focus of this study is on package response to accident conditions, the effect of emergency response actions on accident population dose is not within the current scope of the Package Performance Study.

5.3.3.7 Transportation Modes

Although most spent fuel shipments will be made by rail or truck, some may involve the use of barges or heavy-haul trucks. Transportation by heavy-haul truck is likely to occur between rail spurs and reactor, temporary storage, or permanent repository sites that are not directly serviced by a rail line. Transport by barge may occur for shipments that originate at coastal reactor sites or reactors located on major rivers. Shipment of power reactor spent fuel in seagoing ships is likely only if the spent fuel is shipped to or from overseas locations. Shipment of power reactor spent fuel by plane is not expected to take place. Ship, barge, and air transport are not within the current scope of the Package Performance Study.

5.3.3.8 Loading and Unloading Accidents

Two types of accidents might occur during loading or unloading of a spent fuel cask. First, a spent fuel assembly might be dropped while it is being loaded into or removed from the cask. Second, the cask itself might be dropped while it is being loaded onto or removed from the transport vehicle. Because it is customary to treat loading and unloading as a facility rather than a transportation activity, accidents that occur during loading and unloading of spent fuel casks at the shipment origin and destination are not normally examined by transportation risk assessments and will not be studied unless NRC broadens the scope of the Package Performance Study.

Current spent fuel shipping practice is to ship spent fuel directly to the shipment destination without any interim storage. Because some spent fuel shipment routes may involve shipment by barge and many reactor sites and some interim storage sites may not be serviced by a rail spur, shipment by barge or rail may require intermodal transfers of the cask, most likely to a truck. Thus, any risk assessment that examines transportation routes that involve intermodal cask transfers will also examine accidents that might occur during these transfers. However, if a cask were dropped during an intermodal transfer, the fall height would almost always be less than 10 meters and the impact would almost certainly not be onto an unyielding surface. Therefore, because cask certification requires that the cask be shown capable of surviving a 10 meter fal onto an unyielding surface without loss of containment, the dropping of a spent fuel cask during an intermodal transfer is not expected to pose any significant risk.

5.3.4 Issue Resolution Options

Two of the issues raised, examination of loading and unloading accidents and of spent fuel transportation by barge and plane are not within the scope of the Package Performance Study. The other issues raised are all amenable to study although most do not lend themselves to study by more than one method.

5.3.4.1 Correlations Among Accident Risk Parameters

The correlation of accident rates with weather conditions, terrain, population density, and time of day, day of the week, and season of the year was discussed in Section 5.2.4.1 where it was concluded (1) that, although these correlations could be developed, the development would entail a costly and time-consuming study and (2) if developed, the correlations would be unlikely to change risk estimates significantly. Correlations are also possible between weather, population density, and terrain. For example, high population densities are unlikely along route segments in the Rocky Mountains. As with accident rates, development of these correlations using all available data would be a daunting undertaking, because for many states the desired data would only be available in hardcopy in state or county archives. Moreover, development of correlations between weather conditions, terrain, population density, and time of day, day of the week, and season of the year should be considered only after the dependence of accident rates on these parameters has been examined, because unless that dependence is strong, these correlations are also likely to be weak and thus to have little effect on risk.

If a study of the dependence of accident rates on other risk parameters, described in Section 5.2.4.1, showed that accident rates depended strongly on at least some other risk parameters, then the accident rate study could be broadened to search for significant dependencies between other risk parameters. Again, although this study might improve the picture of the range of transportation accident severities, it is unlikely to significantly alter risk estimates. Thus, it is not rated very highly.

Sandia Rating **C**

Estimated Cost **Low (as an add-on to the accident rate study)**

5.3.4.2 Occurrence Frequencies of Route Wayside Surfaces.

Geographic Information System (GIS) methods of analysis could be used to develop frequencies of occurrence for route wayside surfaces for representative sets of interstate and mainline rail routes and also for the surfaces of accident locations for accidents in databases. Comparison of these data would show whether the distribution of accident site surfaces is similar to or quite different from the distribution of the wayside surfaces along the representative interstate highway and mainline rail routes. Appropriate combination of these results would then generate an updated set of route wayside surface occurrence frequencies for use in truck and rail transportation accident event trees. Finally, if the analysis suggested that transportation risks might have strong dependencies on regional route characteristics, construction of a few additional event trees might determine whether the use of larger sets of event trees would significantly alter estimates of spent fuel transportation risks.

Occurrence frequencies for man-made wayside structures and the surfaces of cuts (e.g., through rock) can be determined by surveying selected transportation corridors. GIS analyses should provide relatively precise occurrence frequencies for the surfaces of naturally occurring wayside slopes that can be impacted during collision accidents. Comparison of the occurrence frequencies developed by surveying cut surfaces along corridors to those developed by GIS methods would then show whether cut surface frequencies are adequately represented by average wayside surface frequencies (e.g., cuts are likely to go through rock and thus to have rock surfaces).

Accurate determination of the frequencies of occurrence of hard wayside surfaces could alter risk estimates significantly. Moreover, this is an issue called out explicitly during the public meetings. Thus, it is given an A rating.

Sandia Rating **A**

Estimated Cost **Medium**

5.3.4.3 Human Errors

The frequencies of human errors during the design, fabrication, loading, and inspection of spent fuel casks can be estimated by examining data on the human errors that occur during the design, fabrication, operation, and inspection of other moderately complex pieces of equipment. Introduction of this error rate data into a representative subset of the accident scenarios depicted on the Modal Study spent fuel accident event trees will allow the effect of human errors on the probabilities of these scenarios to be estimated. Comparison of the new scenario probabilities that reflect the possibility of human errors not accounted for by historic accident data to the old scenario probabilities will then allow the significance of these human errors to be estimated.

The influence of human errors on spent fuel transportation risk estimates has not been extensively studied. Rigorous requirements for the preparation and inspection of casks are applied before they are shipped. Therefore, if analyzed, human errors are not expected to have a large impact on risk estimates. Nevertheless, because the effect of human errors on risk estimates is not well characterized, although the effect is not expected to be large, this resolution option is given a B rating.

Sandia Rating **B**

Estimated Cost **Low**

5.3.4.4 Speed and Fire Duration Distributions

New distributions of initial accident speeds and accident fire durations can be easily developed from recent accident data. New distributions of interstate highway and mainline railway bridge heights can also be developed. Comparison of these new distributions to those developed for the

Modal Study would then show whether the Modal Study distributions are still representative of current accident data.

This task could also use GIS methods to develop a distribution of wayside slope heights for a few representative truck and rail routes. Comparison of these distributions to the distributions of truck or rail bridge heights would show whether the use of a vector sum of initial accidents speeds and impact velocities based on bridge heights is a reasonable way to estimate impact speeds for accidents where the transport vehicle or the cask plunges down a slope. In addition, inspection of the conditions of singular unusually severe historic accidents would then show whether these speed and fire duration distributions encompass the conditions and likely frequencies of occurrence of the severe historic accidents.

Because the Modal Study accident speed and fire duration distributions are based on data that is over 17 years old, these distributions should be reconstructed using recent data. Because reconstruction of these distributions is not expected to change them dramatically, this resolution option is given a B rating.

Sandia Rating **B**

Estimated Cost **Low**

5.3.4.5 Event Tree Structures and Branch Point Probabilities

Results from the tasks described in Sections 5.3.4.1 through 5.3.4.4 and review of recent accident data would allow new values to be developed for all of the branch point probabilities on the Modal Study truck and train accident event trees. This review would also allow the structure of those event trees to be reevaluated and changed if new important paths were identified or paths on the current trees were shown to be unimportant and thus to be candidates for elimination by collapse into other branches on the tree. After these trees have been reconstructed, comparison of the new trees, especially the probabilities of the accident scenarios important for risk, to the original Modal Study trees would show whether the original Modal Study trees were suitable for use in transportation risk assessments.

Because the Modal Study event trees are now dated, they should be reconstructed in order to determine whether recent data would identify new important accident scenarios or significantly alter the probability estimates for old important scenarios. This is especially true for the rail accident event tree, which may need to be significantly elaborated to capture the effects of terrain, track type, and consist.

Sandia Rating **A**

Estimated Cost **Medium**

5.3.4.6 Specific Historic Severe Accidents

The occurrence frequencies and the conditions (e.g., speed, impact surface hardness, fire temperature and duration) that characterize a substantial set of historic severe accidents can be estimated and compared to the range of accident conditions represented by the reconstructed truck and rail accident event trees and their associated impact and fire distributions. The comparison would determine whether the reconstructed event trees encompass the conditions that characterize the accidents in the set of historic severe accidents.

Sandia Rating	**A**
Estimated Cost	**Low**

6. OTHER TRANSPORTATION SAFETY ISSUES

6.1 Comments and Issues Raised

The following indented paragraph summarizes the comments about other transportation safety issues that were made at the four public meetings and in the written materials submitted to the NRC as a result of these meetings.

> **Sensitivity to various parameters needs to be studied. Uncertainty should be accounted for in the analysis. When presenting data, include error bars. The analysis should be risk-informed: What increases safety? What adds to safety? Where is the biggest safety "bang for the buck?" We need to bound the studies, and not extend them infinitely.**

These comments raise the following issues:

(1) The parameters that dominate risk estimates need to be identified.

(2) The uncertainties associated with consequences and risks should be estimated.

(3) Bounding accidents should be examined; all accidents need not be examined.

(4) Risk assessment results should be used to increase the safety of spent fuel shipments in a cost-effective manner

Ways to address bounding accidents in risk analyses were discussed above in Section 5.2, Accident Statistics, and Section 5.3, Accident Scenarios. Use of risk assessment results to support the making of cost-effective decisions could be demonstrated by an illustrative case study, but isn't a package performance issue. Accordingly, the remainder of this section focuses on the benefits of performing sensitivity and uncertainty studies when conducting risk assessments.

6.2 Sandia's Discussion of These Issues

Estimates of the risks associated with future spent fuel shipments can at best be qualitative. Consequently, it is important to develop a picture of how qualitative the predictions are. This would normally be done in three steps: (1) Identification of important parameters by a Sensitivity Study, (2) Construction of Uncertainty Distributions for important parameters, and (3) Performance of an Uncertainty Study.

Sensitivity Study. Broad relatively flat uncertainty distributions are defined for all of the input variables that enter the risk calculation. Then, structured Monte Carlo sampling methods are used to examine the effect on predicted risks of sampling from these uncertainty distributions. Because broad flat uncertainty distributions are used, the sensitivity of risk predictions to each input parameter is magnified. This allows all possibly important parameters to be identified.

Uncertainty Distributions. Realistic uncertainty distributions are constructed for all important input parameters by review of technical literature, performance of appropriate experiments, and/or unbiased polling of experts.

Uncertainty Study. Finally, the sensitivity calculations are repeated using the more precise uncertainty distributions that were constructed for each important input parameter. The results of this study, would then be expected to predict with reasonable precision the uncertainties associated with the risk predictions.

Usually, risk predictions are examined qualitatively by performing only the first step, the sensitivity study. Full uncertainty studies are rarely performed because development of precise uncertainty distributions for important input parameters would be expensive and time-consuming. Development of realistic uncertainty distributions for important parameters would be laborious, time-consuming, and expensive because little data is available to use to define the uncertainties associated with most risk input parameters, especially those that determine cask response to severe accident conditions, fission product release, downwind transport of radioactive materials, and the induction of radiation health effects. Thus, to develop semi-quantitative uncertainty distributions for these many parameters is a major task, one that has rarely been undertaken. However, if these distributions can be developed, then rerunning the sensitivity calculations using the more precise distributions will efficiently yield the desired picture of the uncertainties associated with spent fuel transportation risk predictions. Finally, performance of a full uncertainty study would automatically provide a reliable picture of the consequences and the risks associated with the worst credible accidents; and the risks associated with these worst credible accidents would constitute a set of bounding accident risks. In addition, if the sensitivity of various operational choices is investigated by performing some suitable suite of calculations, then a picture of cost-effective ways to conduct the shipment campaign will be developed.

6.3 Issues Resolution Options

6.3.1 Sensitivity Study

If precise estimates of the uncertainties associated with spent fuel transportation risk estimates are needed, then a full uncertainty study (i.e., definition of broad relatively flat uncertainty distributions for all input parameters, performance of sensitivity calculations to identify important input parameters, development of precise uncertainty distributions for important parameters, repetition of the sensitivity calculations using the more precise uncertainty distributions for the important parameters) should be performed. If bounding estimates of uncertainties are sufficient, then only the sensitivity study (i.e., definition of broad relatively flat uncertainty distributions for all input parameters, performance of sensitivity calculations to identify important input parameters) would need to be performed.

Sensitivity Study

Sandia Rating	**A**
Estimated Cost	**Low**

6.3.2 Full Uncertainty Study

If the uncertainty estimates developed by the sensitivity study are so large that the upper bounds on the consequences and risks posed by the more severe accidents are unacceptably large, then a full uncertainty study could be conducted. First, realistic uncertainty distribution would be developed for the set of parameters shown by the sensitivity study to dominate risk estimates. After these distributions had been developed by expert elicitations, analysis, and/or experiments, the sensitivity calculations would be rerun using these more precise uncertainty distributions. Because these distributions are not likely to be broad and flat, their use would be expected to diminish the uncertainties associated with the risk estimates that were obtained from the sensitivity study.

Performance of an uncertainty study will be important if the estimated uncertainty range on risk estimates for the risks predicted for the more severe accidents examined are unacceptably large. As this is not believed to be the case, performance of an uncertainty study is given a rating of B.

Full Uncertainty Study

Sandia Rating **D**

Estimated Cost **Medium**

7. SUMMARY, DISCUSSION, AND RECOMMENDATIONS

The analysis methods and results of two NRC studies, NUREG/CR-4829 [1], which is usually referred to as the Modal Study and NUREG/CR-6672 [3], Sandia's recent "Reexamination of Spent Fuel Shipment Risk Estimates," in large measure set the agenda for any new examination of the response of spent fuel casks to severe accident conditions. Thus, this section begins by summarizing the analysis methods and results developed by each study.

7.1 Modal Study Analysis Methods.

The Modal Study examined the effects of mechanical and thermal accident forces on simple representations of a generic truck and a generic rail cask and the magnitude of the fission product releases to the atmosphere that these forces might cause. For each of these casks, finite element analyses were performed for impacts onto various surfaces. The finite element cask models constructed for the Modal Study did not include any details of the cask closure or of any cask penetrations. In fact the casks were modeled as if the lids were rigidly attached to the cask body. Incremental cask failure was assumed based upon the peak level of strain in the inner shell of the steel-lead-steel sandwich wall design of these casks.

The Modal Study investigated the thermal response of each of these generic casks to fires by performing 1-D analyses of the thermal response of the middle portion of the cask for fires with average temperatures of 800 and 1000 C. The effect of the cask position relative to the fire on thermal loads was assessed by simple geometric analyses. Lead layer mid-thickness temperature histories were calculated, but not the peak temperatures attained, which are delayed in time due to continued thermal energy transport through cask components after fire termination. Cask seal area temperatures were not directly calculated, but were inferred from cask design details. Because fuel rod temperatures were not estimated, the fire durations needed to cause rod failure by burst rupture were not estimated.

Accident consequences (e.g., population dose, radiation induced cancer fatalities) were not estimated for the Modal Study. Instead, for each bin in the Modal Study accident matrix, estimates were developed for the number of curies of noble gases, condensible vapors, and particulates that would be released by the accidents that were assigned to that bin. Multiplication of these curie amounts by the bin probability then produced a result termed the curie risk of the bin. Bin release fractions were developed by multiplying release fraction estimates, developed by Lorenz [17-20] from high-temperature burst rupture tests on sections of H. B. Robinson spent fuel rods, by an estimate of the fraction of the fuel rods in the cask that might be failed by the accidents assigned to each bin. This yielded estimates for the fractions of materials in spent fuel rods that would escape to the cask interior. Then, because fission product transport from the cask to the environment was not modeled, all species released to the cask were assumed to escape to the environment undiminished by any deposition to cask internal surfaces (i.e., cask-to-environment release fractions were assumed to be 1.0).

Accident matrix bin probabilities were developed by constructing generic truck and rail accident event trees, determining which scenarios on these trees might threaten the integrity of a spent fuel cask, estimating the impact speed, angle, and orientation and fire size, offset, and duration that would be required to cause cask integrity to be compromised, and calculating the probabilities of each combination of a scenario and a set of accident conditions that might lead to cask leakage.

7.2 Analysis Methods Used in NUREG/CR-6672

For NUREG/CR-6672, Sandia examined the effects of impact and thermal loads on four generic casks, estimated the magnitudes and probabilities of the source terms that might be produced by unusually severe accidents, and calculated the consequences that would be caused by the release of those source terms. The four generic casks studied were steel-lead-steel truck and rail casks, a steel-DU-steel truck cask, and a monolithic steel rail cask.

Finite element calculations were performed in order to estimate the damage that might be caused by impacts of these four generic casks onto unyielding surfaces. The finite element calculations used simplified representations of each generic cask (e.g., cask penetrations were not modeled; and in order to minimize computational time, lid bolts were represented by square shapes). The size of cask seal failures was estimated from the relative perpendicular and normal displacements of the cask lid relative to the cask body. The strains generated in spent fuel rods by extra-regulatory impacts were estimated by extrapolation of regulatory impact rod strains and comparison of these extrapolated strain values to the rod failure strain criterion published in SAND90-2406 [34]. The results of the unyielding surface calculations were extrapolated to real yielding surfaces by partitioning the available impact energy between the real yielding surface and the cask, and assuming that the damage caused by deposition into the cask of a given amount of energy was independent of the characteristics of the impact surface once energy loss to that surface was properly accounted for.

The time-temperature history of the inner shell of each generic cask was estimated by 1D thermal calculations which modeled only the cask body including the neutron shield compartment but not the cask lid or closure. These time-temperature histories were used to estimate the times required to reach temperatures in the cask closure and in the fuel assemblies being carried in the cask that would cause elastomer seals to fail due to thermal degradation and rods to fail by burst rupture. Because these calculations modeled an engulfing optically dense hydrocarbon fuel fire, the effects of cask offset from the fire, shielding of the cask by the bed of the transport vehicle, and loss of energy from the cask to the ground, were not examined.

A critical review of the values of the spent fuel release fractions developed by Lorenz [17-20] was performed for NUREG/CR-6672. This review developed new estimates of spent fuel release fractions, including a model for release of Cs that reflects release as a constituent both of particles and of vapors. Although the values developed for aerosol release fractions attempted to correct for the effects of particle production by impact fracturing of fuel pellets and CRUD and of particle filtering by the formation of fuel particle beds in the fuel-cladding gap and in any crack network in the fuel pellets, the values developed were at best qualitative.

The truck and train event trees developed by the Modal Study were used with only minor modification of the probabilities of wayside surfaces, especially hard rock wayside surfaces. The Modal Study frequency distributions for accident speeds and accident fire durations were used without any attempt to show that more recent data would produce similar distributions.

Distributions of route parameters were constructed from the results of HIGHWAY and INTERLINE calculations for the real routes that connect each commercial reactor to six possible interim storage locations and these six locations to three possible permanent repository locations. Values for the aggregate urban, suburban, and rural segments of 200 generic shipment routes were then selected by structured Monte Carlo sampling of these route parameter distributions. Route parameter values were also developed for the aggregate urban, suburban, and rural segments of four real routes. The effects of the use of aggregated route segments on consequence estimates were not examined. Finally, population doses were estimated for each hypothetical severe accident that led to a release of radioactivity by performing RADTRAN calculations for each of the 200 generic routes developed by structured Monte Carlo sampling and also for each of the four real routes. The impact of uncertainties in important input parameters on these consequence estimates was not examined by these calculations.

7.3 Technical Issues Raised by the Modal Study and NUREG/CR-6672

Both the Modal Study and NUREG/CR-6672 used finite element methods to examine cask failure due to impact and 1D thermal heat transport calculations to examine cask and rod failure due to heating by a severe fire. Although these analysis methods are routinely used to examine the effects of mechanical and thermal loads on structures, only a very few comparisons of the results generated by these methods to the results of cask crash and thermal tests have been made. Thus, the use of these methods to predict cask damage due to severe collisions or severe fires needs to be validated by comparing computational predictions to the results of cask crash and fire tests. Because any reexamination of spent fuel cask response to severe accident conditions will be a high visibility program, the casks tested and modeled for the Package Performance Study should have designs very similar to those currently in use or, if at all possible, to the dual-purpose cask designs that are likely to be the designs of choice during future spent fuel transport campaigns.

Failure of spent fuel rods, fracturing of spent fuel pellets and of CRUD deposits, formation of particle beds in the fuel cladding gap and in internal pellet crack networks, and filtering of small particles during transport through these beds to the rod failure all strongly influence the release of radioactive particulates from failed rods to the cask interior. Because very little experimental data exists on which to base estimates of rod failure fractions, impact fracturing of fuel pellets and CRUD, particle bed formation, and bed filtering, both the Modal Study and the Sandia study were forced to use expert judgement and hand calculations to estimate release fractions for particles from failed fuel rods to the cask interior upon rod failure due to impact or burst rupture. Accordingly, rod failure, fuel pellet and CRUD fracturing, particle bed formation inside of fuel rods, and filtering of respirable particles by particle beds should be examined experimentally.

Finally, although the Modal Study conducted extensive analysis of truck and train accident data and used the data to develop event trees and distributions of severe accident speeds and severe fire durations, this data is now quite dated, and in need of reexamination using recent truck and train accident data.

7.4 Tasks Recommended for Study by Sandia

In light of the preceding discussion, Sandia recommends that the Package Performance Study should:

- Demonstrate the validity of the finite element and heat transport computational methods used in prior transportation risk studies to model the impact and thermal response of Type B spent fuel transportation casks by comparing the predictions obtained using these methods to the results of cask crash and fire tests.
- Experimentally examine the failure of spent fuel rods, fracturing of CRUD and spent fuel pellets, formation of particle beds inside of spent fuel rods, and filtering of respirable particles by those beds.
- Reconstruct the Modal Study truck and train accident event trees and accident speed and fire duration distributions using recent accident data.

Cask damage due to impact onto hard surfaces would be estimated by performing 3-D finite element impact calculations on a parallel processing computer using a detailed realistic nodalization of the cask. Cask damage due to exposure to fires would be estimated by performing 3-D heat transport calculations for a detailed representation of both the cask, its closure, and the spent fuel assemblies contained in the cask. In order to demonstrate that these computational methods are able to credibly predict the results of hypothetical severe collision and fire accidents, pretest computational predictions should be compared to the results of crash and fire tests on a large-scale or a full-scale cask.

The behavior of fuel cladding embrittled by autoclaving under hydrogen, of rods coated with simulated CRUD, and of surrogate and real spent fuel pellets, when each is subjected to impact loads should be examined by performing bench-scale experiments that allow rod failure modes, fracturing of the simulated CRUD deposits, formation of particle beds inside of the fuel rods due to fracturing of fuel pellets, filtering of respirable particles by these particle beds, and the size distributions of the particles produced to be determined. Table 8.1 depicts the relationships between these bench-scale experiments and the test crash of a cask that contains a fuel assembly loaded with surrogate fuel pellets.

GIS analyses of shipment routes and accident sites and review of truck and train accident data for the years 1985 to the present should be performed in order to develop the data needed to support the reconstruction of the Modal Study truck and train accident event trees and the accident speed and fire duration distributions that are associated with those trees.

Table 8.2 summarizes the results of the discussion of the issues raised by the discussions held at the public meetings held during the fall of 1999 last fall in Bethesda MD, and Las Vegas and Pahrump NV. Inspection of the table shows that all of the technical issues raised by the methods of analysis and results of the Modal Study and the NUREG/CR-6672 study were also raised by the discussions and comments made at the four public meetings. Inspection of Sandia's ratings of each issue in the table also shows that these ratings are entirely consistent with Sandia's evaluation of the technical issues raised by the Modal Study and by NUREG/CR-6672. Consequently, the options that SNL recommends for study are the same as the set of studies developed by SNL's review of the technical issues raised by the Modal Study and the NUREG/CR-6672 study.

Table 8.1 Relationships between Cask Crash and Rod and Pellet Impact Tests

Process/Phenomenon	Study					
	Pellet Impact Tests		**Rod Impact Tests**	**Rod + Pellet Impact Tests**	**Cask Crash Tests**	**Finite Element Modeling of Cask Crash Tests**
	Real Pellets	**Surrogate Pellets**	**Embrittled Rods**	**Embrittled Rods with Surrogate Pellets**	**Full or Large-Scale Casks with at least one assembly containing unembrittled rods and surrogate pellets**	
	SNL	**GRS**	**GRS**	**GRS**	**SNL**	**SNL**
Pellet Fracturing						
Size distribution	x	x		x	x	(not modeled)
Dependence on impact energy	x	x		x	x	
Particle bed formation				x	x	
Particle filtering by particle beds				x	x	
Rod failure (type, frequency, dependence on embrittlement)			x	x	x	(not modeled)
Assembly Behavior						
Spacer impacts on rods					x	x
Assembly loads on cask					x	x
Cask Failure						
Closure					x	x
Penetrations					x	x

Table 8.2 Summary of the Issues Raised at the Four Public Meetings

Resolution Option [section where discussed]	Sandia's Rating	Estimated Cost	Recommended Options
Purchase of full scale rail cask [2.9]	**A**	**Very High**	**X**
Full scale rail cask rocket sled collision test [2.9]	**A**	**High**	**X**
Design and construction of 1/3 scale rail cask [2.9]	**B**	**High**	
1/3 scale rail cask cable pulldown collision test [2.9]	**B**	**High**	
Validation of scale model testing [2.8] **If a scale model cask is tested** **If a real full-scale cask is tested**	 **A** **C**	 **Low** **Low**	
Finite element modeling of either cask collision test [2.4]	**A**	**Medium**	**X**
Dual-purpose casks (effect cansister, storage) [2.7]	**A**	**Medium**	**X**
Impact response of pellets, rods, and fuel assemblies [4.3]	**A**	**Medium**	**X**
Calorimeter pool fire test [3.1]	**A**	**High**	**X**
3D thermal modeling of pool fire test [3.1]	**A**	**High**	**X**
Cask pool fire test [3.1] **Undamaged cask** **Damaged cask**	 **A** **B**	 **Medium** **Medium**	
Fuel types [3.1]	**B**	**Medium**	
Event tree structures and branch point probabilities [5.2.4.5] **Occurrence frequencies of route wayside parameters [5.3.4.2]**	**A** **A**	**Medium** **Medium**	**X** **X**
Specific historic severe accidents [5.3.4.6]	**A**	**Low**	**X**
Speed and fire duration distributions [5.3.4.4]	**B**	**Low**	
Human error probabilities [5.3.4.3]	**B**	**Low**	
Specific routes [5.2.4.2]	**B**	**Low**	
Sensitivity study [6.3.1]	**B**	**Low**	
Collisions with non-planar objects [2.2] **By finite element analysis** **Using NTP and Eiffort results**	 **B** **C**	 **Medium** **Low**	
Impacts onto yielding targets [2.5] **Analysis by finite element calculations** **Using deformable test cask** **Using rigid test cask** **Analysis by engineering calculations** **Analysis using empirical data**	 **B** **B** **C** **D**	 **High** **Medium** **Low** **Low**	
Crushing environments [2.3]	**B**	**Medium**	
Characteristics of collision accidents (orientation, impact angle) [2.1]	**B**	**Medium**	
Finite element calculations to examine effects of human errors [2.6] **Using models developed for the Package Performance Study** **Using NUREG/CR-6672 models**	 **B** **C**	 **Low** **Low**	
Differences between truck and rail fires [3.2.3.2]	**C**	**Low**	
Torch fires [3.2.3.1]	**C**	**Low**	
First responder fire accident actions [3.4.3.1]	**C**	**Low**	
Cask damage from explosions [3.4.3.2]	**D**	**Medium**	
Accident test sequence [3.3]	**D**	**Low**	
Dependence of accident rates on accident conditions [5.2.4.1]	**C**	**Low**	
Correlations among accident risk parameters [5.3.4.1]	**C**	**Low**	

Full uncertainty study [6.3.2]	**D**	**High**	
Accident rate uncertainties [5.2.4.4]	**D**	**Medium**	

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