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A Compendium of Spent Fuel Transportation Package Response Analyses to Severe Fire Accident Scenarios

Draft Report for Comment

Office of Nuclear Material Safety and Safeguards

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ABSTRACT

This document summarizes studies of truck and rail transport accidents involving fires, relative to regulatory requirements for shipment of commercial spent nuclear fuel (SNF). These studies were initiated by the U.S. Nuclear Regulatory Commission in response to a 2006 National Academy of Sciences review of procedures and regulations. The fire accident scenarios were based on the most severe historical railway and roadway fires in terms of their potential impact on SNF containers.

While no such accidents involving SNF have ever actually happened in shipments either by rail or roadway, accidents resulting in fires do occur in both modes of transport and, however unlikely, plausible arguments can be made for the possibility of SNF containers being involved in such accidents. A regulatory framework for SNF containers is in place in the United States (10 CFR 71) and internationally (International Atomic Energy Agency) to ensure that risk due to such accidents is small and that the danger to the public is within accepted standards. The history of this regulatory framework is briefly summarized.

The combined summary of this work on fire accidents demonstrates that current U.S. Nuclear Regulatory Commission regulations and packaging standards provide a high degree of protection to the public health and safety against releases of radioactive material in real-world transportation accidents, were such events to involve SNF containers.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

PNNL wishes to thank Christopher Bajwa of the International Atomic Energy Agency (IAEA) for providing a copy of their draft report, Technical Basis for the IAEA Regulations for the Safe Transport of Radioactive Material, and for permission to use the section on historical background of the accident-simulating thermal test in our report. The contributions of Earl Easton of the U.S. Nuclear Regulatory Commission (NRC) (who provided the summary of transportation safety studies that we borrowed from the Baltimore tunnel fire report) were also invaluable in appropriately quantifying the risk of severe fire accidents in rail transportation.

The authors also appreciate the efforts of technical communications staff Colleen Winters and Susan Tackett, in making this a clear and concise presentation of our work.

ABBREVIATIONS AND ACRONYMS

AAR	Association of American Railroads
ADAMS	Agencywide Documents Access and Management System
AEC	Atomic Energy Commission
BWR	boiling water reactor
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CHP	California Highway Patrol
CRUD	Chalk River Unknown Deposit (generic term for various residues deposited on fuel rod surfaces, originally coined by Atomic Energy of Canada, Ltd. (AECL) to describe deposits observed on fuel removed from the test reactor at Chalk River.)
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPDM	ethylene-propylene (diene monomer)
FDS	Fire Dynamics Simulator (computational fluid dynamics computer code)
FRA	Federal Railroad Administration
HAC	Hypothetical Accident Conditions
HAZMAT	Hazardous Material
HLW	high level waste
IAEA	International Atomic Energy Agency
ISO	International Organization for Standardization (The International Organization for Standardization has decreed the use of the initials ISO for reference to the organization, regardless of the word order of the organization's name in any given language. This defines a uniform acronym in all languages.)
LWT	legal-weight truck
MAIT	Multi-Discipline Accident Investigation Team
MPC	Multi-Purpose Canister
NAC	Nuclear Assurance Corporation
NAS	National Academy of Sciences
NCT	Normal Conditions of Transport
NIST	National Institute of Standards and Technology
NRC	U.S. Nuclear Regulatory Commission
NTIS	National Technical Information Service
NTSB	National Transportation Safety Board
NUREG	U.S. Nuclear Regulatory Guide
PCT	Peak Cladding Temperature
PTFE	polytetrafluoroethylene
PWR	pressurized water reactor
SAR	safety analysis report
SNF	spent nuclear fuel
TFE	tetraflouro-ethylene

1.0 INTRODUCTION

This document summarizes recent studies of truck and rail transport accidents involving fires relative to regulatory requirements for shipment of commercial spent nuclear fuel (SNF). The U.S. Nuclear Regulatory Commission (NRC) has conducted case studies for accident scenarios involving the most severe fires and results have been compared with existing requirements of SNF containers. Safe transport of SNF is also dependent on effective procedures and administrative controls, such as the NRC requirements governing planning and security of SNF shipments[1], however these topics are not addressed in this report.

While no such accidents involving SNF have been documented, for shipments either by rail or truck, accidents resulting in fires do occur in both modes of transport and, however unlikely, plausible arguments can be made for the possibility of SNF containers being involved in some future accidents. A regulatory framework for SNF containers is in place here in the United States (10 CFR 71 2012) and internationally (IAEA 2012) to ensure that risk due to such accidents is small and that the danger to the public is within accepted standards.

For the most part, the requirements for SNF package performance in a fire accident have remained unchanged since 1964. Specifically, the requirement is survivability (meaning no release above regulatory limits) in an 800°C fire for 30 minutes. This fire temperature and duration bounds a broad range of possible fire exposures for a transportation package, but surveys of rail and roadway accidents involving fires show a small number of severe fires in which the peak fire temperature and duration have exceeded these regulatory values. The NRC and others have conducted analyses for a number of these severe fires to investigate the response and potential consequences if an SNF package had been involved (NUREG/CR-6886 2009; NUREG/CR-6894 2007, NUREG/CR-7206 2015, NUREG/CR-7207 2015). Results of these analyses have been useful in assessments of the adequacy of the current definition of the regulatory fire to protect public health and safety.

The adequacy of regulations for managing SNF transportation risks has been investigated by the National Academy of Sciences (NAS), and was documented in their 2006 report, *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States* (NAS 2006). Among the materials reviewed by the investigating committee was an early and very conservative analysis by the NRC based on the 2001 Howard Street Tunnel fire in Baltimore (also known as the Baltimore tunnel fire), which resulted from derailment of a train carrying hazardous materials. This analysis of a hypothetical SNF package response considered package exposure to maximum temperatures for up to 150 hours. Subsequent detailed analyses of the accident showed that the fire could have burned for no more than 3 to 12 hours before being extinguished, and due to poorly ventilated conditions within the tunnel, the peak temperature in the flaming region was estimated to have lasted for less than an hour (NUREG/CR-6886 2009). The reviewers acknowledged the significant conservatisms contained in the earlier analysis. One of the recommendations of the NAS report was that,

- NRC “undertake additional analyses of very long-duration fire scenarios that bound expected real-world accident conditions.”

The NAS committee was provided, but did not have time to review, draft results of a more plausible scenario of a well-ventilated version of the Howard Street Tunnel fire lasting only

[1] See 10 CFR 73.37, Requirements for physical protection of irradiated reactor fuel in transit.

7 hours (NUREG/CR-6886 2009). That study was a significant response to the NAS recommendation. NRC followed this with analyses of three additional severe fires that are expected to bound real-world accident conditions for road and railway transport of SNF (NUREG/CR-6894 2007; NUREG/CR-7206 2015; NUREG/CR-7207 2015). The results of these four studies are discussed in detail in this report.

Section 2.0 of this report begins with a description of SNF transport package regulatory requirements pertaining to accidents involving fire, and the historical background behind them. Section 3.0 summarizes the results of NRC commissioned surveys of truck and rail transport accidents involving fires. Section 4.0 describes the approach to assessing SNF package response in hypothetical fire accident scenarios. Section 5.0 provides a detailed summary of NRC accident scenarios corresponding to four of these severe fires, one of which occurred in a rail tunnel. The other three involved trucking accidents, two of which occurred in roadway tunnels, and the third occurred in a stacked layer of freeway interchange ramps. Section 6.0 gives a brief summary of analyses performed to determine package response in each scenario. Consequences in terms of radiation exposure and radioactive material release are discussed in Section 7.0. In Section 8.0, conclusions and recommendations are provided regarding the results of these and other case studies relative to the adequacy of the current regulatory requirements for truck and rail transport of SNF. This evaluation considers the frequency of occurrence and variety of historical accidents, as well as the severity of the fires involved. References are provided at the end of this report.

2.0 REGULATORY REQUIREMENTS FOR TRANSPORT OF SNF

The summary here is limited to SNF, which by definition requires a Type B package, since spent fuel assemblies contain in excess of the amount of radioactive material permitted in a Type A package. A Type B package can carry more radioactive material than is permitted in a Type A package and must retain the integrity of containment and shielding under normal conditions of transport (as per 49 CFR 173), and meet specified release limits for hypothetical accident conditions.

2.1 Genesis and Regulatory History

The early regulatory history for radioactive material transport regulation was laid out in a proposed rule for air transport[1] that was included in NUREG-0170 (*Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes*):

- These regulations had begun with the Interstate Commerce Commission in 1948 and were based on a report by National Academy of Sciences-National Research Council Subcommittee on Transportation of Radioactive Material. Preceding this was the ban on “shipment of radioactive material by mail in 1936 to protect unexposed film.” The Interstate Commerce Commission regulations were adopted with small changes by the International Atomic Energy Agency (IAEA) in 1961. Evolution since then saw revised standards by the IAEA to incorporate specific accident damage test standards, which were adopted by the Atomic Energy Commission (AEC) and U.S. Department of Transportation (DOT) (under the Interstate Commerce Commission) by 1968. Apart from changes to deal with leak testing of shipments of liquids, handling and inspection procedures, and “restrictions on shipment of plutonium on passenger aircraft,” regulations have remained unchanged since that time.

- Spent fuel transport, due to radioactive material quantity, falls under the category of a Type B package. In a memorandum of understanding between the DOT and AEC in 1968, which was revised in 1973, the AEC [now NRC] “develops performance standards for package designs and reviews package designs for Type B fissile and large-quantity packages.”

- As to the relationship between various regulators, it is stated that, “DOT requires AEC (now NRC) approval prior to use of all Type B, fissile and large-quantity package designs. DOT is the National Competent Authority with respect to foreign shipments under the IAEA transport standards. IAEA Certificates of Competent Authority are issued by DOT with technical assistance provided by NRC as requested.”

- For air shipments, it is stated that containers are required to satisfy drop and puncture tests as well as a 30-minute fire at 1475°F and a 3-ft. water immersion test for eight hours.

The fire test standard noted here remains the same today for SNF transport containers. A historical background for that standard is provided in the next section.

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[1] PROPOSED RULES, NUCLEAR REGULATORY COMMISSION [10 CFR Parts 71 and 73] RADIOACTIVE MATERIAL, Packaging and Transportation by Air, Federal Register, Vol. 40, No. 104-Monday, June 2, 1975.

2.1.1 Historical Background in the Development of Accident-Simulating Thermal Test[2]

In considering potential fire environments, Messenger and Fairbairn (1963) indicate that the IAEA's Panel considered the frequencies, probabilities, and many other factors that can work together in defining the environment a package might experience in a severe accident. These included:

- types of fuel, quantities of fuel, rate of spillage of fuel, and dispersal of spilled fuel;
- possible ranges of temperatures in a fire, and associated effects of size of fuel source and effects of oxygen supply (wind);
- duration of fires; and
- size and mass of the package.

It was recognized that the maximum temperatures achieved in a fire are typically the result of a "local torching," which would not provide a significant threat to large packages due to the localized nature of the heat source. Further, they noted that melting of materials could be a reasonable indicator of effective or average flame temperatures, for which it was shown that large fires in railway accidents had resulted in the following:

- zinc (with melting point of 419°C) was melted,
- aluminum (with melting point of 660°C) was partially melted,
- glass (with melting point of about 1000°C) sagged but was not melted, and
- steel (with melting point of 1500°C) was not melted.

After consideration of the data presented, and tests (both open-fire and oven environments) that were then being used, and noting that some of these tests precluded any intervention (i.e., quenching of burning packaging elements) following thermal exposure until package temperatures had begun to drop, it was recommended the test include exposure "*to a furnace temperature of 800°C for 30 minutes with no quenching until after the temperature of the interior has started to fall*."

In elaborating on the discussion relative to the thermal test, Appleton and Servant (1964) stated that there "was considerable discussion on the kind of fire to which a package might be exposed. The majority opinion was in respect of a large conflagration as might occur when a tank of petrol or kerosene spilled and took fire, but reference was also made to "torching" flames from a ruptured compressed gas tank vehicle. Temperatures in the order of 1000°C were considered relevant." They further noted that reported tests in open fires provided thermal environments very similar to those attained in hot wall, 800°C oven tests. It was further noted (Appleton and Servant 1964, Fairbairn and George 1966) that the basis for the average temperature was initially established using work of various individuals, including that of Bader (1965) where, following the detailed analysis of a number of open pool fire tests and consideration of work of others, he concluded: "an exact prediction of temperatures expected in a particular fire cannot be made. Examination (of data) which shows the wide range of fire environments measured in "similar" fires, indicates the difficulty one would have in predicting the

[2] This section (with same title) is taken verbatim from IAEA draft report: Pope, Ronald B., Dennis Mennerdahl and Christopher S. Bajwa, ***Technical Basis for the IAEA Regulations for the Safe Transport of Radioactive Material (SSR-6)***. 12 September 2013 draft provided in 21 May 2014 email from C.S. Bajwa to H.E. Adkins.

temperatures expected in a given fire. On the other hand, the range of fire temperatures to be expected can be stated with some certainty, and over a large number of tests, the fire temperatures will produce an average. This average turns out to be approximately 1850°F."

The average temperature of 1850°F proposed by Bader equates to 1010°C. The average fire temperature of 1010°C is, of course, higher than the 800°C that was ultimately used in the early regulations, and continues to be used today. Fairbairn and George (1966) stated that severe transport fires "*seldom last more than half an hour, ... and information on the temperatures attained suggests that although flame temperatures of liquids such as petrol can be about 1000°C, such peak temperatures are reached only very locally by metallic material involved in the fire.*"

Following much deliberation, the experts felt it necessary to consider all factors in establishing the thermal test condition, not just the maximum average attainable temperature in a "perfect" fire situation. The ramifications of accounting for multiple, "real-life" parameters were considered including, *inter alia*: (a) radiant, conductive, and convective heat inputs; and (b) exposure scenarios, which require specification of:

- an effective source (i.e., flame) temperature and effective flame thickness where, for pool fuel fires, this requires consideration of such parameters as: fuel type, size of package, mass of package, size of pool (too small and the flame is not luminous, too large and the flame suffers from oxygen starvation), location of package above the pool, and wind effects;
- emissivity coefficient of the heat source (i.e., the flame and its luminosity);
- absorption coefficient of the package surface;
- duration of exposure;
- support of the package at specified height; and
- whether the package should be cooled following termination of heat source exposure.

These deliberations resulted in inclusion of the statement in the regulations that any thermal test shall be considered as satisfactory provided that the parameters for satisfying the test were then specified in terms of:

- source temperature (800°C),
- duration of test (30 min),
- source emissivity (0.9),
- package surface absorptivity (0.8),
- flame thickness of not less than 0.7 m (2 ft) and not more than 3 m (10 ft),
- the flame must surround the package during the entire test, and
- there would be no intervention after exposure to the thermal source until the inner components of the package began to cool.

A panel of technical experts convened in mid-1964 (IAEA, Servant and Capet 1964) deliberated on the many issues associated with the thermal test. On pages 2 through 14 of *Notes on the Panel Meeting on the Design and Testing of Packaging for Radioactive Materials* (IAEA, Servant and Capet 1964) deliberations based on inputs from the U.S., the U.K. and the Eurochemic Company are documented. Issues addressed included (a) open pool fire tests versus oven tests, (b) the size of the package versus the size of the open pool and the size of the oven, (c) the thickness of a luminous flame, (d) the temperature to be reached by the package in the test and the length of time it should be required to remain at that temperature, (e) the heat input to the package, (f) the coefficient of emissivity of the flame or furnace wall,

(g) the coefficient of absorption of heat by the package surface, (h) whether high humidity could depress the flames in an open pool test, (i) the effect of wind upon flames in an open pool fire, (j) the height of the bottom of a package above the fuel reservoir, (k) the choice of fuel for a pool fire, (l) the depth of the fuel in the pool and its effect on the height of the walls of the pool retention system, and (m) whether to allow mechanical cooling of the package immediately following termination of the fire test.

From this extensive discussion, it was recommended by that panel of experts that the text for the fire test for the 1964 Edition of the Regulations be written as follows:

> *"Any thermal test employed shall be considered satisfactory provided that the heat input to the package is not less than that which would result from the exposure of the whole package to a radiation environment of 800°C for 30 minutes with an emissivity coefficient of 0.9 assuming the surfaces of the packages had an absorptive coefficient of 0.8."*

Fairbairn and George (1966) discussed the positioning of the package so that its lower surface would be 1 m above the surface of the burning fuel, and that the package should be supported "*such that it does not prevent direct exposure of any significant area of the package to the heat generated,*" with a view to ensuring maximum damage to the test package. They further emphasized that an open-fire test method or appropriate furnace test methods that are "*equally considered to meet the requirements of the general specifications. There are two main advantages in giving this open-fire test; first it can be conducted with relative 'home-made' facilities without the need for much detailed work by highly qualified scientific personnel, and second, the conditions of an open-fire have the merit of being seen to be similar, in their essential aspects, to those of an actual transport fire*."

With minor changes in wording, this is essentially the test that exists in paragraph 728 of SSR-6 (IAEA 2012) today; and much of the discussion contained in Appleton and Servant (1964) has been included in the advisory material on this test contained in TS-G-1.1 (IAEA 2008, 2011).

They further discussed the fire duration, noting that *"... when the actual heat input to the interior of the package is examined it can be shown, particularly for large packages, that a test involving a 30 min period of exposure to heat input, and a subsequent natural cooling period until the innermost temperature has started to fall before any artificial cooling is applied, might well be more severe in its effect on the package than one in which heat is applied for 60 min according to a specified time-temperature curve with artificial cooling applied immediately afterwards."*

Another topic addressed in the 1964 panel discussions (Appleton 1964) was whether or not to allow artificial cooling of the package following thermal exposure. It was agreed that this would not be allowed. Specifically, the experts noted "*there is a considerable body of opinion that the post exposure conditions up to thermal equilibrium, prohibiting the use of artificial cooling, should also be specified.*"

2.2 Summary of Current Regulations

The regulations for packages designed for domestic SNF transport are described in the Code of Federal Regulations (CFR), specifically under Title 10 (Energy), Chapter 1 (Nuclear Regulatory Commission), Part 71 (Packaging and Transportation of Radioactive Material), or more commonly, 10 CFR 71. Those parts of the CFR relevant to fire accidents are summarized

below. Additionally, as described in Section 2.1, internationally licensed containers are regulated by the IAEA standards and these are substantially the same. These are referenced briefly in Section 2.2.2 below.

2.2.1 Domestic Licensed Containers (CFR)

Regulatory requirements pertaining to fire accidents are found in 10 CFR 71, Subpart F – Package, Special Form, and LSA-III Tests. Section 71.73, "Hypothetical Accident Conditions," deals with this topic specifically, but Section 71.71, "Normal Conditions of Transport," is commonly referenced in accident analyses, and is referenced in this report, since it dictates the initial conditions for the package accident condition.

Section 71.71, Normal Conditions of Transport, which is referred to as Normal Conditions of Transport (NCT) in this report and related references, specifies (b) "Initial Conditions" for ambient temperature and initial internal pressure within the containment prior to NCT tests. The temperature preceding and following a test is to be held constant "at that value between -29°C (-20°F) and 38°C (100°F) which is most unfavorable for the feature under consideration." Internal pressure within the containment is to be the maximum normal operating pressure, unless a lower pressure, consistent with the ambient temperature considered for a test, is more unfavorable. For conservative analysis of a fire accident, the choice of initial condition is the highest temperature in this range and the initial condition for containment pressure is the maximum normal operating value. This initial condition is called out specifically in Section 71.71 as the first item under (c) "Conditions and Tests,"

1. *Heat*. An ambient temperature of 38°C (100°F) in still air, and insolation according to the following table:

Table 2.1. Insolation Data

Form and location of surface	**Total insolation for a 12-hour period (gcal/cm^2)**
Flat surfaces transported horizontally:	
Base	None
Other surfaces	800
Flat surfaces not transported horizontally	200
Curved Surfaces	400

Section 71.73, Hypothetical Accident Conditions, or HAC, repeats the same temperature range and internal pressure requirements under (b) Test Conditions, which is perhaps why reference is instead made to use of the "Hot" NCT conditions for initial conditions of a fire accident analysis. The tests in this section, which include 1) Free drop, 2) Crush[3], 3) Puncture, 4) Thermal, and 5) Immersion, are to be carried out sequentially, except that an undamaged package can be used for the immersion test. The conditions for the HAC Thermal test are detailed and, as the subject of this report, are repeated here for reference:

> "Exposure of the specimen fully engulfed, except for a simple support system, in a hydrocarbon fuel/air fire of sufficient extent, and in sufficiently quiescent ambient conditions, to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800°C (1475°F) for a period of 30 minutes, or any other thermal test that provides the equivalent total heat input

[3] This test is excluded for SNF packages.

to the package and which provides a time averaged environmental temperature of 800°C. The fuel source must extend horizontally at least 1 m (40 in), but may not extend more than 3 m (10 ft), beyond any external surface of the specimen, and the specimen must be positioned 1 m (40 in) above the surface of the fuel source. For purposes of calculation, the surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater; and the convective coefficient must be that value which may be demonstrated to exist if the package were exposed to the fire specified. Artificial cooling may not be applied after cessation of external heat input, and any combustion of materials of construction, must be allowed to proceed until it terminates naturally."

This HAC Thermal test or HAC Fire presents a significant design test for SNF packages. In Section 3.0, survey results of actual fires are compared to this regulatory fire definition and some of the historical fires are found to be, in some aspect, more severe than the regulatory fire.

2.2.2 International Licensed Containers (IAEA)

The regulatory requirements for internationally licensed containers are described in the IAEA document, SSR-6, Regulations for the Safe Transport of Radioactive Material (IAEA 2012). The equivalent definitions to package tests in 10 CFR 71 are found under Section VII, "Test Procedures" and within that section under "Tests for Packages." The equivalent definitions for NCT tests are found under the sub-heading, "Tests for demonstrating ability to withstand normal conditions of transport." References within this document are given by numbered paragraphs, and the specific paragraphs for NCT are numbered 719 through 724. The equivalent tests for HAC follow under the sub-heading, "Tests for demonstrating ability to withstand accident conditions of transport" and the associated paragraphs are numbered 726 to 729. Although wording differs, the test requirements are identical to those in 10 CFR 71.

Design and testing requirements for specific package types are detailed in Section VI, "Requirements for Radioactive Material and for Packagings and Packages." For example, requirements for Type B(U) packages are specified in part under paragraph 653:

> 653. A *package* shall be so designed that, under the ambient conditions specified in paras 656 and 657, heat generated within the *package* by the *radioactive contents* shall not, under normal conditions of transport, as demonstrated by the tests in paras 719–724, adversely affect the *package* in such a way that it would fail to meet the applicable requirements for containment and shielding if left unattended for a period of one week.

As noted above, paras 719 – 724 define the NCT tests. The "ambient conditions specified in paras 656 and 657" are the temperature (38°C) and solar insolation, respectively, and these are identical to those spelled out for the NCT *Heat* condition under 10 CFR 71.

Finally, the equivalent specification for internal containment pressure is given in paragraph 663:

> 663. A *package* shall be so designed that if it were at the *maximum normal operating pressure* and it were subjected to the tests specified in paras 719–724 and 726–729, the levels of strains in the *containment system* would not attain values that would adversely affect the *package* in such a way that it would fail to meet the applicable requirements.

The NCT tests are again cited here, and the HAC tests (paras 726 – 729) are also included.

Notwithstanding a different approach to writing, this comparison between IAEA and CFR requirements shows that equivalent thermal requirements are made for SNF packages when licensed in the U.S. or internationally. More specifically and relative to the topic of this report, the definition of the HAC Thermal test or HAC Fire is equivalently specified and recognized worldwide.

3.0 ACCIDENT HISTORY, SAFETY FACTORS, AND TRANSPORT PLANS

This section presents accident statistics from NRC studies to illustrate the frequency and severity of fire accidents in rail and roadway transport of cargo of all types. It is shown that severe fire accidents are very rare. A description of design factors and administrative controls is provided to indicate why fire accidents involving SNF are especially unlikely in rail transport. Lastly, elements of SNF shipment plans are discussed, which rely on this mode of transport.

3.1 Surveys of Rail and Truck Accidents

The NRC recently completed surveys of truck and rail accidents (NUREG/CR-7034 2011, NUREG/CR-7035 2011). These studies had a common objective, which was to determine the types and frequency of accidents involving severe, long-duration fires that could impact transport of SNF. The motivation for these studies was the recommendation by the NAS committee (NAS 2006) for NRC to analyze fires that exceed the 30-minute duration of the hypothetical accident condition in 10 CFR 71. The results of the railway accident survey are summarized in Section 3.1.1 and the summary for roadway accidents is provided in Section 3.1.2.

3.1.1 Survey of Railway Accidents Involving Fires

In this NRC commissioned study (NUREG/CR-7034 2011), databases analyzed included those from the Federal Railway Administration and the DOT – Pipeline and Hazardous Materials Safety Administration. The study found that the number of accidents involving the release of hazardous material has been decreasing and, because of that, accident data from the past 12 years (1997 to 2008) were used to calculate current accident rates.

When analyzing these databases, it was not possible to identify whether or not a fire was fully engulfing, as defined in 10 CFR 71. The approach taken in this study (NUREG/CR-7034 2011) was to identify historic railway fires as a severe fire if they had a reasonable potential to approach a fully engulfing fire under the 10 CFR 71 definition. In their analysis, the two criteria for this were, 1) that a railcar "must have been substantially engulfed in a fire that persists for an extended period of time", and 2) that the principal source of fuel for the substantially engulfing fire must have been derived from another railcar."

Using the railway accident data from the past 12 years (1997 to 2008) and this definition of severe fires, only nine such accidents were identified. (The specific causes were not identified for these nine accidents.) The occurrence of nine accidents over twelve years was used by the authors to estimate a frequency of occurrence of severe railway fire accidents of 6.2×10^{-4} accidents per million freight train-km (1×10^{-3} accidents per million freight train-mi).

3.1.2 Survey of Roadway Accidents Involving Fires

This NRC commissioned study (NUREG/CR-7035 2011) examined data from the DOT – Pipeline and Hazardous Materials Safety Administration. The surveyed data was limited to the past 12 years (1997 to 2008), matching the final interval for the railway study (NUREG/CR-7034 2011). Initial screening was for accidents involving more than one vehicle, with one or both carrying hazardous materials.

Accidents in the initial screening were examined further to identify those severe enough to potentially affect an SNF package on another vehicle. This selection was based on the following criteria: 1) the principal source of fuel for the fire was from another vehicle, 2) the fuel was a flammable liquid that could pool beneath another vehicle, 3) multiple vehicles were involved, and 4) the fire lasted for an extended period of time (defined in the study as at least 30 minutes). Because information about accidents typically did not include fire duration, this last criterion was based on a released volume of fuel sufficient to burn in a pool fire for at least 30 minutes. Collisions with a train were not included.

A total of 23 severe fire accidents out of more than 23,106 in-transit Hazardous Material (HAZMAT) accidents were identified using these criteria. Together with vehicle mileage data from the U.S. Census Bureau and the Bureau of Transportation Statistics, the frequency of occurrence of severe roadway fire accidents was estimated at 4.9×10^{-5} accidents per million HAZMAT vehicle-km (7.89×10^{-5} accidents per million HAZMAT vehicle-mi). In the study of trends in these 23 accidents, no dominant cause was identified.

3.2 Rail Accidents in Perspective

This report describes results of the NRC study of the Baltimore tunnel fire accident scenario along with three other studies of accident scenarios based on historical severe fire accidents. The Baltimore tunnel fire study is the only railway accident scenario in this group, and as part of background, NRC described salient features of a railway tunnel fire and provided a summary of railway accidents and factors that will further lessen the potential for any fire accident involving SNF. The following two sections are taken from the Baltimore tunnel fire report (NUREG/CR-6886 2009).

3.2.1 Evaluation of Tunnel Fire Characteristics

The 30-minute fully engulfing fire prescribed in the current NRC regulations defines a bounding fire for essentially all credible fire accidents involving SNF shipping packages. A fully engulfing open pool fire would generally be expected to subject a package to the hottest possible conditions for a given fuel supply. However, when considering potential accidents involving rail transport of SNF or high level waste (HLW), it is arguable that a rail tunnel fire could also present one of the more severe thermal challenges to a spent fuel transportation package. This is one of the reasons the staff chose to study the Baltimore tunnel fire event.

In examining real-world accidents that could involve a spent fuel transportation package, a number of significant differences are apparent between tunnel fires and severe fires occurring in an open (non-tunnel) environment. These factors include: 1) the possible position of a spent fuel package in relation to the fire location; 2) the nature of the flammable material involved; 3) the rail bed materials; 4) the types of fires that can occur and; 5) emergency response to fire accidents.

In a fully engulfing fire, in which the fuel is generally assumed to form a pool, the most severe conditions, by definition, occur in the hottest flaming region of the fire. In a typical regulatory fire analysis (defined by the fire conditions in 10 CFR 71.73), an SNF package is assumed to be located within the flaming region of the fire 3.3 ft (1 meter) above the surface of the pool. However, because many railroad tracks are elevated above grade and are constructed on porous substrate, pooling of spilled flammable liquid is less likely in an open environment when compared with a tunnel environment, where the rail bed surface is often rock, concrete, or

pavement. Historically many of the fires resulting from rail accidents have involved the leakage of flammable gas (such as propane), rather than a liquid. A flammable gas cannot form a pool. If ignited, flammable gas leaking from a tank car will generally result in a localized pressure fire that is incapable of engulfing a spent fuel transportation package.

In a rail accident involving a fire, it is extremely unlikely that a spent fuel transportation package would end up directly adjacent to a tank car carrying flammable liquid. Federal regulations issued by the DOT, in 49 CFR 174.85, require very specifically defined spacing between rail cars carrying radioactive materials and hazardous materials of any kind, including flammable liquids. Typical requirements specify that a rail car carrying radioactive material must be separated from cars carrying other hazardous material by at least one buffer car. A rail car carrying a spent fuel package would not be coupled directly to a tank car carrying flammable or combustible liquid. Figure 3.1 shows an example of a buffer car arrangement in an actual radioactive material shipment by rail.

Figure 3.1. Radioactive Material Rail Shipment

The location of the spent fuel package relative to the fire, for a fire in an open environment (i.e., a non-tunnel fire), will determine the amount of heat absorbed by the package (assuming a direct exposure to the fire). This is because thermal radiation is the main mechanism[1] for heat transfer from the fire to the package. In an open environment, the energy imparted to the package from the fire falls off rapidly with distance from the fire. In a tunnel environment, by contrast, the fire may result in elevated temperatures on adjacent tunnel surfaces, which could

[1] For a discussion of this phenomenon see NUREG/CR-4892, *Shipping Container Response to Severe Highway and Railway Accident Conditions*, Vol. II, pages 175 to 178.

result in a package being subjected to an "oven" effect due to heat radiating from hot tunnel surfaces for an extended period of time, possibly for several hours after the fire has been extinguished.

In rail accidents involving fires and hazardous materials in tank cars (including flammable gas or liquid), emergency responders follow the DOT Emergency Response Guidebook[2]. Emergency personnel are directed to provide water spray cooling to tank cars, to prevent boiling liquid expanding vapor explosions from occurring. In tunnel fires, space restrictions may make it difficult or impossible to mount an effective emergency response, either to cool tank cars or extinguish the fire. This could result in a fire burning unchecked, having a longer duration, and possibly reaching higher temperatures, compared to a fire with essentially the same fuel supply occurring in an unobstructed (non-enclosed) environment. Based on these factors, fires occurring in tunnels have the potential of being more severe than fires occurring in non-tunnel environments. The only significant limiting factor in a tunnel fire, which would not affect a fire in an open environment, is the potential for limited ventilation in a tunnel (due to tunnel length or small degree of slope), which could greatly reduce the amount of oxygen available for combustion. This would tend to reduce the burn rate, which would reduce the intensity of the fire, and thus tend to produce lower temperatures, even for a longer fire duration.

3.2.2 A Review of Rail Transportation Accidents

As part of its investigation of the impact of the Baltimore tunnel fire on the transportation of SNF, NRC staff conducted a detailed survey of rail transportation accidents in the United States. The staff reviewed accident reports (particularly those of the National Transportation Safety Board [NTSB]), historical media accounts, and data from the Federal Railroad Administration (FRA) safety database, and from the Association of American Railroads (AAR). This review showed that severe rail fires, either in tunnels or open environments, are extremely infrequent events.

The staff's review revealed several facts about rail accidents in the United States in general, and those involving hazardous materials specifically. These facts, which are summarized below, aid in putting the Howard Street Tunnel fire into perspective.

- In nearly 34 billion kilometers (21 billion miles) of travel on American railroads between 1975 and 2005, there have been 1700 reported incidents involving release of hazardous materials.

- Many of the 1700 incidents involved minor releases of non-flammable hazardous materials. None of the incidents reviewed involved the release of any radioactive material.

- Of the 1700 incidents, there were eight that involved a significant quantity of flammable material and that resulted in a long-duration fire. These incidents[3] were as follows:

  1. Derailment of CSX freight train, Baltimore, Maryland, July 18, 2001 (the subject of this report)

  2. Derailment of Union Pacific Freight train, Eunice, Louisiana, May 27, 2000 [NTSB report RAR-02-03; NTIS report PB2002-916303]

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[2] 2004 Emergency Response Guidebook, U.S. Department of Transportation, pages 115 and 128.

[3] The reports on these incidents are available on the NTSB web site, www.ntsb.gov, under the link "Accident Reports," or from the National Technical Information Service (NTIS) web site, www.ntis.gov.

3. Derailment of Wisconsin Central freight train, Weyauwega, Wisconsin, March 4, 1996[4]

4. Derailment of BNSF freight train, Cajon Pass, California, February 1, 1996 [NTSB report RAR-96-05; NTIS report PB96-916305]

5. Derailment of CSX freight train, Akron, Ohio, February 26, 1989 [NTSB report HZM-90-02; NTIS report PB90-917006]

6. Derailment of MT Rail freight train, Helena, Montana, February 2, 1989 [NTSB report RAR-89-05; NTIS report PB89-916305]

7. Derailment of CSX freight train, Miamisburg, Ohio, July 8, 1986 [NTSB report HZM-87-01; NTIS report PB-87-917004]

8. Derailment of Illinois Gulf Central freight train, Livingston, Louisiana, September 28, 1982 [NTSB report RAR-83-05; NTIS report PB83-916305]

Of these eight accidents, only one (the Baltimore tunnel fire) occurred in a tunnel. Based on an examination of the NTSB accident reports on the seven accidents listed above that did not occur in a tunnel, the staff concluded that none of them could have provided a fully engulfing fire environment for a spent fuel package, had one been involved in the event.

This conclusion is based on three mitigating factors present in the accidents examined above: the potential proximity of a hypothetical SNF transportation package to the fire that occurred, the available fuel for the fire, and the emergency response time for each accident. These factors are expanded upon below:

1. Proximity: Using diagrams of the rail car configurations in the seven accidents, as given in the NTSB reports, a rail car carrying a spent fuel package and its required buffer cars could not have been located close enough to any tank cars that ruptured in these accidents. An SNF package, had one been involved, would not have been positioned near enough to the burning flammable material in these accidents to be fully engulfed.

2. Fuel for the fire: The flammable material involved in a majority of the accidents were gases that resulted in localized pressure fires, so these accidents did not involve the pooling of flammable liquids. In those that did involve flammable liquids, pooling did not occur because of the nature of the track bed, which is elevated over porous media.

3. Response time: The emergency response times were extremely rapid in these seven accidents (most were responded to within 1-2 hours), and response efforts included cooling the tank cars, effectively minimizing fire intensity and duration.

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[4] The NTSB did not issue a report on this accident. Information describing the accident is available in the public docket, *National Transportation Safety Board Public Docket for Railroad Accident at Weyauwega, WI, March 4, 1996*. Docket ID: 8867, Released August 18, 1997, Washington, D.C. This document is available on the website: http://www.postcrescent.com/specials/assets/APCweyauweatrain/default.htm.

The Howard Street rail tunnel derailment and fire is unique in that none of the mitigating factors noted above (for non-tunnel fires) were acting to significantly limit the severity or duration of the fire. However, the staff's examination of the FRA database shows that the Howard Street Tunnel derailment and fire is the only severe rail tunnel fire involving hazardous materials shipments that has occurred in the nearly 21 billion rail miles of transportation that took place in the United States between 1975 and 2005.

When this accident frequency is coupled with the expected number of shipments of radioactive material in the future, the risk of an accident of this type still remains low. In addition, several factors work to reduce the risk of this type of accident even further. These include:

1. The intent of the U.S. Department of Energy (DOE) to ship the bulk of SNF and HLW to the Proposed Geological Repository for the Disposal of SNF and HLW at Yucca Mountain (Yucca Mountain) via dedicated rail[5];

2. FRA consideration of enactment of regulations that would require the use of dedicated trains[6] for the shipment of SNF and HLW;

3. AAR enacting, at the recommendation of the NRC, a "no-pass" rule[7] for single bore dual-track rail tunnels. The rule specifies that trains carrying tank cars containing hazardous materials, such as flammable or combustible liquids, and trains carrying SNF or HLW may not pass one another within the same tunnel.

This investigation has shown that accidents involving hazardous materials and long-duration fires on railroads in general and in rail tunnels in particular occur with extremely low frequency. As discussed above, DOE, FRA, and AAR have taken steps to further preclude the possibility of such an accident involving SNF or HLW and other hazardous (flammable or combustible) materials in a rail tunnel. Consequently, the frequency of any rail accident involving an SNF or HLW shipment in conjunction with a long-duration fire in a rail tunnel essentially approaches zero.

3.3 SNF Transport Plans

Two DOE efforts involve planning for transport of radioactive material to interim and/or permanent storage. The first is the National Transportation Plan (DOE 2009) prepared by the Office of Civilian Radioactive Waste Management in preparation for shipment of radioactive materials to the proposed Yucca Mountain repository. A significant feature of this plan is the design of the train and the design of the rail car that will carry the SNF package. The design standard is described in AAR S-2043. This standard results in a transport vehicle that is capable of carrying the SNF package at normal speeds on commercial rail lines while providing reasonable assurance that the cask maintains secure linkage to the AAR S-2043 railcar. Elements of the train are mentioned in the section above, including the use of buffer cars, which in this case are ballasted, and use of a train dedicated for the SNF transport. A security escort car is attached to the rear of the train. Figure 3.2 shows a schematic of the proposed arrangement. The second, and more recent, activity, known as the Nuclear Fuel Storage and

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[5] Letter to Stakeholders from Paul M. Golan, Principal Deputy Director Office of Civilian Radioactive Waste Management, July 18, 2005.
[6] This consideration is mandated pursuant to Section 5105(b) of the Hazardous Materials Transportation Uniform Safety Act of 1990, As Amended.
[7] Circular No. OT-55-I (CPC-1174), American Association of Railroads, July 17, 2006.

Transportation Planning Project, addresses transfers of SNF from shutdown sites[8], i.e., shut down commercial nuclear power stations where the stored fuel in the independent spent fuel storage installation is one of the final vestiges of a decommissioned site (Maheras et al. 2014). The transport trains planned for this effort will match those described under the National Transportation Plan: "Cask-carrying railcars, buffer cars, and security cars will be required to meet AAR Standard S-2043."

As described above, railway transport figures prominently in both plans, either directly from the site or after heavy-haul on roadway or barge to the nearest practical rail link; several elements of these plans offer enhancements to SNF rail transport safety.

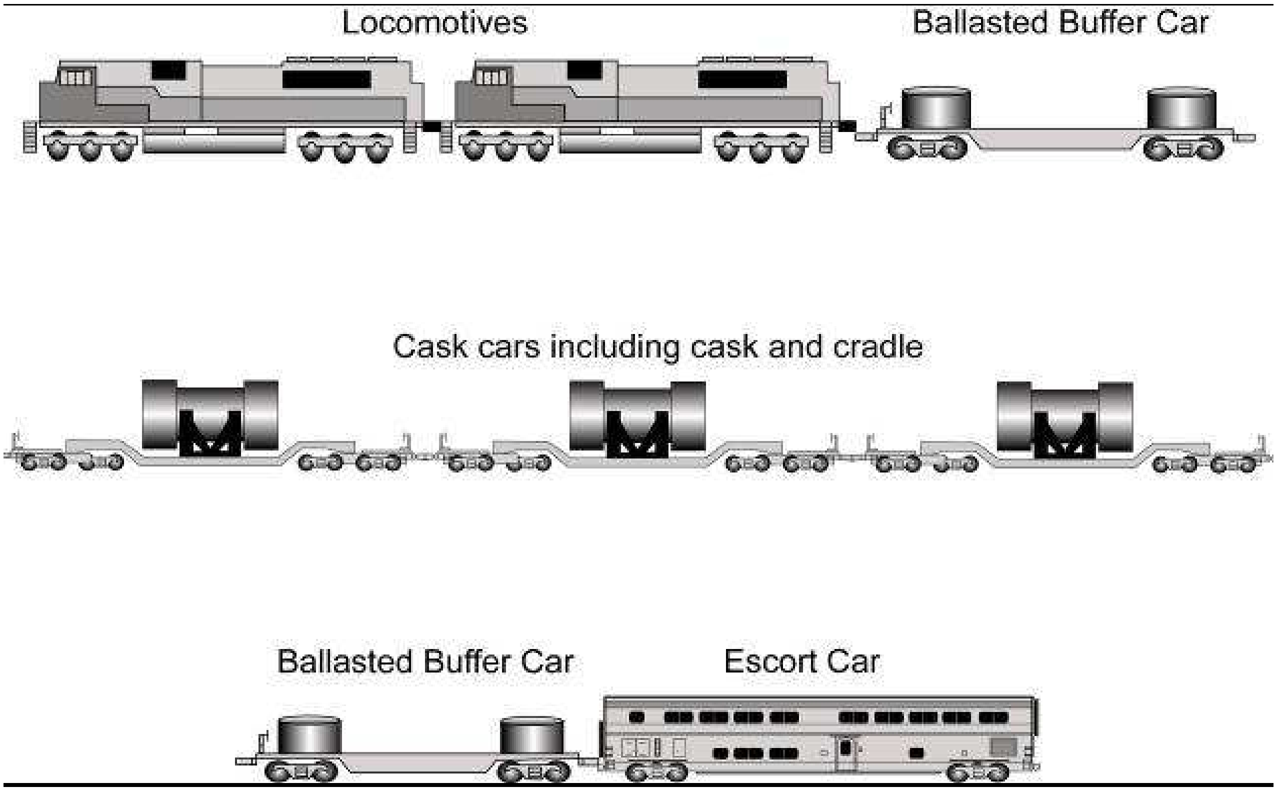

Figure 3.2. Rolling Stock, Escort, and Buffer Car Schematic (Figure 'E' in DOE 2009)

[8] M. Bates, "Preparation for Transportation of SNF Stored at Commercial Nuclear Power Plants", Presented June 24, 2015 to Nuclear Waste Technical Review Board, Golden, Colorado.

4.0 STUDIES TO EVALUATE ADEQUACY OF DESIGN REQUIREMENTS

As part of the process of establishing the regulatory basis for issuance of certificates for transportation of radioactive material under 10 CFR 71, the NRC has sponsored studies of the risks associated with the shipment of spent power reactor fuel by truck and rail. When these studies address risks associated with a spent fuel package in a fire, the analysis is performed with numerical models. NRC has also supported studies of component performance, in particular seals.

Section 4.1 summarizes the steps followed in fire accident analyses described in this report. Section 4.2 briefly describes qualifications of models that have been used in these studies in terms of model validation and verification. A summary of current testing of seal performance at elevated temperatures is provided in Section 4.3. Section 4.4 is a brief description of the SNF packages used in the fire accident scenarios summarized in this report.

4.1 Approach to Analysis of Fire Accident Scenarios

The approach taken in analyses of fire accident scenarios is as follows:

1. Describe fire to extent possible with available photos, video, first responder reports, and post-fire documentation.
2. Supplement if possible with temperature estimates using post-fire materials examination.
3. Perform Computational Fluid Dynamics (CFD) analysis of the fire behavior, using boundary conditions consistent with observations in 1) and 2).
4. Define SNF accident scenario with plausible, most conservative package location for thermal response.
5. If structural damage is suggested by accident, define associated accident scenario with plausible, most conservative package location.
6. Perform transient thermal analysis for package in defined scenario, using hot NCT as the initial steady-state condition, and simulate the fire with boundary conditions based on combustion gas temperatures and velocities predicted by analyses in Step 3).
7. Perform structural analysis consistent with defined scenario; this may be required before or following the thermal analysis, or between successive thermal analyses (see [NUREG/CR-7206 2015]).
8. Assess any impact to shielding.
9. Assess possibility of release of package radioactive contents based on seal temperatures, closure seal function (which may require structural analysis, again see [NUREG/CR-7206 2015]) and cladding temperatures.
10. Assess potential for cladding failure and rod rupture when estimating potential for release. Assume 100% spalling of surface Chalk River Unknown Deposit (CRUD) from fuel rods, for intact or failed fuel rods.

11. If peak clad temperatures approach or exceed short-term limit for accident conditions (570°C [1058°F]), perform best estimate calculation of cladding burst rupture based on initial pressurization and thermal transient, using an appropriate fuel rod material performance code.

12. Evaluate potential for release, based on containment integrity (e.g., seal performance), and estimate potential release if/as required.

4.2 Numerical Models

Analyses of the fire behavior, which was used to generate boundary conditions to define the fire scenarios, were performed with the Fire Dynamics Simulator (FDS) code (McGrattan 2001a). Thermal and structural models of SNF packages subjected to the fire conditions were developed for the ANSYS (ANSYS 2003) code and the COBRA-SFS (Michener et al. 1996) code. Independent validation efforts were not undertaken for the various codes used in the analyses, as this was beyond the scope of the fire analysis work. Instead, the validation of the codes, as documented in their base references, was relied upon to justify their use in these fire accident scenarios. However, the specific models of SNF packages developed using these codes were verified by appropriate comparisons to reference cases, generally from the relevant package Final Safety Analysis Report, or evaluations of sensitivity studies, using typical "good practices" standards (for example, see NUREG-2152 2013).

4.2.1 Fire Dynamics Simulator

The validation of the FDS code is extensive and widely documented[1] in the open literature. The most relevant validation work, for the purposes of the fire studies summarized in this report, includes comparisons to results of tunnel fire tests with conditions similar to the tunnel fire scenarios discussed in Section 5.0. The National Institute of Standards and Technology (NIST) developed fire models using FDS based on the geometry and test conditions from a series of tunnel fire experiments conducted by the Federal Highway Administration and Parsons Brinkerhoff, Inc. as part of the Memorial Tunnel Fire Ventilation Test Program (Bechtel/Parsons Brinkerhoff 1995). NIST modeled both a 6.83×10^7 Btu/hr (20 MW) and a 1.71×10^8 Btu/hr (50 MW) unventilated fire test from the Memorial Tunnel Test Program, and achieved results using FDS that were within 100°F (56°C) of the recorded data (McGrattan et al. 2001a, 2001b).

The fire conditions predicted with FDS for the various scenarios considered were verified to the extent possible using available information on fuel sources, geometry of the fire, and actual fire duration, based on reports and photographs from first responders at the scene. In some cases, additional information on temperatures reached in the fire was obtained from material sampling of structures engulfed in the fire.

[1] See http://firemodels.github.io/fds-smv/.

4.2.2 COBRA-SFS

COBRA-SFS was developed by Pacific Northwest National Laboratory for thermal-hydraulic analyses of multi-assembly spent fuel storage and transportation systems. The code uses a lumped-parameter finite-difference approach for predicting flow and temperature distributions in spent fuel storage systems and fuel assemblies under forced and natural circulation flow conditions. It is applicable to both steady-state and transient conditions in single-phase gas-cooled spent fuel packages with radiation, convection, and conduction heat transfer. The code has been validated in blind calculations using test data from spent fuel packages loaded with actual spent fuel assemblies, as well as electrically heated single-assembly tests (Creer et al. 1987; Rector et al. 1986; Lombardo et al. 1986).

As the only thermal analysis code that has been systematically validated against essentially all of the available experimental data on spent fuel storage systems, particularly multi-assembly storage systems, results from models developed for COBRA-SFS are used as the standard of evaluation of models developed with other CFD codes. Verification of specific COBRA-SFS models developed for the fire analyses was obtained by comparison to specific cases from the safety analysis report (SAR), and cross-comparison with other CFD models.

4.2.3 ANSYS

Systematic validation of the ANSYS code against experimental data for spent fuel storage and transportation packages has not been published in the open literature. However, this code is widely used in the industry to model thermal and structural response of SNF storage and transportation packages, for design purposes, and licensing basis calculations. The models developed for specific packages evaluated in the fire scenarios discussed here were verified by comparison to specific cases documented in the relevant SAR for normal conditions of transport, and in some cases for the standard HAC fire. In addition, the results obtained with the ANSYS model were evaluated by comparison to results obtained with a COBRA-SFS model of the same or similar system.

4.3 Seal Performance Testing

The NRC and NIST tested seals in thermal conditions simulating fire environments that exceed the rated temperatures for the seals tested (NUREG/CR-7115 2015). Testing was conducted in three phases.

The first phase of these tests evaluated the performance of one type of metallic seal and two different polymeric compound seals typically used in SNF transportation packages. The test fixture consisted of a small stainless steel cylindrical vessel fitted with a flange and lid closure for a single O-ring seal. The test vessel was pressurized at room temperature with helium to 73.5 psia (5 bar) for the tests with metallic seals, and to 29.4 psia (2 bar) for the tests with polymeric seals. The fire was simulated using an electric furnace that could maintain a controlled thermal environment for a specified duration, which was varied in different tests from several hours to 24 hours, and in some cases up to 72 hours. (These tests were designed to simulate accident conditions. Typical seal tests for long-term normal operating conditions are performed for a minimum of 1000 hours.) Following the simulated fire exposure duration, the test vessel was allowed to return to room temperature within the electric furnace.

A total of 15 tests were conducted in this study, including the initial shakedown test for which results were not recorded, due to instrumentation failure. Of the 14 tests for which measurements were recorded, 11 tests were with a metallic seal, 2 tests were with an ethylene propylene (EPDM) seal, and one test was with a polytetrafluoroethylene (PTFE) seal. In terms of the applicability of this testing to the evaluation of the packages used in the fire scenarios described in this report (see Section 4.4), the two tests with EPDM seals are of significance since this is the seal material used in the GA-4 package for the lid closure, the gas sampling port valve, and the drain valve. The Nuclear Assurance Corporation (NAC) legal-weight truck (LWT) uses Teflon (PTFE) seals for the drain and vent ports and a combination of metallic and Teflon seals for the bolted lid, and the HI-STORM and TN-68 both use metallic seals (NUREG/CR-6886 2009).

The majority of the metallic seal tests were performed at (or near) a maximum temperature of 1472°F (800°C) and this temperature was held for 9 hours. The ability to maintain vessel pressure during these tests was mixed, with leakage observed in three of the six tests. No leakage was observed in two shorter duration[2] tests at 1472°F (800°C). Also no leakage was observed in the single test at 1160°F (627°C), nor in the three 9-hour tests at 800°F (427°C).

The most severe exposure for EPDM seals in the testing was at 842°F (450°C). The seal material failed in this test within the first three hours of the simulated fire transient, but exhibited a much slower leak rate than would be expected for the test vessel with no seals at the test conditions. The second test with EPDM seals reached a much lower peak temperature, with incremental heating from 302°F (150°C) to 572°F (300°C). The total duration of this test was more than 20 hours, but the seal held with no measurable leakage.

The single test with the PTFE seal was limited to a maximum temperature of 572°F (300°C). The seal held for the duration of the 22 hour heated portion of this test, but did have leakage during the cooling phase.

Subsequent testing in Phase II extended the polymeric O-ring seal materials tested to include butyl, Viton, and silicone. Additional tests were also completed with EPDM and PTFE seals. These tests used the same initial fill pressure as used for polymeric seals in Phase I, 29.4 psia (2 bar), but in this series the test vessel was held at 600°F (316°C) for 8 hours. Of the eighteen tests completed, only in one test with a silicone seal was there a loss of pressure that exceeded the measurement uncertainty. In the other tests pressure returned to the initial value after the test vessel returned to room temperature. While largely retaining their sealing function, the seals suffered significant damage in the process. The Viton seal tests displayed the unique behavior of a net internal pressure *increase* during the test, presumably due to off-gassing.

Phase III testing used the same test vessel except that it was fitted with a flange and lid with a double O-ring seal configuration. In one group of tests, the inner seal was in all cases metallic, and tests were conducted with or without an EPDM outer seal. A second group of tests used polymeric O-ring seals exclusively, the first set with EPDM O-rings in both seal locations and the second with butyl O-rings in both seal locations. A final group of tests used metallic seals for both the inner and outer seals. As in the Phase I metallic seal tests, the initial helium fill pressure was 5 bar at room temperature. In the first two EPDM-metallic tests, the test vessel was heated to 1472°F (800°C), held for 9 hours, and allowed to return to room temperature. The remaining tests used the same procedure, except that the vessel was heated to 1652°F (900°C). Results of tests using a metallic seal were again mixed, showing no leakage in the first

[2] The initial shakedown test was run for 30 minutes and a second test was run for 4 hours.

group of tests that had an EPDM or blank outer seal, and showing some leakage in all of the final group of tests with metallic seals in both locations. Leakage was detected in all of the dual polymeric seal tests prior to the test temperature being reached.

Results of these seal tests demonstrate that seals used in SNF packages may have a short-term performance envelope that far exceeds the conservative temperature limits indicated in the ratings for long-term performance provided by the seal manufacturer. While these results are encouraging from the standpoint of lower potential releases in the event of an accident, seal function at these elevated temperatures has not shown consistent performance; therefore for the purpose of safety analysis, when temperatures in the area of the seal exceed the rated values provided by the seal manufacturer, the seal must be assumed to have failed as part of the containment analysis.

4.4 SNF Packages Included in Case Studies

Detailed descriptions (including engineering drawings, technical specifications, and material data sheets) for the three spent fuel transportation package designs selected for these analyses are documented in proprietary versions of their respective SARs. This subsection presents a general overview of the SNF packages that have been evaluated in fire accident scenarios. Section 4.4.1 describes the TransNuclear TN-68 rail transportation package. Section 4.4.2 describes the HOLTEC HI-STAR 100 rail transportation package. The NAC LWT transportation package is described in Section 4.4.3 and General Atomics GA-4 LWT transportation package is described in Section 4.4.4.

4.4.1 TransNuclear TN-68 SNF Transportation Package

The TN-68 spent fuel shipping package is designed to transport boiling water reactor (BWR) spent fuel assemblies by rail. The package can be loaded with up to 68 BWR spent fuel assemblies, with a maximum total decay heat load of 72,334 Btu/hr (21.2 kW). The fuel assemblies are contained within a basket structure consisting of 68 stainless steel tubes with aluminum and borated aluminum (or boron carbide/aluminum composite) neutron poison plates sandwiched between them. The containment boundary is provided by the package outer steel shell and lid seals. The general structure of the TN-68 package is illustrated in Figure 4.1 and Figure 4.2. Detailed information on the design can be found in the appropriate sections of the TN-68 SAR (NRC 2000).

The basket structure is supported by aluminum alloy support rails bolted to the inner carbon steel package shell, which also serves as the inner gamma shield. This inner steel shell is shrink-fitted within an outer carbon steel shell that serves as the outer gamma shield. The gamma shielding is surrounded by the neutron shielding, which consists of a ring of aluminum boxes filled with borated polyester resin. The outer shell of the package is carbon steel, as is the package base and inner steel shield plate. The package lid is also carbon steel with a steel inner top shield plate. During transport, the ends of the package are capped with impact limiters made of solid redwood covered with a thin layer of balsa wood and enclosed within stainless steel sheathing. The TN-68 package weighs approximately 260,400 lb (118,115 kg) when loaded for transport.

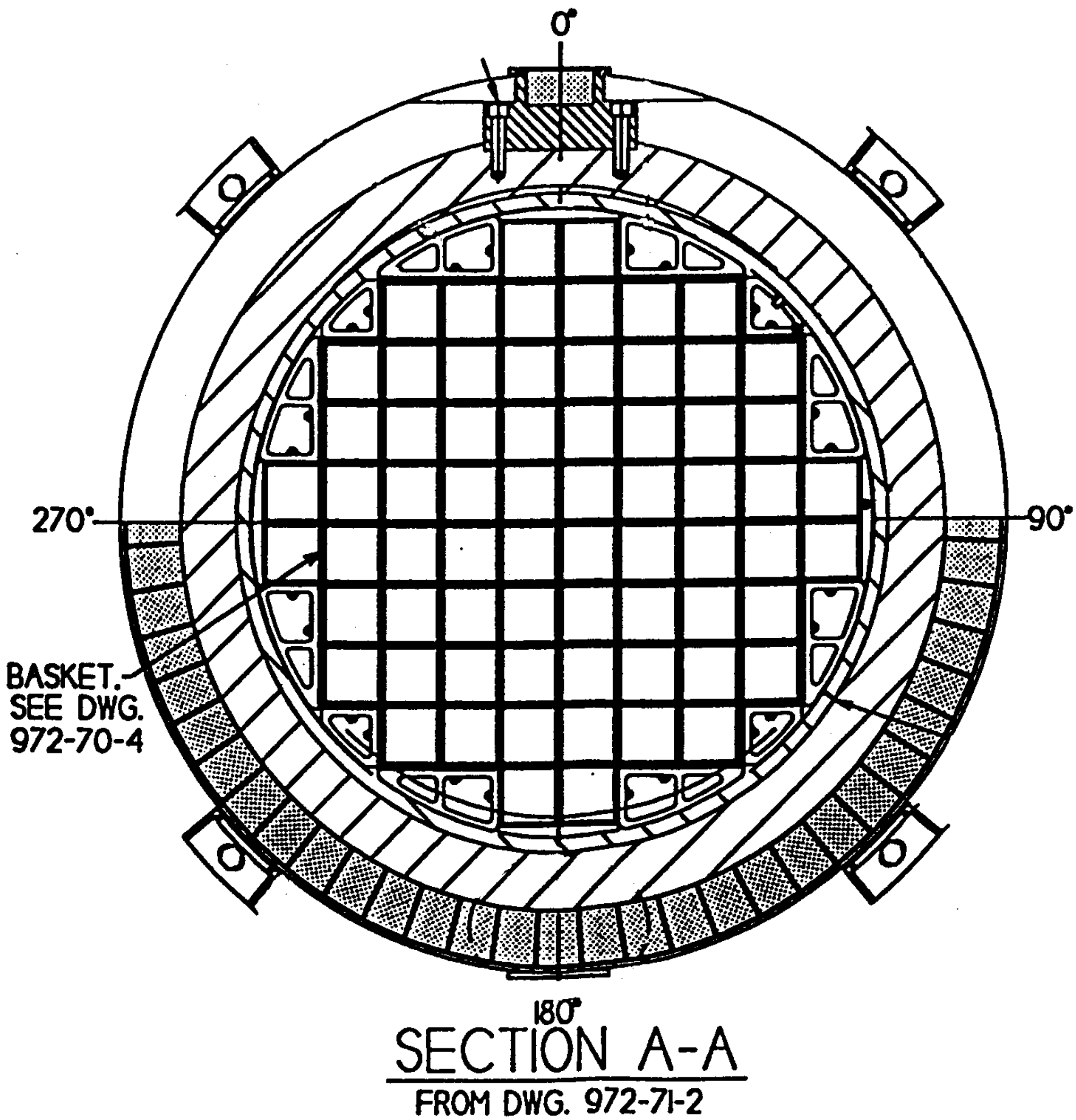

Figure 4.1. Cross-section of TN-68 Package (drawing 972-71-3 Rev. 4, "TN-68 Packaging General Arrangement: Parts List and Details")

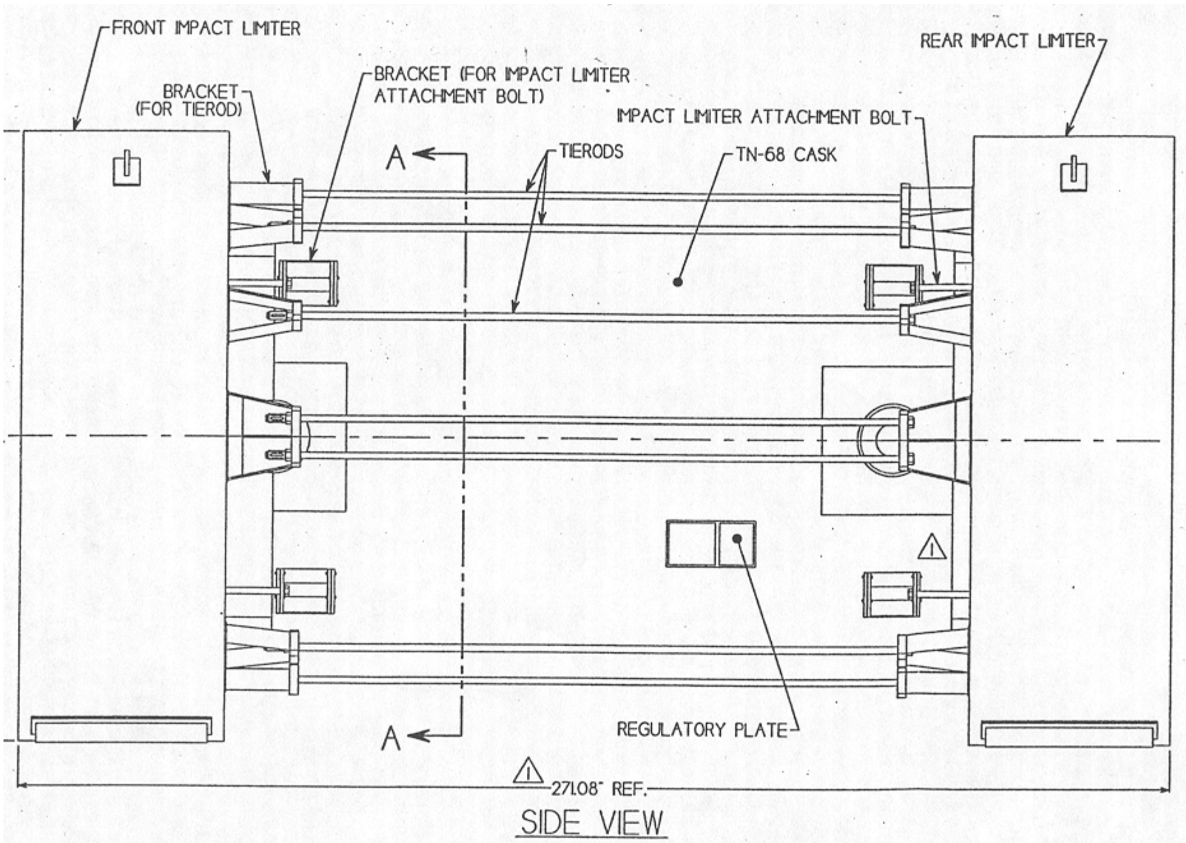

Figure 4.2. Exterior View of TransNuclear TN-68 Spent Fuel Transportation Package with Impact Limiters Installed

4.4.2 HOLTEC HI-STAR 100 SNF Transportation Package

The design of the HOLTEC HI-STAR 100 SNF transportation package is similar to that of the TN-68 in that it consists of a heavy steel outer shell, base, and lid, with an internal basket structure designed to contain multiple SNF assemblies. In addition, the HI-STAR 100 design encloses the basket structure containing the spent fuel within a welded multi-purpose canister (MPC). This provides an inner containment barrier, in addition to the package outer shell and lid seals. The HI-STAR 100 can accommodate a variety of MPC configurations containing three different spent fuel support basket designs; one for up to 24 pressurized water reactor (PWR) assemblies, another for up to 32 PWR assemblies, and one for up to 68 BWR assemblies.

The MPC-24 configuration was selected for this evaluation, because it is the limiting configuration for this system. It has the highest operating temperature of the HI-STAR 100 licensed fuel loading configurations, and therefore is likely to be the most adversely affected by exposure to the postulated severe fire scenario. This design has an integral fuel basket that accommodates 24 PWR spent fuel assemblies with a maximum total decay heat load of 68,240 Btu/hr (20.0 kW). The MPC is loaded with SNF and welded shut, and then placed in the transportation package (also referred to as the overpack) for shipment. An exploded cut-away diagram of the HI-STAR 100 package system (MPC and overpack) is shown in Figure 4.3. The package inner shell is stainless steel, and six layers of carbon steel plates comprise the gamma shield. The next layer is a polymeric neutron shield, strengthened by a network of carbon steel stiffening fins. The outer shell of the package is carbon steel, with a painted exterior surface.

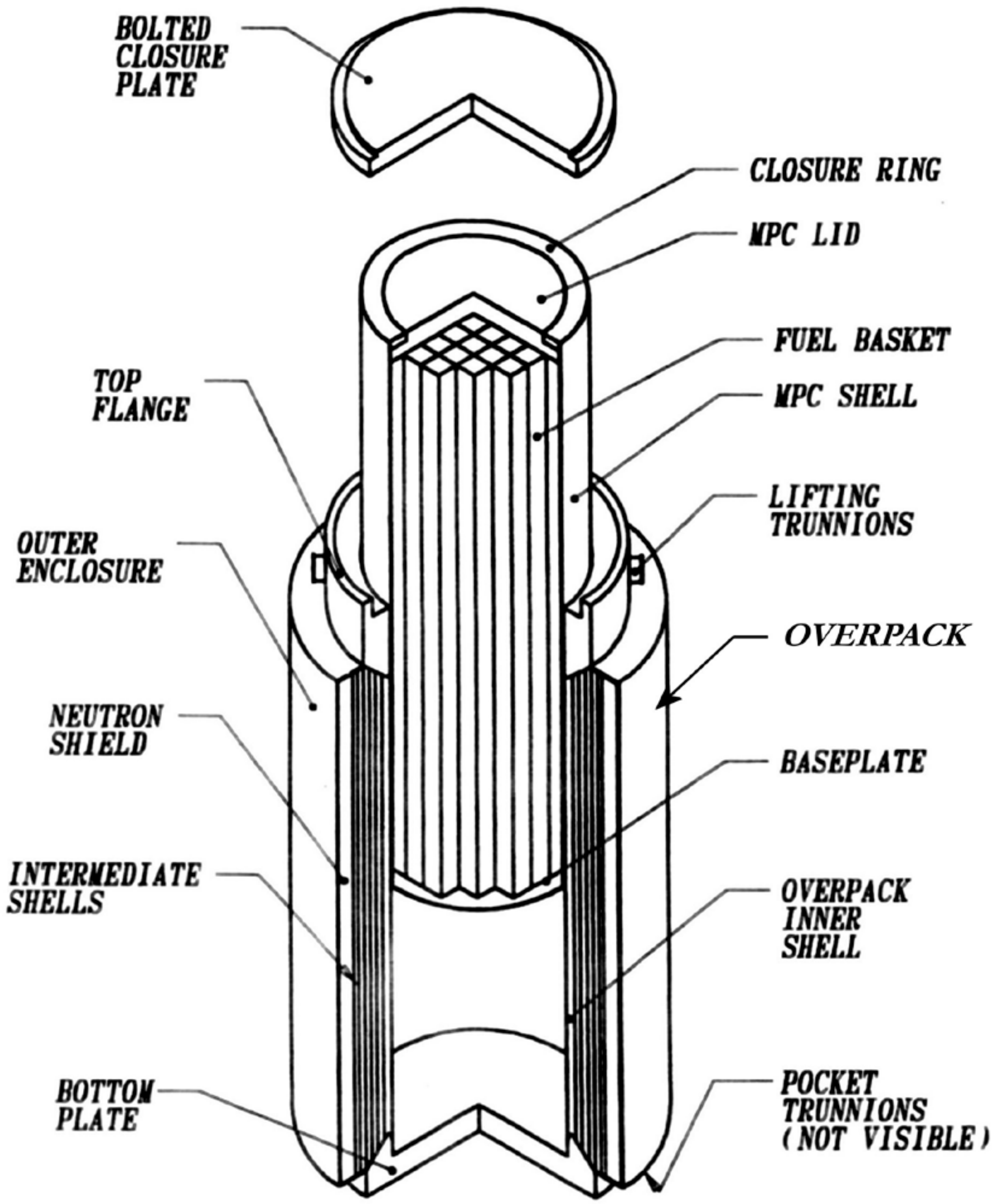

Figure 4.3. HOLTEC HI-STAR 100 Spent Fuel Package

Aluminum honeycomb impact limiters with stainless steel skin are installed on the ends of the package prior to shipping. Impact limiters protect the closure lid, MPC, fuel basket, and contents from damage in the event of a package drop accident. The impact limiters also provide thermal insulation to the lid and port cover components in the event of fire exposure. Figure 4.4 shows an illustration of this package secured to a railcar, with impact limiters installed. This package weighs approximately 277,300 lb (125,781 kg) when loaded for transport. Additional configuration details are provided in the HI-STAR 100 Package System SAR (NRC 2001a).

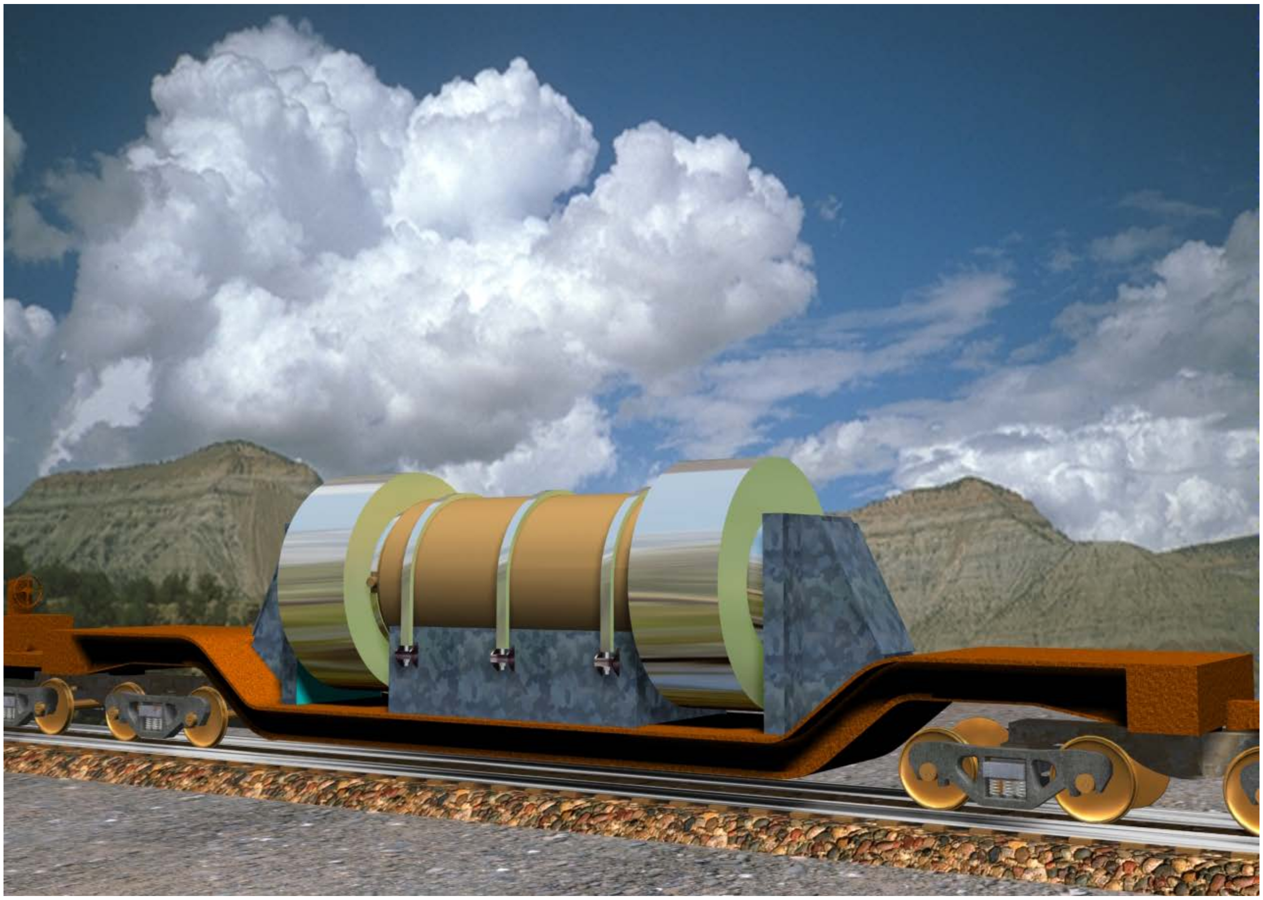

Figure 4.4. Spent Fuel Transportation Package on Railcar[3]

4.4.3 NAC LWT SNF Transportation Package

The NAC LWT is a small transportation package certified for transport on a standard tractor-trailer truck, but can also be transported by rail. When shipped by rail, the NAC LWT is typically placed within an International Organization for Standardization (ISO) shipping container. It can also be placed within an ISO when shipped by truck. Figure 4.5 shows a NAC LWT package on a flat-bed trailer with a personnel barrier installed, but without an ISO container. Figure 4.6 shows an exterior view of the package within an ISO container on a flat-bed trailer. This package is designed to transport a variety of commercial and test reactor fuel types with widely varying maximum decay heat load specifications for the different fuels. For the purposes of this thermal analysis, the package was assumed to contain a single PWR SNF assembly with a maximum decay heat load of 8,530 Btu/hr (2.5 kW). This is the highest heat load the package is rated for with any spent fuel it is designed to carry[4], and thus provides a conservative thermal load for the fire accident scenario.

[3] Image courtesy of HOLTEC International.

[4] As of Revision 34 of the SAR for this package; see (NRC 2001b).

The loaded package weighs approximately 52,000 lb (23,586 kg). The containment boundary provided by the stainless steel package consists of a bottom plate, outer shell, upper ring forging, and closure lid. The package has an additional outer stainless steel shell to protect the containment shell, and also to enclose the lead gamma shield. Neutron shielding is provided by a stainless steel neutron shield tank containing a mixture of borated water and ethylene glycol. An additional annular expansion tank for the mixture is provided, external to the shield tank. This component is strengthened internally by a network of stainless steel stiffeners. Aluminum honeycomb impact limiters covered with an aluminum skin are attached to each end of the package. Additional configuration details are provided in the SAR for this transport package (NRC 2001b).

Figure 4.5. NAC LWT Transport Package (without ISO Container)

Figure 4.6. NAC LWT Transport Package (with ISO Container)

4.4.4 General Atomics GA-4 LWT SNF Transportation Package

This is an NRC-certified SNF transportation package that can carry a relatively large payload for an over-the-road transportation package, and therefore the potential consequences of package failure could be more severe than for packages with smaller payload capacities. The GA-4 package is designed to transport up to four intact PWR spent fuel assemblies with a maximum decay heat load of 2105.4 Btu/hr (0.617 kW) per assembly, for a total package decay heat load of 8423 Btu/hr (2.468 kW). The payload capacity of the GA-4 is 6,648 lb. (3,015 kg), and the fully loaded package weighs approximately 55,000 lb (24,948 kg).

Figure 4.7 shows an exploded view of the package, illustrating the main design features. The package containment boundary is provided by the following structures:

- stainless steel package body wall
- stainless steel bottom plate
- stainless steel package closure lid secured by Inconel fasteners
- dual O-ring seals for the closure lid, gas sample port, and drain valve.

The stainless steel package body encloses the gamma shield, which consists of an inner shell of depleted uranium. Neutron shielding is provided by a stainless steel neutron shield tank, external to the package body, which contains a water/propylene glycol mixture. Aluminum honeycomb impact limiters, completely enclosed in a thin stainless steel outer skin and inner

housing, are attached to each end of the package. Configuration details, including design drawings, are provided in the SAR for this transport package (General Atomics 1998).

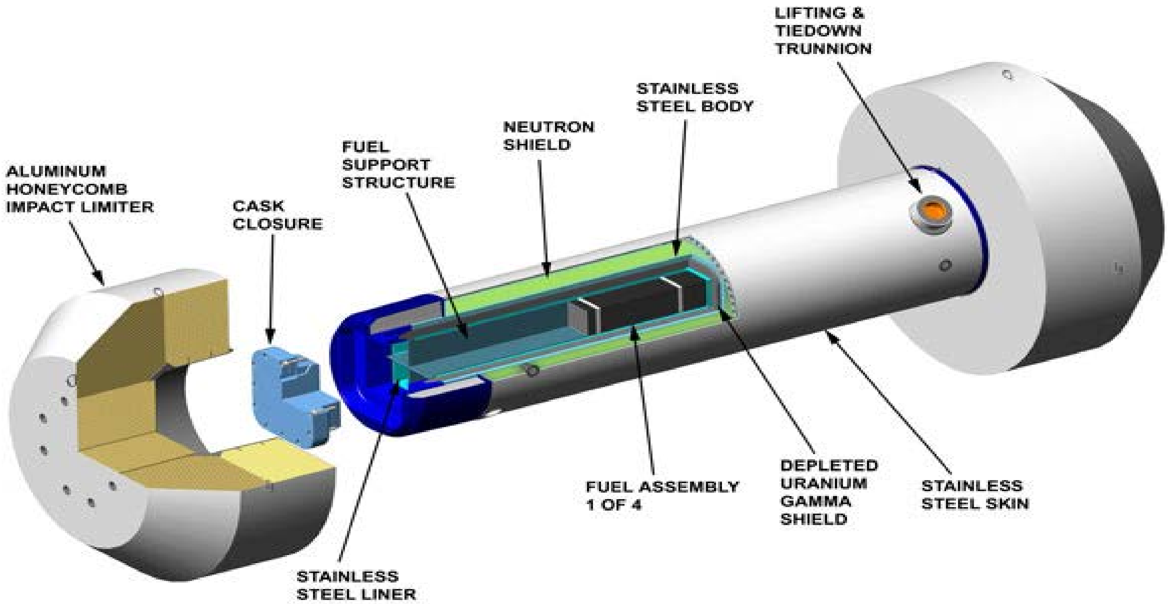

Figure 4.7. GA-4 Package: Exploded View

5.0 ACCIDENT SCENARIOS INVOLVING SNF PACKAGES IN SEVERE FIRES

This section describes the four NRC developed accident scenarios based on four historical severe fires. Using the wording of the recommendation in the NAS study (NAS 2008), these are all "very long-duration fire scenarios that bound expected real-world accident conditions." One of the fires occurred in a rail tunnel. The other three involved trucking accidents, two of which occurred in roadway tunnels, and the third occurred in a stacked layer of freeway interchange ramps.

A description of the actual fire is presented first, followed by a summary of analyses and post-fire testing to establish conditions in the fire. The accident scenario defined for each case is then described, which incorporates bounding assumptions and places selected SNF transportation packages in the most adverse configuration within the fire.

5.1 Baltimore Tunnel Fire

The first accident scenario is based on the railway fire that occurred in 2001 in the Howard Street Tunnel in Baltimore, Maryland. This accident is in some contexts referred to as the Baltimore tunnel fire. This section is a summary description from the detailed discussion of the fire accident in the final report (NUREG/CR-6886 2009) on the modeling study.

5.1.1 Description of the Baltimore Tunnel Fire

On July 18, 2001, a CSX freight train carrying hazardous (non-nuclear) materials derailed and caught fire while passing through the Howard Street railroad tunnel in downtown Baltimore, Maryland. The Howard Street Tunnel is a single-track railroad tunnel of concrete and refractory brick. Originally constructed in 1895, later additions extended it to its current length of 1.65 mi (2.7 km). The tunnel has an average upward grade of only 0.8% from the west portal to the east portal, and at the time of the accident, the active ventilation system was not in operation. The tunnel is approximately 22 ft (6.7 m) high by 27 ft (8.2 m) wide in the vicinity of the accident (see Figure 5.1); however, these dimensions vary somewhat along the length of the tunnel.

The freight train had a total of 60 cars pulled by three locomotives, and was carrying paper products and pulp board in boxcars, as well as hydrochloric acid, liquid tripropylene[1], and other hazardous liquids in tank cars (McGrattan and Hammins 2003, Barabedian et al. 2003). As the train was passing through the tunnel, 11 of the 60 rail cars derailed. A tank car (Figure 5.2) containing approximately 28,600 gallons (108,263 liters) of liquid tripropylene had a 1.5-inch (3.81-cm) diameter hole punctured in it (Figure 5.3) by the car's brake mechanism during the derailment.

Ignition of the liquid tripropylene led to the ensuing fire. The exact duration of the fire is not known with certainty. Based on NTSB interviews of emergency responders, it was determined that the most severe portion of the fire in the Howard Street Tunnel lasted approximately 3 hours. Less severe fires burned in the tunnel for periods of time greater than 3 hours. Approximately 12 hours after the fire started, firefighters were able to visually confirm that the tripropylene tank car was no longer burning.

[1] Tripropylene carries an NFPA hazards rating of 3 for flammability, which is the same as that of gasoline.

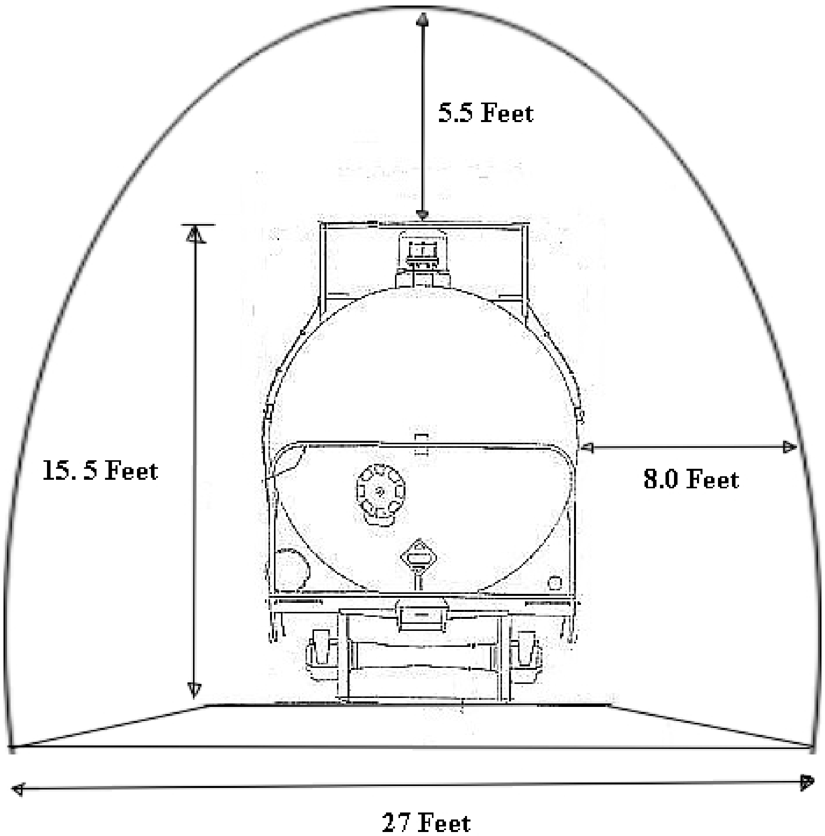

Figure 5.1. Dimensions of Howard Street Tunnel with Tank Car on Track


Figure 5.2. Liquid Tripropylene Tank Car

Figure 5.3. Puncture in Tank Car

Tripropylene, which is also called nonene, is a liquid hydrocarbon compound used for industrial processes. Table 5.1 lists the heat of combustion for tripropylene and a number of other hydrocarbon fuels that are commonly shipped by rail. Gasoline and jet fuel are also included in the table, but for comparison purposes only, as these fuels are rarely, if ever, transported by rail. Tripropylene has a heat of combustion comparable to that of gasoline and has a higher heat of combustion than that of jet fuel. When compared to other common hydrocarbon liquids, tripropylene falls near the high end of the range of values for heat of combustion for hydrocarbon liquids. The range of values shown in Table 5.1 for hydrocarbon fuels is relatively narrow, however, which indicates that when burned under the same conditions, these hydrocarbon liquids will generally have similar combustion characteristics. Therefore, while tripropylene was the specific fuel for the Baltimore tunnel fire, its combustion characteristics are generally representative of the behavior of other hydrocarbon fuels.

Table 5.1. Comparison of Various Hydrocarbon Liquids

Liquid Hydrocarbons	**Molecular Formula**	**Heat of Combustion[a] Btu/lb. (kJ/kg)**
Propane	C_3H_8	19,800 (46,000)
Butane	C_4H_{10}	19,500 (45,400)
Isobutane	C_4H_{10}	19,600 (45,600)
Pentane	C_5H_{12}	19,300 (45,000)
Hexane	C_6H_{14}	19,200 (44,700)
Heptane	C_7H_{16}	19,200 (44,700)
Toluene	C_7H_8	17,400 (40,500)
Octane	C_8H_{18}	19,100 (44,400)
Nonane	C_9H_{20}	19,000 (44,300)
Nonene (Tripropylene)	$\mathbf{C_9H_{18}}$	**19,000 (44,300)**
Decane	$C_{10}H_{22}$	19,000 (44,300)
Undecane	$C_{11}H_{24}$	19,000 (44,300)
Gasoline (mixture of heptanes, octanes, nonanes and decanes)	C_8H_{15}[b]	19,100 (44,500)[b]
Jet Fuel, grade JP-1		18,500 (43,000)
Jet Fuel, grade JP-2		18,700 (43,500)
Jet Fuel, grade JP-3		18,700 (43,500)
Jet Fuel, grade JP-4		18,500 (43,000)

[a]Values derived from Perry, Chilton, and Kirkpatrick, *Perry's Chemical Engineer's Handbook*, 4th Edition, Table 3-202, Page 3-104.
[b]Typical values. Values will vary slightly depending on formulation. Derived from Ferguson and Kirkpatrick*, Internal Combustion Engines, Applied Thermosciences*, 2nd Edition, Page 316 and Table 10.8.

5.1.2 Analysis of the Baltimore Tunnel Fire

NIST developed a model (McGrattan and Hammins 2003) of the Baltimore tunnel fire using the FDS code (McGrattan et al. 2001a, 2001b)[2] to assess the thermal environment within the tunnel during the fire. The NIST study was based on information developed by the NTSB investigation of the tunnel fire, including descriptions of the tunnel structural features, the damage to the rail cars, and the sequence of events in the accident. Using this information as the starting point for the calculations, the analysis was extended to include variation of significant unknown parameters to predict the range and distribution of temperatures that could have been sustained in the tunnel during and after the fire, and the duration of the fire.

The FDS model developed by NIST included the full length of the Howard Street Tunnel with the rail cars represented as solid blocks elevated 3.3 ft (1 m) above the rail bed. The source of the

[2] Formal publication of the FDS code documentation began in 2001 with Version 2. Continuing validation and development of the code led to Version 3 in 2002. Version 3 was used in the FDS analyses discussed in this report.

fire was specified in the simulation as a pool of burning liquid tripropylene positioned below the location of the hole that was punctured in the tripropylene tank car during the derailment. Parametric studies of the burning rate of the fire, based on the amount of available fuel, the air flow in the tunnel, the thermal conductivity of the bricks lining the tunnel, and sensitivity studies on the fuel pool area show that the Howard Street Tunnel fire was oxygen-limited.

In the confined space of the tunnel, without forced ventilation, the heat release rate of the fire was constrained by the supply of oxygen rather than the supply of fuel. For a wide range of modeling assumptions, the overall heat release rate (or heat rate) for the fire was predicted to be no more than about 1.71×10^8 Btu/hr (50 MW). The highest peak temperatures predicted in these simulations were 1832-2012°F (1000-1100°C) in the flaming region of the fire. The calculation results showed that the hot gas layer above the rail cars within three to four rail car lengths of the fire was an average of 932°F (500°C). Peak temperatures on the tunnel surfaces were calculated to reach 1472°F (800°C) where flames directly impinged on the ceiling of the tunnel. The average tunnel ceiling temperature within a distance of three to four rail car lengths from the fire was calculated to be 752°F (400°C).

Staff from the Center for Nuclear Waste Regulatory Analysis, along with staff from NRC and NIST, examined the rail cars and tank car removed from the Howard Street Tunnel for evidence of high temperatures experienced by these components (Garabedian et al. 2003). Metallurgical analyses on the material samples collected indicated that material temperatures on the roof of the boxcar located approximately 66 ft (20 m) from the tank car were in the range of 1382-1562°F (750-850°C) for approximately 4 hours. Material temperatures on other components of this boxcar were estimated to have reached values on the order of 1112°F (600°C). The estimates of time and temperature exposures support the detailed predictions of the NIST FDS model of the Howard Street Tunnel fire.

5.1.3 Accident Scenario for Baltimore Tunnel Fire

The Howard Street Tunnel fire was severe at least in terms of duration and it was very challenging in terms of accessibility for first responders. However the peak temperature at 20 m from the fire, the nearest possible location of an SNF package, had one been carried by the train involved in this derailment accident, was lower than that specified in the regulatory HAC fire. However, the conditions in this fire would have been much different if ventilation had been operating at the time of the fire. The fire would not have been oxygen-starved to the same extent it was with the ventilation system off.

In an effort to investigate possible scenarios that could produce long-duration, high temperature fires within this tunnel environment, and with an objective of identifying a conservative fire scenario, additional FDS simulations were performed using the model of the Howard Street Tunnel. In these simulations, the tunnel was assumed ventilated in a manner that allowed the fire to be fully oxygenated, and the fire was assumed to burn until the entire inventory of fuel in the tank car was consumed by combustion. This was accomplished in the model with additional ventilation inlets in the tunnel walls, rather than explicitly modeling the Howard Street Tunnel ventilation system. The area of the pool of fuel was assumed to correspond to the footprint of the tank car and the leak rate from the tank car was matched to the burn rate in order to determine the hottest and longest-lasting conditions for a fire scenario.

The resulting scenario was a fire lasting 6.7 hours with peak temperatures of 2084°F (1140°C) in the flame region, and 1958°F (1070°C) at 66 ft (20 m) downstream of the fire. Peak ceiling temperatures at that same downstream location were above 1832°F (1000°C) and were

predicted to last from about 3 hours until the end of the fire. The heat rate for the fire in this scenario is approximately 1.71×10^{9} Btu/hr (500 MW), which is an order of magnitude higher than the heat rate predicted for the fire when modeled with realistic boundary conditions.

The accident scenario assumes that an SNF transport package is located at the shortest possible distance from the tank car carrying liquid tripropylene. With the DOT required "buffer car" between them this distance corresponds to the 66 ft (20 m) location described in the previous section. In the thermal response analyses (Section 6.1), the package is subject to the local temperature and gas velocity history from the FDS fire simulation at that location. The peak gas temperature is shown in Figure 5.4, the peak tunnel surface temperature is shown in Figure 5.5 and the peak horizontal velocity is shown in Figure 5.6.

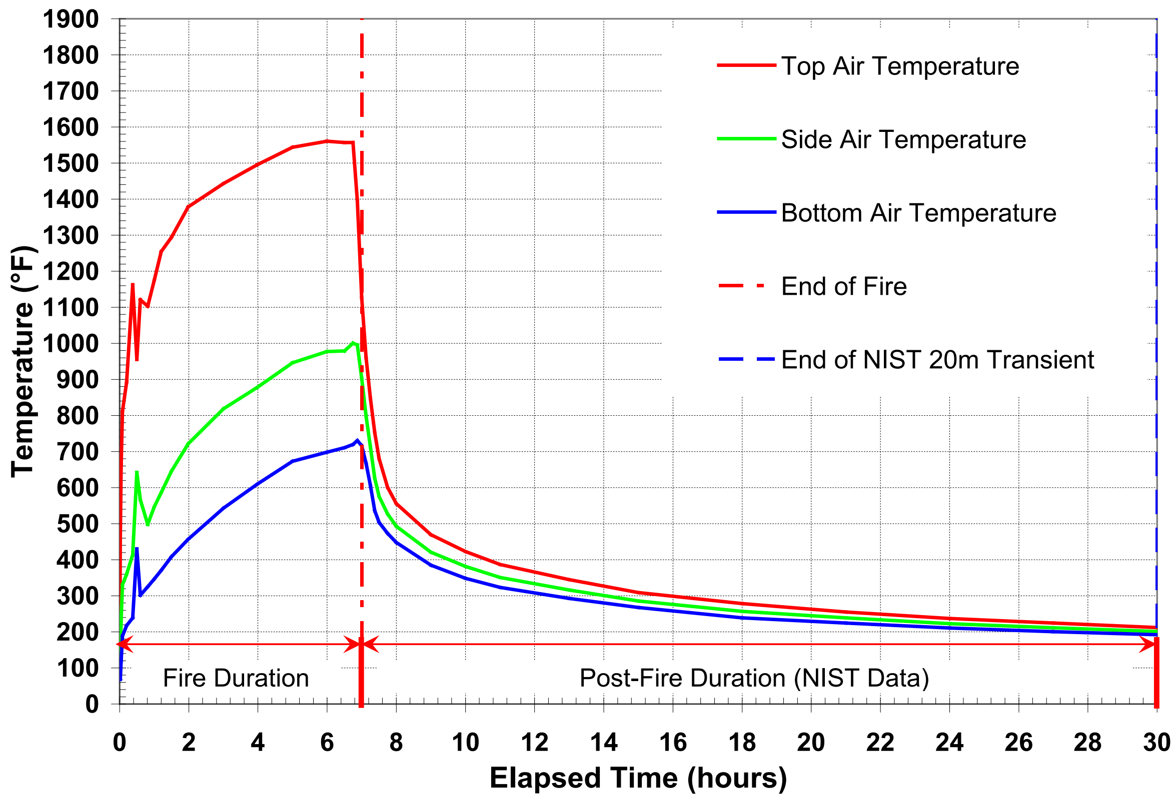

Figure 5.4. Peak Transient Ambient Air Temperatures in FDS Simulation of Baltimore Tunnel Fire Accident Scenario (Smoothed Values, NIST 20-m Data)

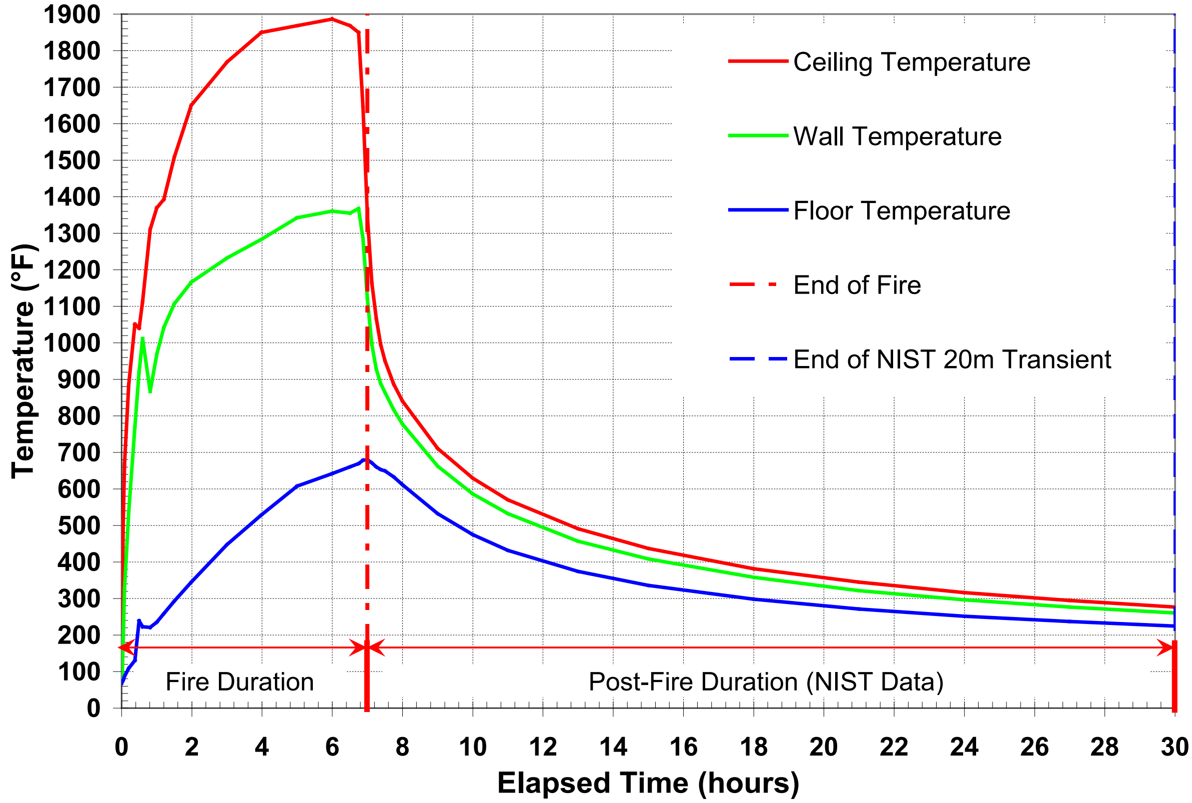

Figure 5.5. Peak Transient Tunnel Surface Temperatures for Floor, Walls, and Ceiling in FDS Simulation of Baltimore Tunnel Fire Accident Scenario (Smoothed Values, NIST 20-m Data)

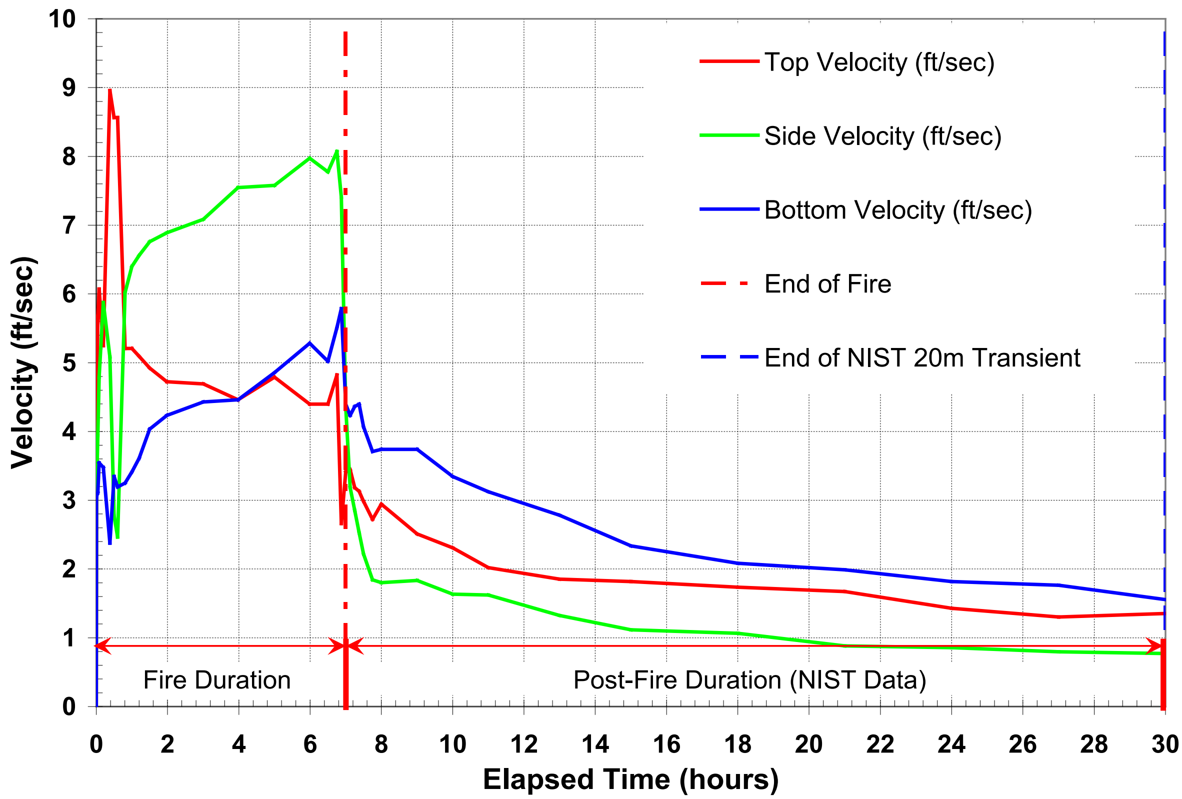

Figure 5.6. Peak Transient Horizontal Velocities near Package Surface in FDS Simulation of Baltimore Tunnel Fire Accident Scenario (Smoothed Values, NIST 20-m Data)

Three different commercial transportation packages were evaluated in this study: the TransNuclear TN-68, the HOLTEC HI-STAR 100 and the NAC LWT. Of these, the TN-68 and HI-STAR 100 are large capacity transport packages designed for rail transport and the NAC LWT is a single-assembly capacity package that is licensed for use on rail and roadways.

5.2 Caldecott Tunnel Fire

The second accident scenario is based on a roadway tunnel fire, which occurred in the Caldecott Tunnel near Oakland California in 1982. This is a summary description from the original report on the thermal evaluation of the potential effect of this fire on an SNF package (NUREG/CR-6894 2007).

5.2.1 Description of the Caldecott Tunnel Fire

Shortly after midnight on April 7, 1982 in Bore No. 3 of the Caldecott Tunnel on State Route 24 near Oakland, California, an accident occurred involving a tank truck and trailer carrying 8,800 gal. (33,310 liters) of gasoline (NTSB/HAR-83/01 1983). This tunnel bore is 3,371 ft (1027 m) long, with a two-lane roadway 28 ft (8.5 m) wide. Traffic is one-way from east to west,

and the roadway has a 4% downgrade. Figure 5.7 shows a photograph[3] of the west portal of the tunnel; Bore No. 3 is the opening on the far left.

In the accident, the tank trailer overturned and the entire vehicle (tanker and trailer) came to rest approximately 1650 ft (503 m) from the west portal of the tunnel. Gasoline spilled onto the roadway from the damaged tank trailer and caught fire. Within four minutes of the accident, heavy black smoke began pouring out the east portal of the tunnel. The tank truck, trailer, and five other vehicles in the tunnel were completely destroyed by the fire, seven persons were killed, and the tunnel incurred major damage.

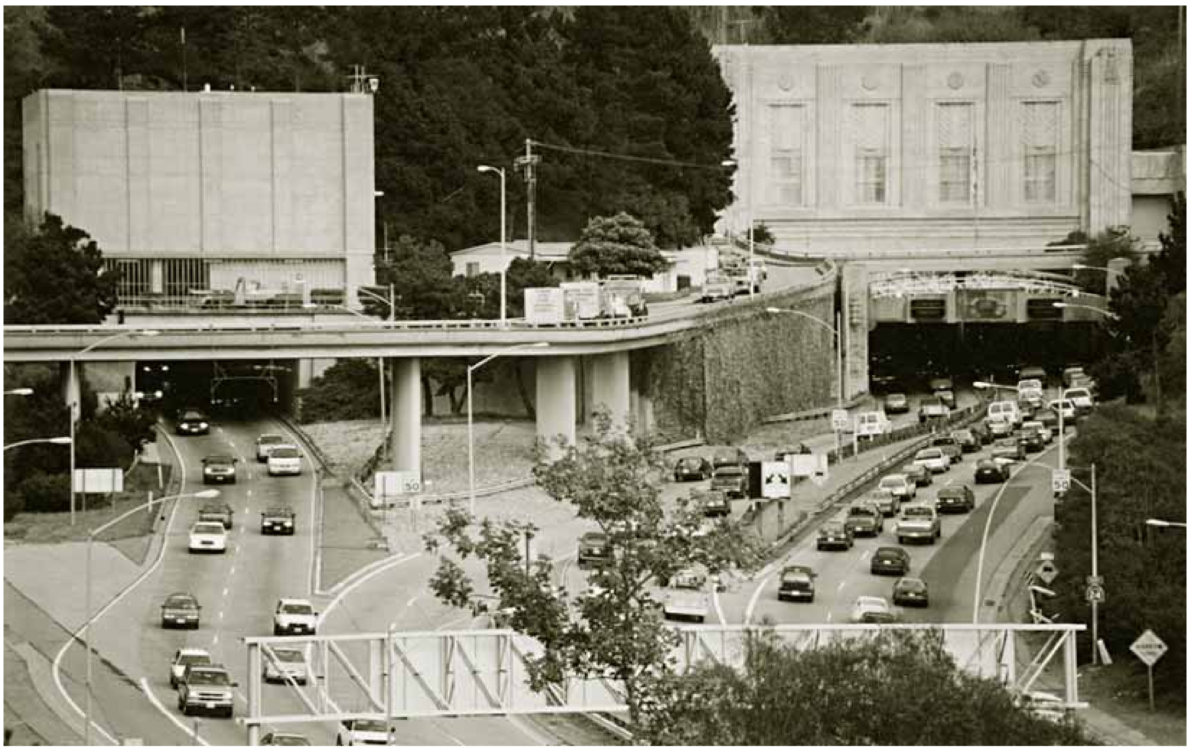

Figure 5.7. West Portal of Caldecott Tunnel

A diagram of a typical cross-section of Bore No. 3 of the tunnel is shown in Figure 5.8. The tunnel can be actively ventilated when conditions warrant, with a total capacity of 1.5 million cubic feet per minute through ducting above the tunnel ceiling. However, the ventilation system was not operating at the time of the accident.

[3] From the Metropolitan Transportation Commission (MTC) newsletter, *Transactions OnLine*, June/July 2000 issue, http://www.mtc.ca.gov/news/transactions/ta06-0700/tunnel.htm. The MTC is the transportation planning, coordinating, and financing agency for the nine-county San Francisco Bay Area.

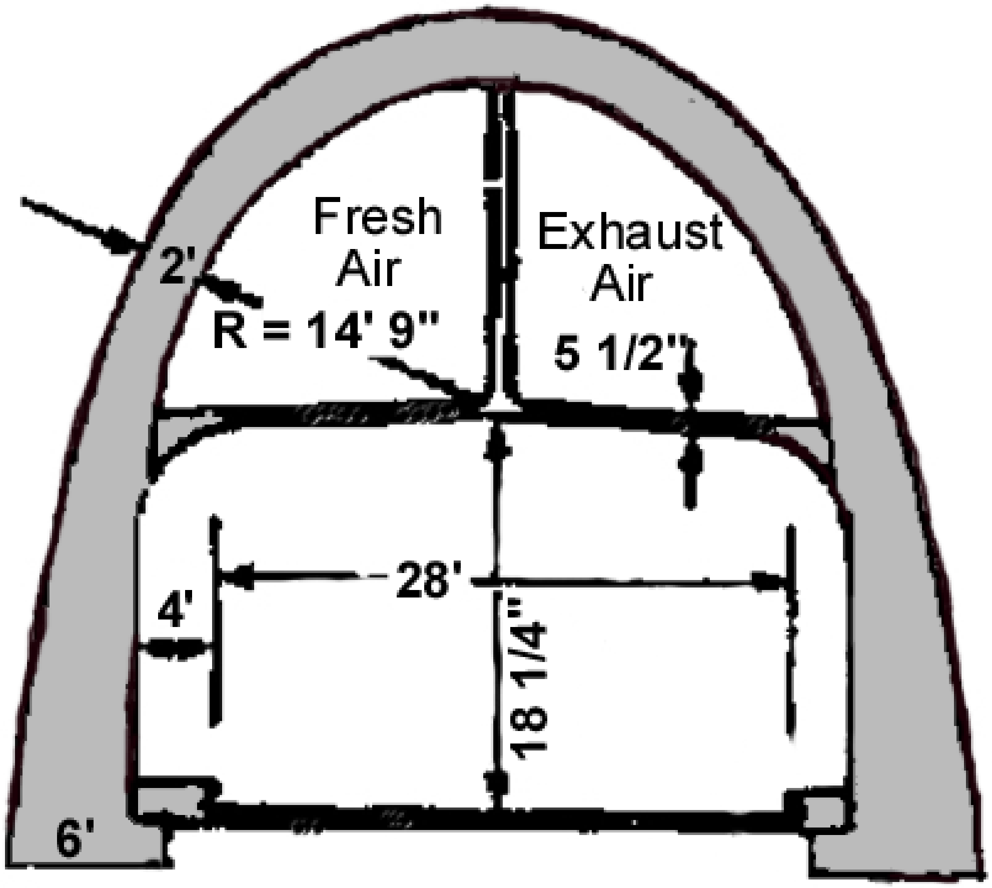

Figure 5.8. Cross-section Diagram of Bore No. 3 of Caldecott Tunnel

The overall duration of the fire is estimated at approximately 2.7 hours, but based on NTSB evaluations of the fire debris and interviews with emergency response personnel, the intensely hot gasoline-fueled portion of the fire is estimated to have lasted about 40 minutes.

5.2.2 Analysis of the Caldecott Tunnel Fire

NIST developed a model of the Caldecott Tunnel with the FDS code for the section of the tunnel that experienced the most severe effects of the fire (McGrattan 2005). In the model, the fire was located in the region between 1673-1706 ft (510-520 m) from the west portal, spanning a length nominally equivalent to the length of the tanker truck and trailer. The FDS model included 50 m of the tunnel upstream of the fire (toward the west portal of the tunnel) and 180 m downstream (toward the east tunnel entrance). Based on boundary conditions, including information on the available fuel and air sources, the FDS code was used to calculate the energy release from the combustion process, the resulting flow of air and hot combustion gases, and local air and surface temperatures throughout the tunnel. The FDS calculation simulated only the gasoline fire, neglecting any contribution to thermal energy release due to the burning vehicles since these were small and widely spaced apart.

The simulation calculates the rise in tunnel surface temperatures and gas velocities (air and combustion product) at different elevations in the tunnel and axial position following the start of the fire. Peak magnitudes occur at the ceiling and as shown in Figure 5.9 (temperature) and

5.10 (velocity). Peak values in both quantities are essentially reached after only 10 minutes into the fire (temperatures within 100°C of the 935°C peak, velocity within 1 m/s of the 9.2 m/s peak) and these are maintained until the end of the gasoline-fueled fire at 40 minutes. The peak values in temperature and gas velocity occur about 80 m downstream of the fire (toward the tunnel entrance). Wall temperatures at mid-line are approximately 100°C below the values at the ceiling, and floor temperatures are approximately 100°C below the mid-line values. The mid-line and floor peak values occur 40 m further downstream than at the ceiling. Air velocities at the mid-line are much higher than near the ceiling or near the floor, reaching a peak of 18 m/s, again at 40 m downstream of the peak at the ceiling. Peak velocity near the floor is lowest at 7.5 m/s.

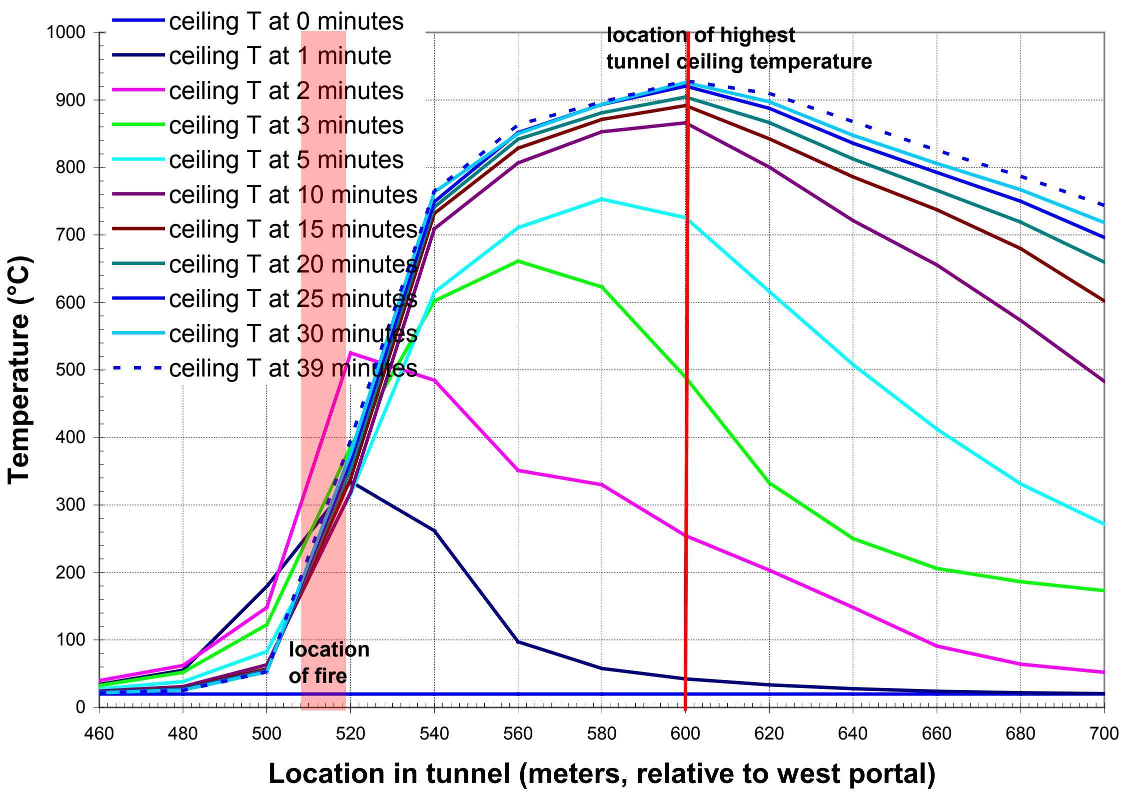

Figure 5.9. Evolution of Ceiling Centerline Temperatures in FDS Simulation of Caldecott Tunnel Fire

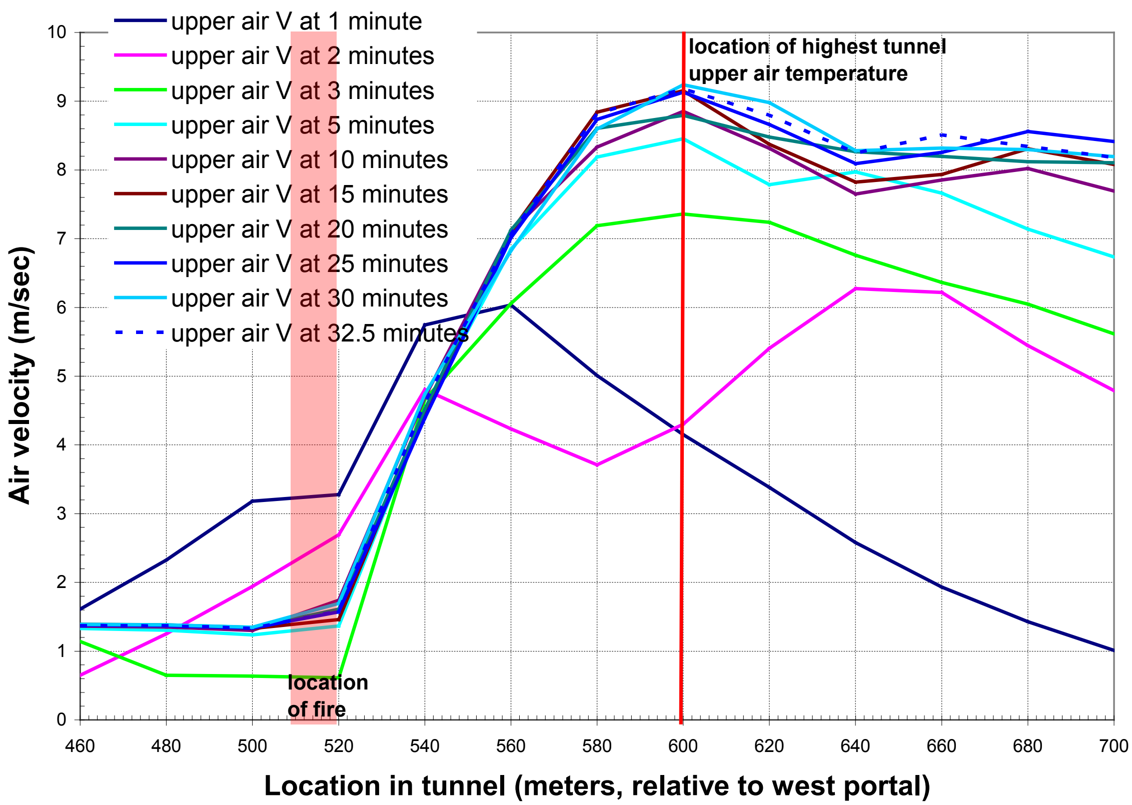

Figure 5.10. Evolution of Gas Velocity Profile near Ceiling Centerline in FDS Simulation of Caldecott Tunnel Fire

5.2.3 Accident Scenario for Caldecott Tunnel Fire

The “hottest” overall location for a hypothetical accident scenario involving an SNF package was chosen to be 100 m downstream of the fire, mid-way between the location of peak temperature at the ceiling and the location of peak temperatures for the mid-line and floor. The surface and air temperatures predicted by the FDS model at that hottest location are shown in Figure 5.11 and Figure 5.12. Air velocities at that location are shown in Figure 5.13.

The accident scenario assumes that an SNF transport package is located at the hottest location defined above. In the thermal response analysis, the package is subject to the local temperature and gas velocity history from the FDS fire simulation. In this analysis the NAC LWT transportation package is used to represent the response of a typical SNF package licensed for use on roadways (for a brief description of the NAC LWT, see Section 4.4.3).

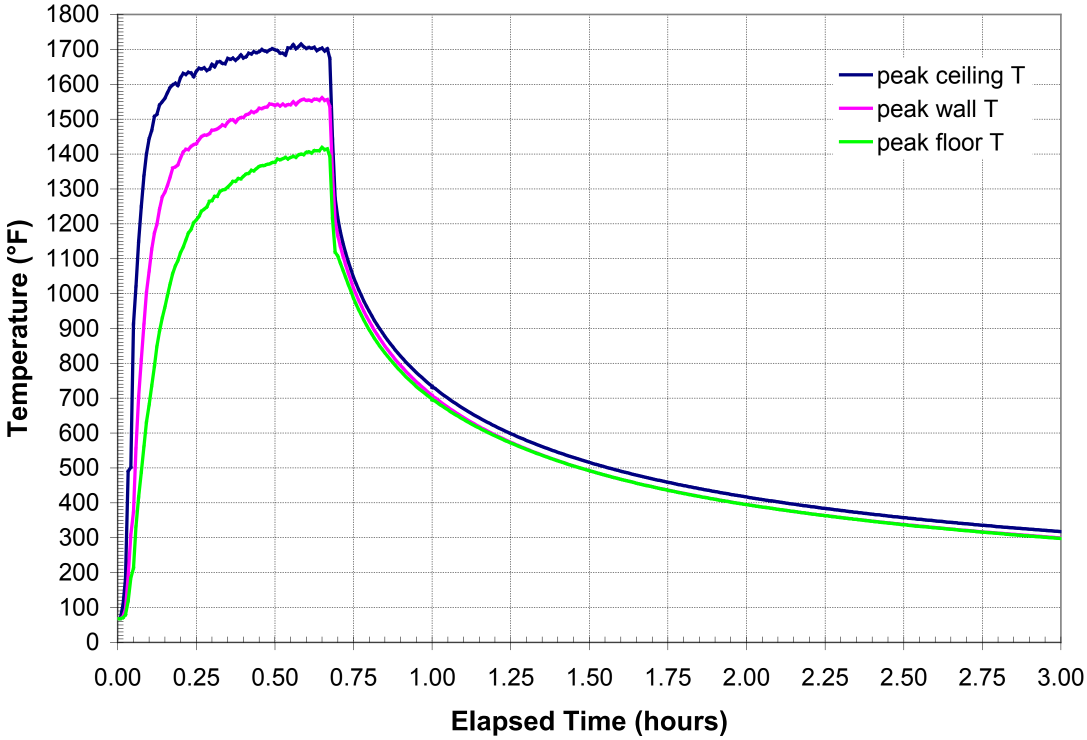

Figure 5.11. Peak Surface Temperatures in 3-hour FDS Simulation of Caldecott Tunnel Fire

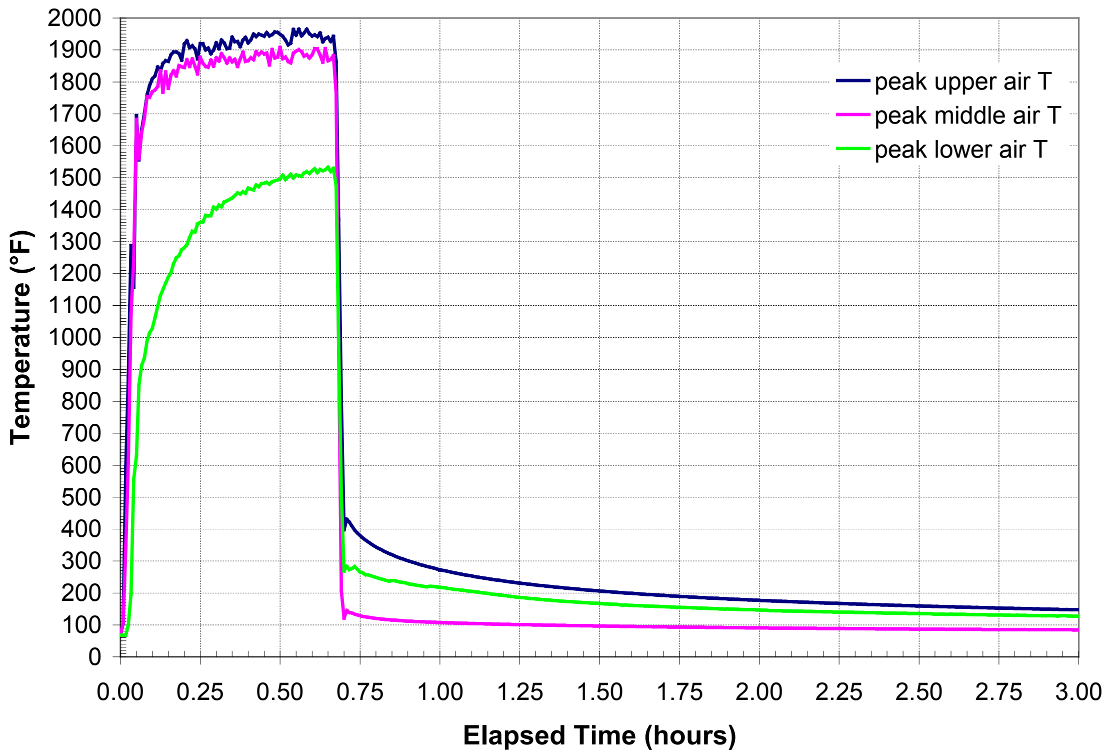

Figure 5.12. Peak Gas Temperatures in 3-hour FDS Simulation of Caldecott Tunnel Fire

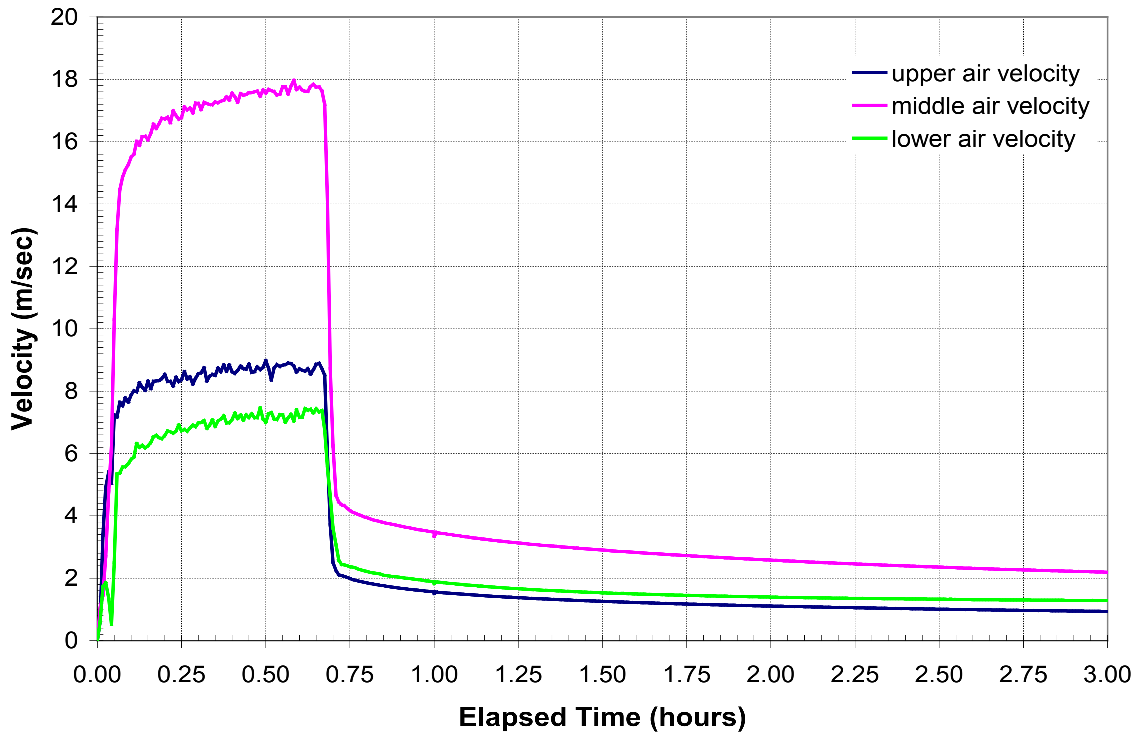

Figure 5.13. Peak Gas Velocities in 3-hour FDS Simulation of Caldecott Tunnel Fire

5.3 MacArthur Maze Fire[4]

While not strictly a "tunnel" fire, the 2007 fire in the MacArthur Maze interchange provided some of the confinement characteristics of a tunnel fire without the constraint of tunnel walls to restrict the flow of air to the fire. Therefore, it was well oxygenated throughout the timeframe of active burning of the fuel source, producing high fire temperatures for the full duration of the fire, and in addition, added the unique effect of the collapse of an elevated roadway onto the wreckage and fire below. The fire peak temperatures and the relatively long fire duration in this case make it a potentially challenging test for any SNF transport package postulated as exposed to such conditions. An additional complication would be the impaired cooling after the fire, and possible structural damage to the package, if it is assumed that the collapsed overhead roadway span fell onto the SNF package. Although the likelihood of an SNF transport being involved in an accident, with such a large fuel source and in such an unusual location, is very small, this third study case presents what may be an actual "worst case scenario," if not *the* worst case scenario for an SNF shipping accident.

5.3.1 Description of the MacArthur Maze Fire

On April 29, 2007 at approximately 3:37 a.m., a tanker truck and trailer carrying 8,600 gallons (32,554 liters) of gasoline overturned and caught fire on the Interstate 880 (I-880) connector of the MacArthur Maze interchange located in Oakland, California. The intense heat from the fire weakened the steel girders of the Interstate 580 (I-580) roadway above, collapsing two adjacent

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[4] This report section is a summary of description and analysis results in draft report *Spent Fuel Transportation Package Response to the MacArthur Maze Fire Scenario*, which will be issued as a NUREG/CR, after posting to the Federal Register for public comment.

spans (approximately 156 feet [47.55 m]) of the elevated roadway onto the section of freeway below. A surveillance camera from the monitoring system of the East Bay Municipal Utility District Wastewater Treatment Plant adjacent to the roadway captured a video of almost the entire fire duration. This video shows the first I-580 roadway span beginning to sag by about 10 minutes into the fire and collapsing completely at approximately 17 minutes. The video also shows one end of a second span of the I-580 roadway descending slowly to the lower (I-880) roadway, beginning at about 17 minutes and reaching its final (partially collapsed) configuration by about 37 minutes. The video shows that the collapse of the second span greatly reduced the size of the fire, but it continued to burn intensely until about 102 minutes. At that point, it began to noticeably decrease in brightness, diminishing to a small glowing spot by approximately 108 minutes after the start of the fire. Figure 5.14 shows a post-fire aerial view of the collapsed spans, extracted from the *California Highway Patrol Multi-Discipline Accident Investigation Team (MAIT)* report (CHP 2007a).

Figure 5.14. Roadway Configuration after the MacArthur Maze Fire (photo from MAIT Report, CHP 2007a)

Part of the NRC analysis of this event included an assessment of the fire exposure temperatures of the upper roadway girders and parts of the remnants of the tanker truck (NRC 2008). Based on analysis of temperature-dependent physical changes in the materials examined, the maximum steel temperatures were estimated to be in the range 1,796-1,868°F (980-1,020°C). These results indicate that material temperatures were generally below 1,832°F (1,000°C), and varied significantly with location in the fire. For example, there were unmelted segments of the tanker's aluminum tank, and only partial melting of at least one of the truck's aluminum wheels.

The material evaluations also suggest that the steel girders experienced maximum temperatures in the range of 1,472-1652°F (800-900°C) at locations deep within the interior of the fire. While well below the melting point of steel, exposure to these temperatures would significantly reduce the strength of the load-bearing girders. The yield strength of the A36 steel at the estimated maximum temperatures experienced during the fire is less than 20% of its normal room temperature value. With such a reduction in strength, the girders could not support the overhead spans.

5.3.2 Analysis of MacArthur Maze Fire

Numerical simulations of the pre-collapse fire were performed with the NIST FDS code. These simulations were used to characterize the fire, consistent with the video record and post-fire examination, to provide a basis for fire temperature and distribution to be used as boundary conditions for SNF package response models. Estimates were based on burn rate for pools formed by realistic fuel spills on concrete. The area of the fire was estimated from the video images and extensive regions of spalled concrete on the I-880 roadway, as shown in Figure 5.15. Modeling results supported characterizing the pre-collapse fire as an “open pool fire with uniform flame temperature of 2012°F (1100°C)” over the period of the first 17 minutes of the fire. The fire directly under the fallen span was essentially extinguished by the blanketing of the fire in that region of the lower roadway. The fire continued to burn in the region beneath the adjacent, still supported span.

During the next 20 minutes, the second span of the upper (I-580) span slowly collapsed onto the lower (I-880) roadway, effectively extinguishing a large portion of the fire. Figure 5.15 illustrates the maximum possible size of the post-collapse fire, compared to the estimated maximum size of the pre-collapse fire. For the purpose of defining the thermal environment of the fire during this 20-minute transition phase, the fire temperature is conservatively assumed to remain at 2012°F (1100°C), consistent with the conditions predicted with FDS for the large, pre-collapse pool fire. The post-collapse fire (out to 108 minutes total time) was modeled using this reduced area and a conservatively bounding flame temperature of 1652°F (900°C). A further level of conservatism was to treat this as a fully engulfing fire, even though its actual size is such that it could only partially engulfing an object as large as an SNF over-the-road transportation package.

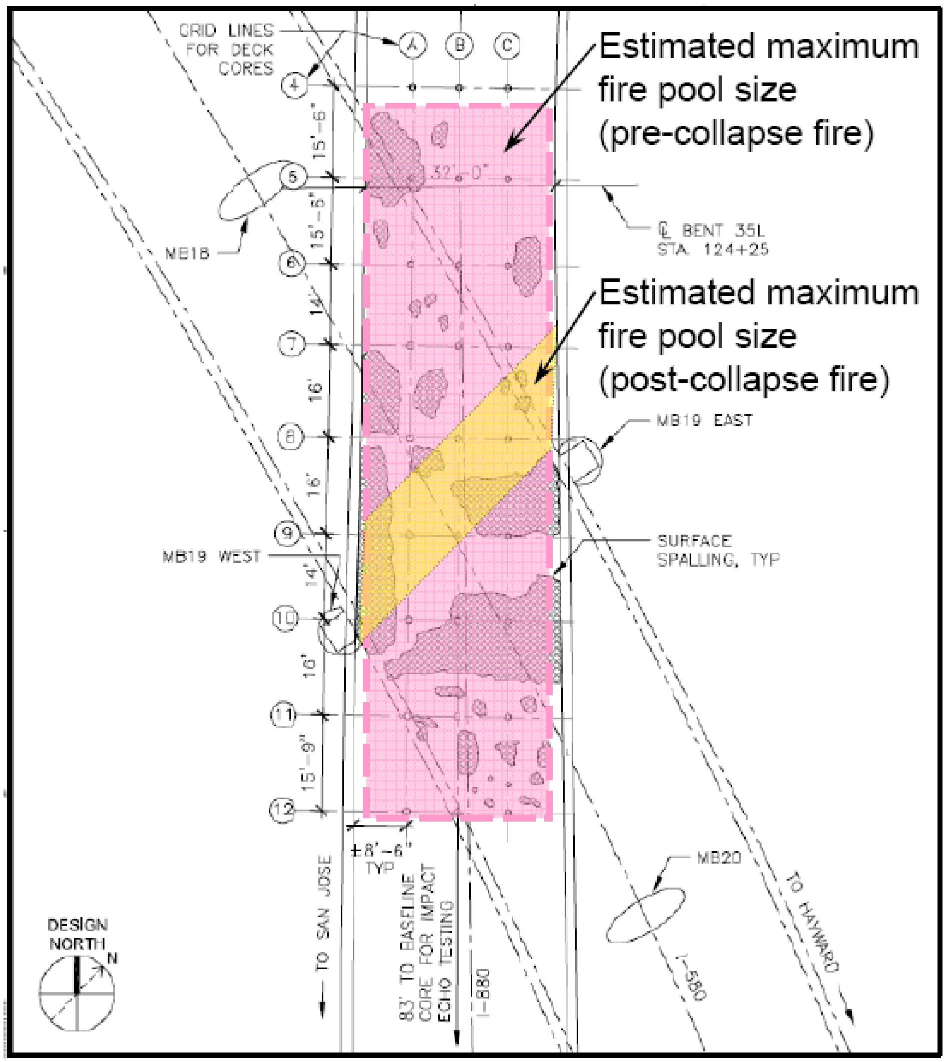

Figure 5.15. Estimated Fire Pool for Pre- and Post-collapse Portion of the MacArthur Maze Fire

5.3.3 Accident Scenario for MacArthur Maze Fire

There are several different aspects of the MacArthur Maze fire that would expose an SNF transportation package to conditions more severe than the HAC fire specified in 10 CFR 71:

1. exposure of the package to a large fully engulfing fire that is more severe than the HAC fire, prior to the collapse of the overhead I-580 roadway span between Bent 19 and Bent 20, at a much higher engulfing flame temperature and conservatively represented with a slightly longer duration (1100°C for 37 minutes, compared to 800°C for 30 minutes)
2. subsequent exposure of the package to the relatively long duration of the fire following the collapse of the overhead spans, which is also at a higher engulfing flame temperature (900°C) and significantly longer duration (71 minutes) than the HAC fire
3. physical impact of a free falling overhead span on the package
4. post-fire cooldown with the package assumed to be covered by the concrete “blanket” of a collapsed overhead span.

The order of events for an SNF package in the MacArthur Maze fire scenario is exposure to fire, followed by a severe impact while still within the fire, and consequently with outer components of the package at high temperature. Because strengths of package materials are adversely affected by fire temperatures, the package might be more vulnerable to damage in this sequence of events.

To conservatively bound the worst that the MacArthur Maze fire could do to the SNF package, the scenario selected for analysis evaluated the most adverse thermal conditions and the most adverse structural configuration. The package was assumed positioned in the most adverse location for the different portions of the thermal analyses and the structural analyses, without realistic constraints on how the package could possibly relocate from one place to another during the fire scenario. For the thermal analysis, the package is assumed to be in the following locations:

- The package is on the lower I-880 roadway, fully engulfed in fire for 37 minutes, exposed to a flame temperature of 2012°F (1100°C).

- After 37 minutes, the package is still on the lower I-880 roadway, fully engulfed in fire, but the flame temperature is assumed to drop to 1652°F (900°C) for the remaining 71 minutes of the smaller post-collapse fire, resulting in a total fire exposure duration of 108 minutes.

- After 108 minutes of fire exposure, the package is still on the lower I-880 roadway, but is enclosed in a concrete "tunnel" simulating the collapsed roadway, which is cooled only by natural convection from the exposed concrete surfaces of the upper and lower roadways.

A realistic location for the package to receive the maximum impact force from the free falling overhead span would be near the edge of the large pool fire, or possibly outside the fire pool entirely. That is, a location that would result in maximum impact loading and post-fire blanketing by the fallen overhead roadway would be a location likely to receive minimum fire exposure. Conversely, if the package were positioned to receive maximum fire exposure (i.e., fully engulfed for both the pre-collapse and post-collapse fire conditions) it would have to be located near the middle of the area encompassed by the smaller post-collapse fire pool (see Figure 5.15), where it could not be struck at all by either of the two collapsed spans.

As a bounding assumption, the peak temperatures predicted in the thermal analysis for the fully engulfing 2012°F (1100°C) fire conditions (see Section 5.3.2 above) were imposed on the package in the structural analysis. The package was positioned at a location where it would receive the maximum force of impact from the collapse of the I-580 overhead span between Bent 19 and Bent 20.

The "package" selected for this scenario was the General Atomics GA-4 LWT (see Section 4.4.4), mainly because it can carry a relatively large payload for an over-the-road transportation package, consisting of up to four intact PWR spent fuel assemblies, and therefore the potential consequences of package failure could be more severe than packages with smaller payload capabilities.

5.4 Newhall Pass[5] Fire

The final accident scenario is based on the 2007 roadway fire in the freeway interchange tunnel referred to as the Newhall Pass, in Los Angeles County, California. The Newhall Pass accident was unique among the fires described in this report, in that it was not a pool fire surrounding a fuel transport vehicle. It was a chain reaction accident where most of the trucks involved were trapped inside this relatively short underpass tunnel. The trucks carried a variety of cargo, none of which was liquid fuel, except for the diesel fuel in their on-board tanks. The fire started in the pile-up of trucks near the tunnel exit, and was carried back through the tunnel from vehicle to vehicle, eventually engulfing all of the tractor-trailer rigs trapped within the tunnel. Within the tunnel, this was a long-duration and rapidly moving hot-spot fire.

5.4.1 Description of the Newhall Pass Fire

On October 12, 2007 at approximately 11:40 p.m. (PDT), a chain reaction traffic collision and fire involving 33 commercial tractor-trailer rigs and one passenger vehicle occurred on a section of the southbound Interstate 5 truck route known as the Newhall Pass Tunnel, which passes under the main north-south lanes of Interstate 5. Figure 5.16 shows an aerial view of the roadway configuration, with the tunnel location marked by a red oval.

The accident began when a tractor-trailer rig went out of control after exiting the tunnel and collided with the concrete median barrier, eventually coming to rest blocking both southbound lanes. The resulting pile-up of on-coming vehicles was reconstructed in the California Highway Patrol (CHP) MAIT report (CHP 2007b) as 13 separate collision sequences consisting of a total of 51 distinct impacts, with 24 of the 33 tractor-trailer rigs trapped within the Newhall Pass Tunnel. A fire started within the close pile-up of vehicles near the tunnel exit and spread rapidly from vehicle to vehicle, eventually filling the entire tunnel.

[5] This report section is a summary of the description and analysis results in the draft report, *Spent Fuel Transportation Package Response to the Newhall Pass Fire Scenario,* which will be issued as a NUREG/CR, after posting to the Federal Register for public comment.

Figure 5.16. Aerial View of Roadway Configuration Showing Location of Newhall Pass Tunnel (image extracted from the CHP MAIT report [CHP 2007b])

Based on the photographic evidence and the timeline in the MAIT report (CHP 2007b), the active, intense fire that destroyed the trucks and their cargoes could have lasted no more than about 5 hours. During this time, fire fully engulfed each of the 24 tractor-trailer rigs within the tunnel, consuming all or most of their respective cargoes, and destroying the vehicles down to their steel frames and engine blocks. Nearly all of the sheet aluminum on the trailer boxes completely vanished, primarily by oxidization rather than by melting. Other more substantial aluminum alloy components showed evidence of local melting.

In an assessment of the fire exposure temperatures within the tunnel (NUREG/CR-7101 2011), melted aluminum samples indicated that temperatures reached at least 1040°F (560°C) at some locations. Studies of hardness changes in graded bolts recovered from destroyed vehicles within the tunnel indicate that these components reached temperatures no higher than about 1382°F (750°C). A single sample of brass material indicated a local temperature of at least 1620°F (880°C) near the middle of the tunnel during the fire. Evaluation of the severe scaling of the carbon steel vehicle frames indicates that these components were exposed to temperatures exceeding 900°F (482°C).

5.4.2 Analysis of the Newhall Pass Fire

The information on the Newhall Pass fire presented by photographs taken during the fire and analysis of materials afterward was insufficient to provide a complete picture of the temperature history at various positions in the tunnel during this accident. Therefore FDS was again used to model the Newhall Pass fire and develop boundary conditions for subsequent analysis of the effect of the fire on an SNF package.

In tanker truck and railway tank car fires, the approach to modeling centers on the pool fire. In the Newhall Pass fire, the source of combustibles was more dispersed and less easily identified. Detailed information on vehicle cargoes was incomplete, but the majority of the trucks involved in the fire were carrying fresh produce of one type or another (apples, oranges, lettuce, tomatoes, melons). One truck was carrying a load of sugar, another a load of coffee, another contained frozen baked goods, yet another carried general freight (most of which was not combustible). Several of the trucks were running empty. Other than the sugar and the coffee, the cargoes by themselves did not present any high-energy fuel sources. This suggests that except for the diesel in their fuel tanks (conservatively estimated as 200 gallons), the fuel load for the fire on any given vehicle was much smaller than the fuel load available in any of the other fires evaluated in this study of severe real-world fires.

For the analysis with FDS, the fuel load for the fires on the individual vehicle within the tunnel was established by creating a fuel budget for each vehicle, based on the assumed diesel fuel, typical combustible mass of the vehicle itself, and the combustible mass of a “typical” cargo. A range of burn rates and fire spread rates were postulated, based on available information on the fire timeline and a matrix of cases was defined to bound the range of possibilities, from short, intense fires on each vehicle, to the longest possible fire durations on each vehicle. Simulation results using these inputs were compared to overall fire duration and temperatures estimated from post-fire material examination. All of these cases were evaluated in the thermal analysis, to determine the bounding fire scenario, in terms of the potential effect on an SNF package, had one been involved in this fire.

5.4.3 Accident Scenario for Newhall Pass Fire

There are two aspects of the Newhall Pass fire that could expose an SNF package to conditions more severe than the hypothetical accident conditions specified in 10 CFR 71. The first is that a package located on any one of the vehicles in the tunnel could potentially be exposed to a fully engulfing fire with a temperature and duration that exceeds the HAC fire. (This requires assuming that an individual vehicle fire could engulf something as large as an SNF package, presumably on a nearby vehicle. How this could occur in reality is difficult to imagine, but assuming a fully engulfing fire is bounding, conservative, and a convenient simplification of the fire boundary conditions.) Second, the overall duration of the fire within the tunnel means that the package would be subjected to a period of pre-heating at ambient temperatures above the design basis for the package (typically 100°F [38°C]) prior to being engulfed in fire.

From the FDS analysis it was clear that the SNF package would experience the highest temperatures in the middle of the tunnel. Those results also showed that the package would experience the longest time above design-basis ambient if it was located a short distance inside the tunnel entrance. It was not obvious which of these would present the worst case for the package, so they were both considered in a matrix of package response analyses. This matrix was developed by considering bounding variations in the fire spread rate and the local vehicle fire burn time, to encompass the known parameters of the fire scenario. Table 5.2 summarizes

these cases[6]. In all cases, the total calculated fire duration is bounded by the uncertainty in the timeline of the fire. The period of intense, fully engulfing fires within the tunnel is known to have been somewhat longer than 2 hours, but less than 5 hours. Table 5.2 also summarizes two sensitivity cases evaluated, to conservatively bound the full range of possible fire behavior. NIST-05 evaluated the effect of the concrete spalling model in FDS on predicted fire temperatures. Case NIST-06 represented a bounding estimate of the actual fuel load for each vehicle, based on available information on the cargo of the various vehicles. This case was developed to verify that the assumed typical fuel load for all vehicles (including the empty ones) produced conservative estimates of the possible range of fire temperatures.

Table 5.2. FDS Cases Modeling Newhall Pass Tunnel Fire

Case	Fuel Load	Burn Rate	Fire Spread Rate
NIST 01	typical fuel budget for each modeled vehicle	1.36 kg/s	0.01 m/s (slow)
NIST 02			0.015 m/s (moderate)
NIST 03			0.022 m/s (fast)
NIST 04	typical fuel budget for each modeled vehicle, but with burn rate doubled	2.72 kg/s	0.01 m/s (slow)
NIST 05	same as NIST 01 – sensitivity study on concrete spalling model in FDS		
NIST 06	fuel load based on actual cargo (if known), typical cargo (if not known); no cargo for empty vehicles	1.36 kg/s	0.01 m/s (slow)

The local vehicle fire durations and peak temperatures for these ten cases are shown in Table 5.3. The boundary temperatures for each case were varied to represent the pre-heat or cooldown for each location, as shown for one of the cases in Figure 5.17.

Table 5.3. Peak Fire Boundary Temperatures at “Hottest Fire” and “Longest Fire” Locations

	Hottest Fire Location			Longest Fire Location		
Case	**Time of Peak (hr)**	**Local Fire Duration (minutes)**	**Peak Fire Temperature**	**Time of Peak (hr)**	**Local Fire Duration (minutes)**	**Peak Fire Temperature**
NIST-01	2.84	~60	1721°F (938°C)	4.29	~60	1579°F (859°C)
NIST-02	1.94	~60	1706°F (930°C)	2.39	~60	1648°F (898°C)
NIST-03	1.47	~60	1668°F (909°C)	1.70	~60	1570°F (854°C)
NIST-04	2.33	~33	1991°F (1088°C)	4.54	~33	1736°F (947°C)
NIST-06	3.46	~68	1861°F (1016°C)	3.91	~26	1646°F (897°C)

[6] A summary of these cases is presented here. For details, see Section 3.3 of NUREG/CR-7207.

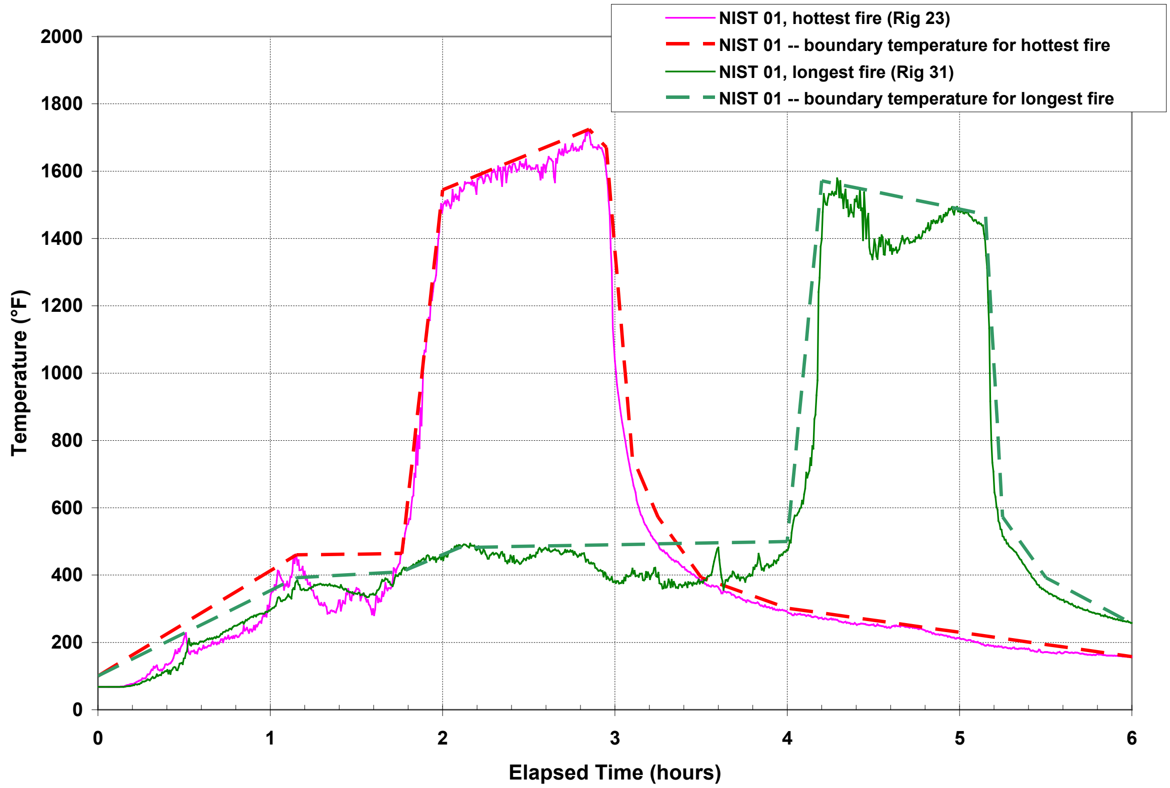

Figure 5.17. Boundary Temperatures for Thermal Analysis of SNF Package in Newhall Pass Fire Scenario at "Most Adverse" Vehicle Locations for Case NIST-01

The General Atomics GA-4 LWT package was again selected for this investigation (refer to Section 4.4.4 for a brief description of this package). As in the MacArthur Maze accident scenario, the package was assumed to contain four WE 14x14 PWR spent nuclear fuel assemblies at the maximum permitted decay heat load for the package. This is the limiting design-basis configuration for thermal analysis of the package.

6.0 ANALYSES OF FIRE ACCIDENT SCENARIOS

This section presents only a brief description of the method and details of the analyses for the fire and accident scenarios. The original references should be consulted for complete details. The Baltimore tunnel fire, Caldecott Tunnel fire and the Newhall Pass Tunnel fire scenarios only required a thermal analysis. The MacArthur Maze fire also required some structural modeling, in addition to the thermal analyses, in order to predict potential consequences of the accident scenario.

6.1 Analysis of Baltimore Tunnel Fire Accident Scenario

Models of the three SNF packages were constructed in parallel with two codes: COBRA-SFS (TN-68) and ANSYS (HI-STAR 100, NAC LWT). Details are provided in NUREG/CR-6886 (2009).

As discussed in Section 5.1.3, this extremely conservative scenario resulted in a fire lasting approximately 7 hours. The FDS analysis of that scenario was extended out to a 23-hour post-fire cooldown, for a total simulation time of 30 hours. To determine the packages' complete transient temperature responses, and to explore the effects of prolonged exposure to post-fire conditions in the tunnel, the COBRA-SFS and ANSYS analyses further extended the post-fire calculation to 300 hours. For boundary conditions, tunnel wall and air temperatures predicted in the FDS analysis at 30 hours were extrapolated from 30 hours to 300 hours using a power function, to realistically model cooldown of the tunnel environment. This conservative approach is equivalent to assuming that the package will be left in the tunnel for nearly two weeks, without any emergency responder intervention.

Beyond the conservatism in the fire and location of the SNF package, a number of additional conservative assumptions were made to maximize heat transfer to the package during the fire and to minimize the heat removal rate during long-term cooldown:

- Rail car and package structure that would reduce heat transfer during the fire were neglected. For example, the ANSYS model of the HI-STAR 100 included the package cradle and rail car section beneath the package, but neglected the rail car ends and honeycomb end blocks adjacent to the impact limiters. The rail car was omitted in the COBRA-SFS model of the TN-68 and ANSYS model of the NAC LWT with the ISO container.

- Rather than directly use the very detailed temperature distribution and history from the FDS simulation, peak temperatures for specific regions were used as boundary conditions in the COBRA-SFS and ANSYS models. The tunnel surfaces in the ANSYS model were divided into three regions, consisting of the ceiling, side walls, and floor (see Figure 5.5).

- During the 7-hour fire, convection heat transfer was assumed to be forced convection and was based on the FDS calculated gas velocities. Beyond 7 hours, the package cooldown neglected any contribution of forced convection and assumed only natural convection.

- Impact limiters and neutron shield materials were assumed to retain their nominal properties during the fire, which would maximize heat transfer, and change to a degraded condition (minimizing heat transfer) for the post-fire cooldown.

- Decay heat thermal loading was at the design limit for each package (21.2 kW for the TN-68, 20 kW for the HI-STAR 100, and 2.5 kW for the NAC LWT) with axial peaking factor from the respective SAR.

Despite all of the conservatisms built into this fire scenario, the thermal analyses showed that the two large packages (TN-68 and HI-STAR 100) suffer very little in this fire. This is primarily due to their large thermal inertia, which is also the reason the peak clad temperature is not reached until 40 hours after start of the fire for the TN-68 and 35 hours for the HI-STAR 100. These peak clad temperatures, 845°F (452°C) in the TN-68 package and 930°F (499°C) in the HI-STAR 100 package, are also well below the regulatory limit[1] of 1058°F (570°C) for zircaloy-clad SNF under accident conditions (NUREG-1536 1997). The package closure and vacuum port seal temperatures exceed material limits for the TN-68, however, and the potential consequences to package integrity are discussed in Section 7.1. The peak seal temperatures reached in the HI-STAR 100 are higher, but they remain below the continuous-use limit for the high temperature metallic seal material used in that package.

The NAC LWT has a much smaller capacity than the multi-assembly packages and consequently is a much lighter transport package. Therefore, it has a much lower thermal inertia than the other two packages considered in this accident scenario. The evolution of component temperatures during the fire and through 23 hours of the post-fire cooldown is shown in Figure 6.1. Peak clad temperature reaches a maximum of 1001°F (539°C) in just 10 hours after the start of the fire, which is only 3 hours after the fire is out. The drain and vent port seals reach a maximum temperature of 1407°F (764°C), and the lid seal reaches 1356°F (735°C) by the end of the fire. The drain and vent ports are sealed with Teflon O-rings. The bolted lid is double-sealed with a metallic seal and a Teflon O-ring seal. The predicted maximum seal temperatures are far greater than the maximum continuous-use seal temperature limits of 735°F (391°C) for the Teflon seals and 800°F (427°C) for the metallic seals. Potential consequences for this accident scenario are discussed in Section 7.1 below.

[1] The short-term temperature limit of 1058°F (570°C) is based on creep experiments performed on two fuel cladding test samples which remained undamaged when held at 1058°F (570°C) for up to 30 and 71 days (Johnson et al. 1983). This is a relatively conservative limit, since the temperature at which zircaloy fuel rods actually fail by burst rupture is approximately 1382°F (750°C) (Sprung et al. 2000).

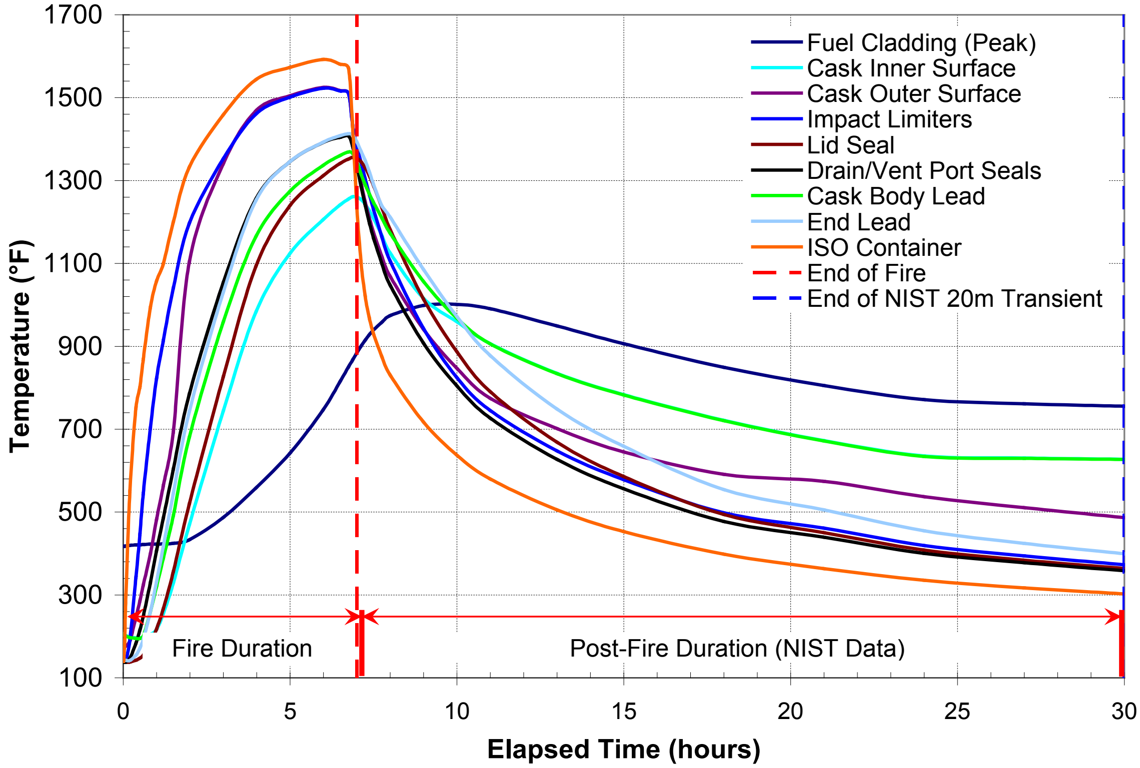

Figure 6.1. NAC LWT Package Component Maximum Temperature Histories for First 30 hours of Fire Transient – Baltimore Tunnel Fire Accident Scenario

6.2 Analysis of Caldecott Tunnel Fire Accident Scenario

The SNF package evaluated in this accident scenario is the NAC LWT. In addition to locating the package at the hottest location in the tunnel fire, several additional conservative modeling assumptions were made in the process of determining the thermal response to this fire scenario:

1. Peak temperatures in each region[2] were used to define boundary temperatures over the entire region, rather than using detailed local temperatures from the FDS simulation.
2. The package cradle and trailer bed were omitted from the ANSYS model to preclude any shielding they would provide from thermal radiation or blockage to forced convection heat transfer from the hot combustion gases.
3. The flow of hot fire gases at the location of the package was treated as forced convection during the fire, to maximize heat transfer rates to the package; forced convection heat transfer was neglected during the cooldown period, even when gas velocities were still significant. After the fire, only natural convection (assuming still air) was considered for the package.

[2] The tunnel surfaces in the ANSYS model were divided into three regions, consisting of the ceiling, side walls, and floor.

4. Attenuation of thermal radiation during the fire due to smoke and particulates is neglected, and the package (or ISO container) is assumed to see peak flame temperature rather than tunnel surface temperatures.

5. The neutron shield material (water/ethylene glycol) was assumed to remain in place until the average temperature exceeded the boiling temperature of the liquid (maximizing heat transfer to the package) and was assumed to be instantly replaced with dry air, conservatively neglecting the absorption of energy that would have occurred due to phase change of the liquid to vapor. Air material properties were assumed during cooldown (minimizing heat transfer from the package).

6. The gas velocities computed with the FDS model were used with a Nusselt number correlation to compute forced convection heat transfer coefficients at the package outer surfaces. This was used for the period of the actual fire and post-fire cooldown. After that (beyond 3 hours) natural convection heat transfer was assumed in the model.

The FDS analysis included the 40-minute fire and a 2.3 hour period of the post-fire cooldown, then the ANSYS model extended the cooldown to 50 hours. The FDS computed values were extrapolated for use as temperature boundary conditions during this period.

Figure 6.2 shows the peak temperatures predicted with ANSYS for the various package components in the first hour of the transient for the NAC LWT package contained within an ISO container. Figure 6.3 shows the peak temperatures predicted for the package without an ISO container for the same boundary conditions. The time interval shown in these plots encompasses the intense gasoline-fueled fire (which lasted about 40 minutes), plus the first 20 minutes of the post-fire cooldown period. Without the ISO container, temperatures of outboard components (i.e., package surface, vent/port seals, and impact limiters) rise somewhat faster than for the case with the ISO container, and reach slightly higher peak temperatures during the fire, but the differences are relatively small. These plots show that the temperature response of the package is essentially the same, with or without an ISO container, during and immediately after the fire. Most components reach their peak temperature values during this interval, closely following the high boundary temperatures during the fire and their rapid decrease once the gasoline is consumed. This behavior is due mainly to the low thermal inertia of the package, because of its relatively small physical size.

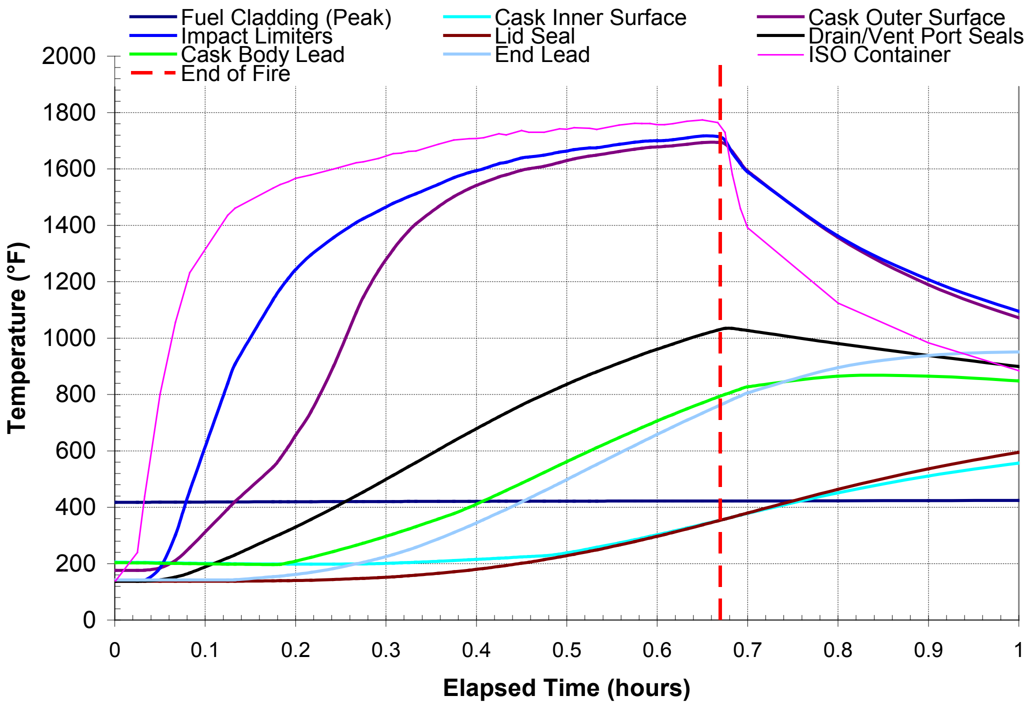

Figure 6.2. NAC LWT Package (with ISO Container): Component Maximum Temperature Histories during Fire Transient – Caldecott Tunnel Fire Accident Scenario

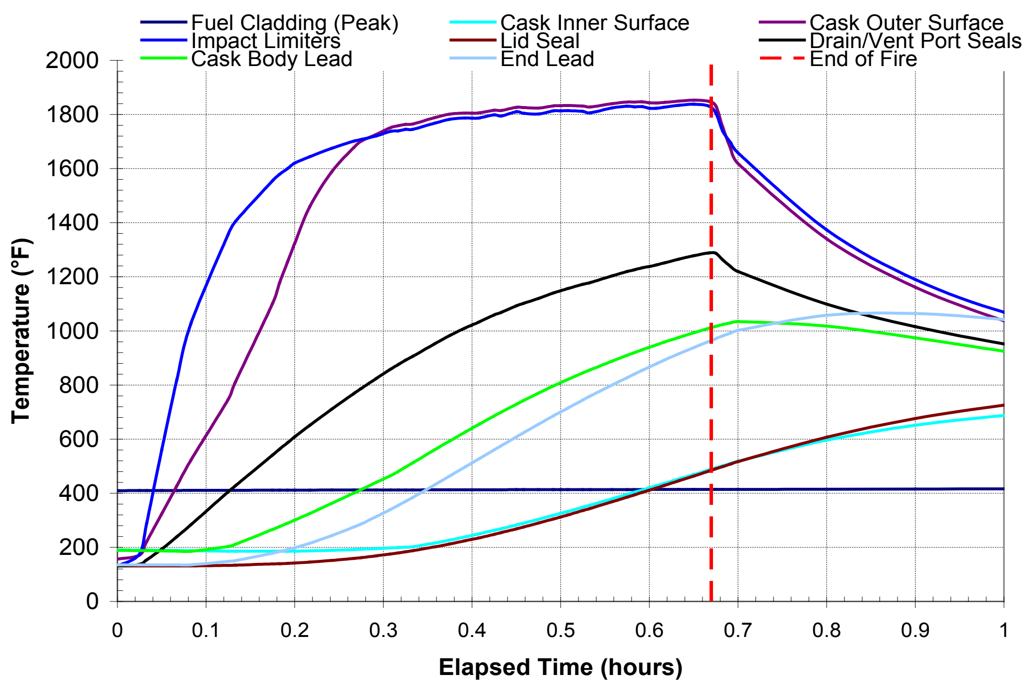

Figure 6.3. NAC LWT Package (without ISO Container): Component Maximum Temperature Histories during Fire Transient – Caldecott Tunnel Fire Accident Scenario

For both cases, the peak temperatures in the lead shielding are considerably above the established operating limit of 600°F (316°C) reported in the SAR (NRC 2001b) for this material, and some local melting of the lead is predicted as a result. To maximize heat input during the transient, it was assumed that overall thermal expansion of the lead and local expansion due to phase change results in the lead entirely filling the cavity between the inner and outer steel shells of the package. For the thermal analysis, possible slumping of the lead due to melting was conservatively ignored, in order to maximize heat input to the package.

Further into the post-fire cooldown, the outboard components follow the decrease in environmental temperatures, but the peak temperatures of the package inner surface and lid seal continue to rise until they reach their maximum within an hour of the end of the fire. In the lid seal region, the predicted maximum seal temperature is 735°F (391°C) for the case with the package in an ISO container, and is 794°F (423°C) without an ISO container. Both values are below the maximum continuous-use temperature limit of 800°F (427°C) for this metallic seal.

The temperature response of the fuel cladding, particularly in terms of peak cladding temperature, is the slowest of all components in the package, due to the significant thermal inertia of the fuel, and because it has the longest heat transfer path to the external environment. For the case with the ISO container, the predicted peak fuel cladding temperature has increased by only about 5°F (2.8°C) by the end of the gasoline-fueled fire. For the case without the ISO container, the increase is slightly smaller, about 4.3°F (2.4°C). However, the peak cladding temperature is still rising at 3 hours into the transient, which is 2.3 hours after the end of the fire. This is due mainly to the decay heat generated in the fuel, which is not being removed from the package during the fire and for some time during the post-fire cooldown, due to the elevated temperatures of the package outboard components, and the higher than design-basis ambient temperature.

The predicted maximum fuel cladding temperature of 544°F (284°C) for the package within an ISO container is not reached until about 8 hours into the transient. Without an ISO container, the peak clad temperature is reached approximately one hour earlier, at 7 hours into the transient, and the maximum temperature is somewhat lower, at 535°F (279°C). With or without the ISO container, the peak clad temperature does not exceed the long-term storage temperature limit of 752°F (400°C) in this transient. In addition, it is far below the currently accepted short-term temperature limit of 1058°F (570°C) for zircaloy-clad SNF under accident conditions (NUREG-1536 1997).

The canister components that do exceed temperature limits are the drain and vent port seals. These limits are 735°F (391°C) for tetraflouro-ethylene (TFE) seals, and 550°F (288°C) for the alterative design Viton® seal material. For the drain and vent port seals, the predicted maximum temperature values 1035°F (557°C) with an ISO container, and 1288°F (698°C) without an ISO container), are several hundred degrees above the maximum continuous-use temperature limits for these seal materials. However, the ANSYS model predicts that these components are above the maximum continuous-use temperature limit for less than two hours. The noted limits for the Viton®, TFE, and metallic O-ring materials are defined for continuous use, so it is possible that the seals might survive these temperature excursions undamaged. Full evaluation of seal performance in a fire scenario requires complete data on seal material response as a function of temperature, which generally can be provided by the manufacturer of the specific seals in a particular application. Such information was not available for evaluation in this study, and as a conservatism, seal temperatures above continuous-use limits were assumed to indicate seal failure (see discussion of consequences for this accident scenario in Section 7.2).

6.3 Analysis of MacArthur Maze Fire Accident Scenario

Analysis of this accident scenario required structural and thermal models. The thermal model is discussed first. Only a summary from the original report is provided here. See the original report for the full description (NUREG/CR-7206 2015).

6.3.1 Thermal Analysis of MacArthur Maze Accident Scenario

Thermal models were produced for the GA-4 package in this accident scenario using two different codes, ANSYS and COBRA-SFS, with different areas of detail. In general the two codes provided good agreement from the initial condition, corresponding to NCT, through the fire and cooldown.

There are two areas of obvious interest when looking at the temperature history, 1) peak cladding temperature in the fuel relative to short-term and burst rupture limits, and 2) temperature in the areas of the package seals relative to seal material limits.

COBRA-SFS and ANSYS models predict the peak cladding temperature to be near, but still below the 1058°F (570°C) short-term limit by the end of the 37-minute long, pre-collapse portion of the fire. However, the peak cladding temperature continues to rise, passing the short-term limit and reaching approximately 1400°F by the end of the 108-minute fire. This value is in excess of 1382°F (750°C), the temperature at which burst rupture of zircaloy cladding has been assumed in previous SNF package transportation studies (NUREG/CR-6672 2000). Burst rupture temperature was looked at closely for this accident scenario and results are summarized in Section 7.3.

Experience with modeling of SNF packages in long-duration fires (for example, see Section 6.1) has shown that the maximum fuel cladding temperature can occur well after the end of the fire, during the post-fire cooldown of the package. In addition to the rise in temperature of the fuel rods in response to heat input from the fire, the temperature also rises due to the high ambient fire temperature preventing decay heat removal from the fuel rods during the fire. This condition persists for some time after the fire, as long as the outboard components of the package remain above the maximum fuel temperature. In addition, as long as the external ambient temperature is above the design basis (typically 100°F [38°C]), the rate of heat removal from the package will be less than optimal, and internal high temperatures may persist for an extended period of time. In the MacArthur Maze scenario, the adverse thermal conditions of this cooldown phase are exacerbated by the presence of the concrete ‘blanket’ of the fallen overhead roadway.

The results obtained with the ANSYS model also show a sustained peak fuel region temperature of nearly 1400°F (760°C) for approximately 3 hours after the end of the fire (see Figure 6.4). The cooldown from this point is slow. The ANSYS model predicts that by 12.2 hours after the end of the fire, the fuel region is at an essentially uniform temperature in the range 1167°F to 1255°F (630°C to 680°C), and the impact limiters and outer shell of the package are at temperatures in the range 1034°F to 1122°F (557°C to 606°C). Only after about 12.5 hours does the package begin to experience a uniformly decreasing temperature at all points, including the sheltered points within the package beneath the impact limiters.

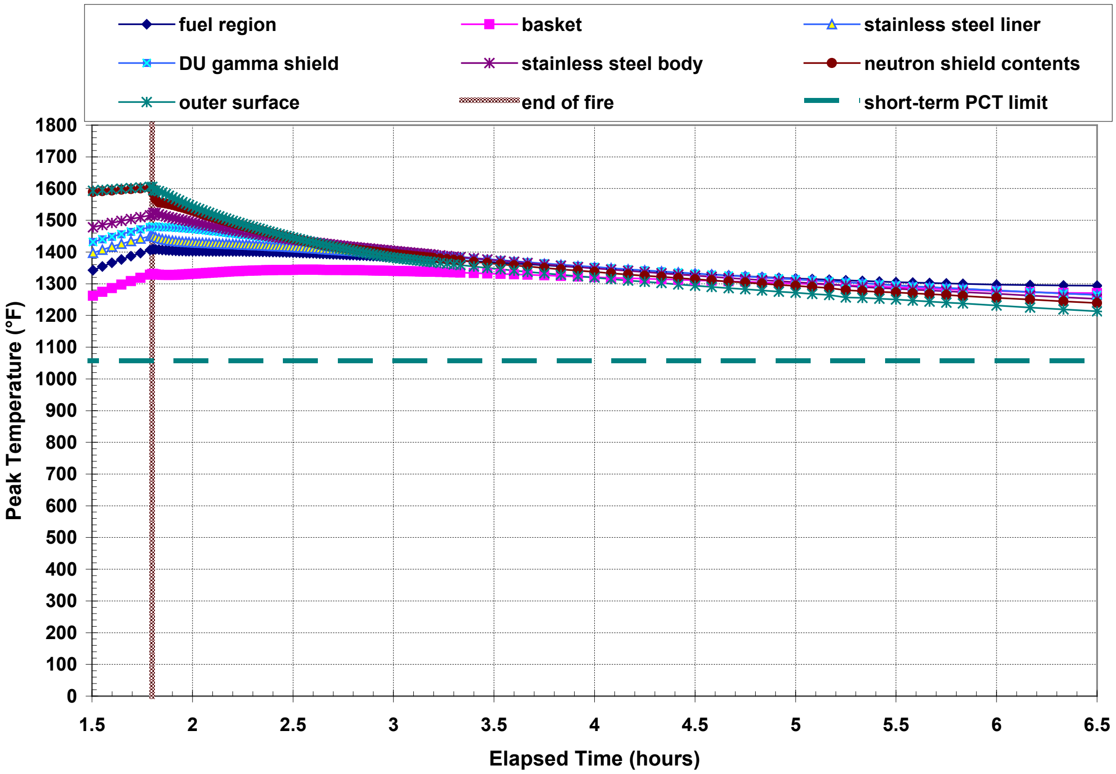

Figure 6.4. GA-4 Package Peak Component Temperatures Predicted with ANSYS Model for Post-fire Cooldown to 6.5 hours – MacArthur Maze Fire Accident Scenario

Containment boundary seals, including drain valve and port, gas sample valve and port, and package lid, are all at the ends of the package and covered by the impact limiters. The thermal insulation provided by the impact limiters allows these seals to survive the HAC fire (GA-4 SAR), however in the higher temperature and longer duration of the MacArthur Maze fire scenario, the maximum short-term design limits for the seal material (800°F for 6 minutes) are approached during the fire and are soon exceeded as local temperatures continue to rise and remain elevated until the overall system begins to cool. The ANSYS model shows that peak temperatures in the seal region locations continue to increase for more than 4 hours after the end of the fire, reaching approximately 1150°F (621°C), and after 14.5 hours are still above 1000°F (538°C).

6.3.2 Structural Analysis of MacArthur Maze Accident Scenario

Structural analyses used to assess SNF package response in the MacArthur Maze fire scenario included:

- Damage resulting from span of upper roadway falling onto SNF package
- Impact of fire and cooldown on package lid bolt clamping force

LS-DYNA (Livermore Software Technology Company 2007) was used to model the roadway collapse as a free-fall of the overhead span onto the GA-4 package. Despite numerous conservative assumptions and evaluation of multiple cases varying package location and orientation, the conclusion was that the structure of the GA-4 package wall would remain largely

undamaged during this fire and roadway collapse scenario. This is because the impact forces that could be generated in a relatively short fall of the roadway span is a small insult relative to the regulatory design requirement in 10 CFR 71 that the package itself must be able to survive a 30 foot drop test onto an unyielding surface.

The analysis of clamping force history for the package lid during the fire and extended cooldown transient was a more critical issue. As shown in the thermal analysis, all of the package seals, including those in the package lid, are predicted to exceed all operating limit temperatures and therefore cannot be assumed to remain functional. It is therefore critical that the clamping force provided by the closure lid bolts can be shown to remain positive at all times during the long and complex transient, to minimize any potential release from the package. The results of detailed and careful analysis of bolt performance and material response at elevated temperatures conservatively show that positive clamping force would be maintained throughout the fire and cooldown transient. The predicted magnitude of that clamping force was used in evaluations to determine the release estimates for this accident scenario, as summarized in Section 7.3.

6.4 Analysis of Newhall Pass Fire Accident Scenario

Two different modeling codes, ANSYS and COBRA-SFS, were used to account for different levels of detail in the thermal model of the GA-4 package. The package is assumed to be in fully engulfing fire, defined using the results of the FDS analysis for each case.

Details were carefully implemented to account for important thermal effects during the fire transient. The neutron shield is modeled with conduction and convection heat transfer using water/propylene glycol properties until the boiling point is reached at maximum design pressure of the tank. Beyond that point it is modeled as air with conduction and radiation heat transfer. Both models include the impact limiters, which are very efficient thermal insulators. In the ANSYS model the distribution of properties in the impact limiters was modified during the cooldown to account for melting and migration of the aluminum honeycomb. This change slowed the rate of heat transfer, which was conservative for cooldown. It was not conservative during the fire, so properties of an intact impact limiter were maintained during that phase of the simulation.

Peak fuel temperatures predicted for all cases are shown in Table 6.1 (where “A” refers to the “hottest fire” location and “B” refers to the “longest fire”). These results suggest that total fire duration may be the most important factor in determining the response of the peak fuel temperature to the fire scenario. Cases NIST-01, -02, and -03 have successively shorter fire durations and peak cladding temperatures for the hottest fire case decrease with decreasing fire duration. This is shown more clearly in Figure 6.5. The same trend is followed for the longest fire in Figure 6.6, except for case NIST-02, where the trend is complicated by the difference in peak temperatures. For the hottest fire, peak temperatures for NIST-01, -02, and -03 have a very similar magnitude and the values decrease slightly with decreasing fire duration. For the longest fire, the peak temperature of NIST-02 is significantly higher, apparently due to increased pre-heating, and this appears to be reflected in the peak cladding temperature for that case.

A comparison between results for NIST-01 and NIST-04 also shows the importance of fire duration. These are essentially the same cases except that the local fire duration is much shorter in NIST-04. This difference is reflected in much higher peak temperatures for NIST-04, but with only small differences in peak cladding temperature, unchanged or decreasing slightly at the hottest fire location (Figure 6.5) and increasing slightly at the longest fire location

(Figure 6.6). Case NIST-06, compared with NIST-04, reinforces this trend; despite having a lower peak temperature, longer local fire duration results in higher peak cladding temperatures.

Table 6.1. GA-4 Package Maximum Peak Fuel Cladding Temperatures for All Cases – Newhall Pass Fire Accident Scenario

Case	Peak Fire °F (°C)	Total Fire Duration (hours)	Local Fire Duration (minutes)	ANSYS: Peak Fuel Region °F (°C)	COBRA-SFS: Peak Cladding °F (°C)
NIST-01-A	1724 (940)	5.1	65	1081 (583)	882 (472)
NIST-01-B	1571 (855)		56	954 (512)	767 (408)
NIST-02-A	1706 (930)	3.0	67	1010 (544)	818 (436)
NIST-02-B	1652 (900)		64	1020 (549)	834 (445)
NIST-03-A	1670 (910)	2.0	62	921 (494)	742 (395)
NIST-03-B	1562 (850)		64	913 (490)	745 (396)
NIST-04-A	2012 (1100)	4.7	43	1074 (579)	853 (456)
NIST-04-B	1742 (950)		36	867 (464)	693 (367)
NIST-06-A	1859 (1015)	4.5	78	1217 (659)	994 (534)
NIST-06-B	1646 (897)		43	881 (472)	702 (372)

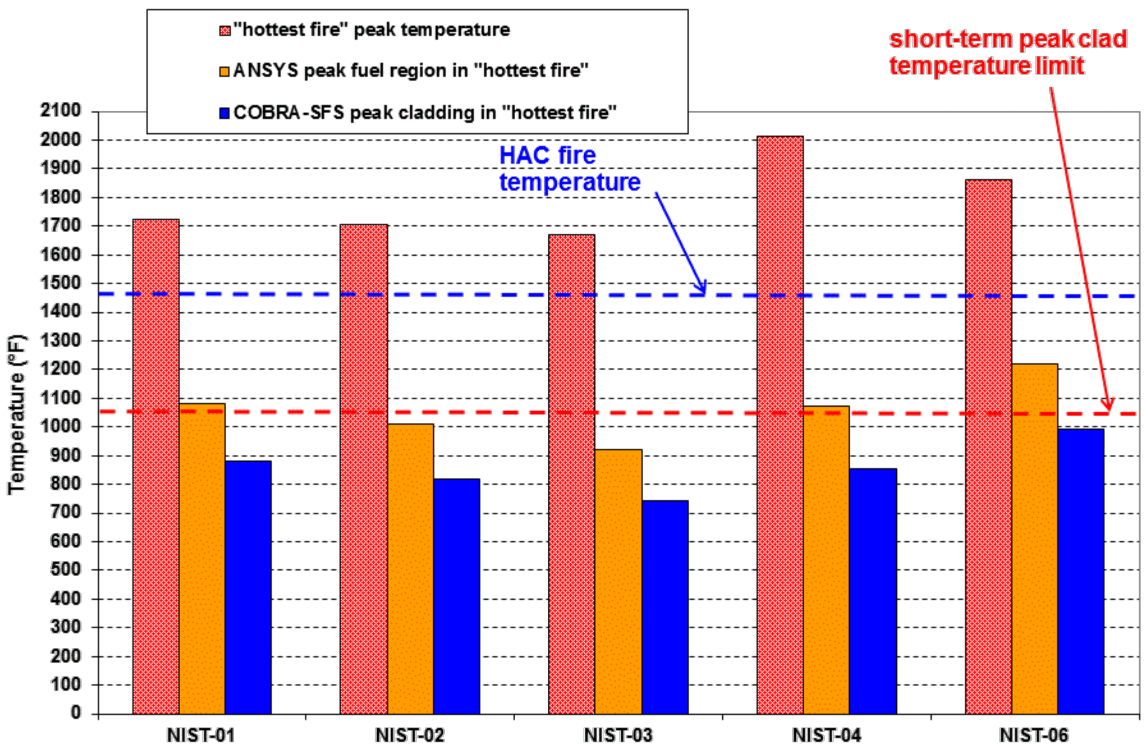

Figure 6.5. GA-4 Package Maximum Temperatures in All Cases for “Hottest Fire” – Newhall Pass Fire Accident Scenario

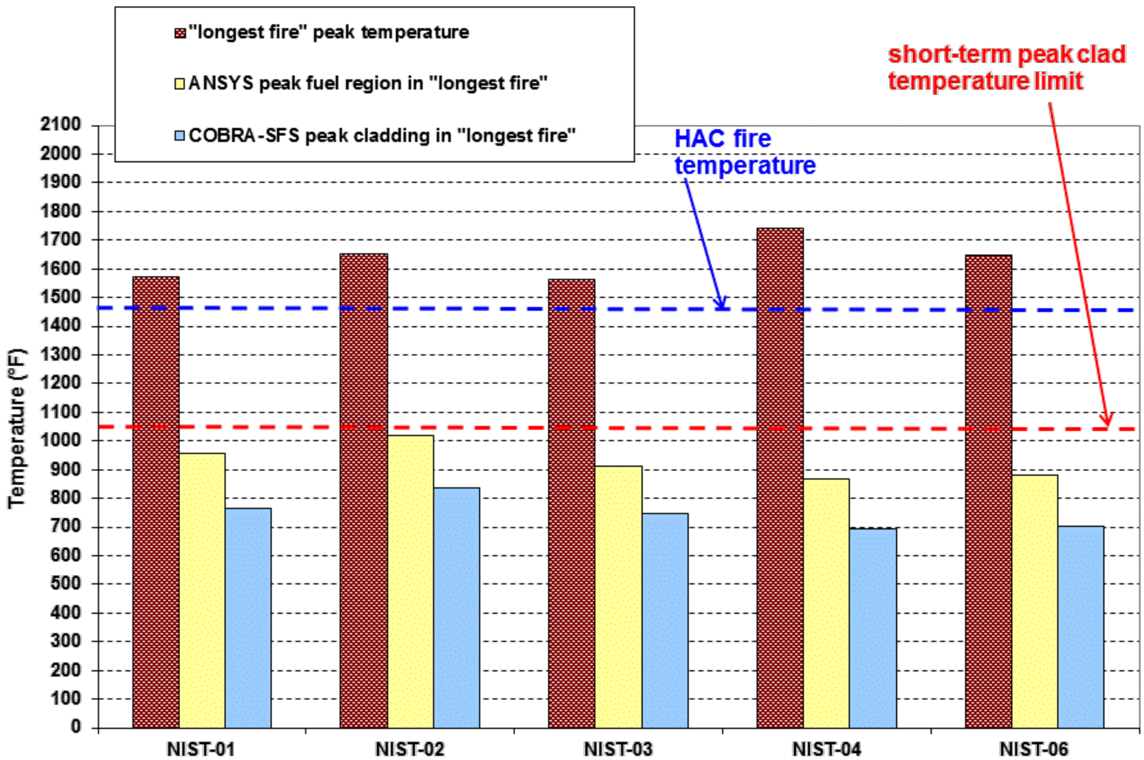

Figure 6.6. GA-4 Package Comparing Maximum Temperatures in All Cases for "Longest Fire" – Newhall Pass Fire Accident Scenario

These results suggest that a shorter fire can have less severe effects on an SNF package, even if it reaches a higher temperature than a longer fire. It is not so much the heat coming into the package from the fire that adversely affects the fuel; it is the lack of heat removal from the fuel during and after the fire, in the cooldown portion of the fire transient that is more likely to be the problem.

7.0 CONSEQUENCES OF FIRE ACCIDENT SCENARIOS

Dose and release consequences for each fire accident scenario are discussed in this section. As noted previously, these are summaries from existing reports. For extended descriptions the reader should consult the original references.

The following statement regarding neutron shielding and associated dose consequence is typical for each fire accident scenario: SNF transport packages with liquid or hydrocarbon resin neutron shields are generally designed to be able to lose their neutron shielding and still meet regulatory accident dose limit requirements. In effect, these SNF packages require neutron shielding only to meet NCT requirements. Additionally, gamma shielding is not compromised, in just about any package, in any credible (and most incredible) accident scenarios. The salient point is that accidents (fire or otherwise) generally will not cause problems due to ionizing radiation; the problem is the potential for release of radioactive material (gases and particulate) due to containment boundary failure.

7.1 Consequences of Baltimore Tunnel Fire Accident Scenario

All three of the packages considered in this evaluation can meet the regulatory limits, even when their neutron shielding has been destroyed by fire. There is also no impact on the gamma shielding for the TN-68 and HI-STAR 100, because they rely on layers of steel. The gamma shielding on the NAC LWT, however, is composed of lead, which will be molten for many hours during the fire and post-fire cooldown. A careful analysis showed that, without a puncture that would release this material, there is no loss of function in this gamma shield and therefore, also, no dose consequence.

In regard to radioactive material release, the HI-STAR 100 is expected to have none in this tunnel fire scenario. This is because the canister is welded and has no leak path and, as an additional redundancy, the metallic lid seal temperature remains below its continuous-use service temperature.

The TN-68 and NAC LWT have the potential for radioactive material release under this scenario due to the package seal temperatures exceeding their design limits. Although the material may retain some sealing function (see Section 4.3), the conservative assumption must be made in the analysis that the seals are gone.

Since the peak fuel cladding temperature in the TN-68 remains well below the regulatory or burst rupture temperature limits, the only source of radioactive material is from CRUD detaching from the fuel rods. Any potential release from that package would be small and is shown to be less than an A_2 quantity. An A_2 quantity[1] is defined in 49 CFR 173.403 as the maximum activity of Class 7 (radioactive) material permitted in a Type A package. This is because an A_2 quantity of radioactive material would not be expected to result in a significant radiological hazard to first responders even if it were released from the package due to a transportation accident. Type B packages (which include SNF transportation packages) can carry more than an A_2 quantity of radioactive material, but must retain the integrity of containment and shielding under normal

[1] The actual amount of a particular material that constitutes an A_2 quantity depends on the radiological properties of the material. Appendix A of 10 CFR 71 defines the A_2 quantities for a large number of different materials in Table A.1, and specifies methods for calculating the appropriate value for any material not listed in the table.

conditions of transport, as required by DOT regulations in 49 CFR 173. Type B packages must also be designed such that if one were subjected to the hypothetical accident conditions specified in 10 CFR 71 (2012), it would release less than an A_2 quantity/week.

The release estimate from the NAC LWT is likely to be similar, less than an A_2 quantity as concluded in the original study (NUREG/CR-6886 2009). However the higher predicted peak clad temperature for this package and the lower burst rupture temperature estimated in more recent analyses (see description of consequences for MacArthur Maze and Newhall Pass accident scenarios in Sections 7.3 and 7.4) suggest that the release estimate for the NAC LWT in the Baltimore tunnel fire scenario should be revisited. This would include an estimate of burst rupture temperature of the postulated fuel, which depends on the temperature history during the accident. If the estimate is below or within the uncertainty estimate of the predicted peak cladding temperature, a revised release estimate should be performed.

7.2 Consequences of Caldecott Tunnel Fire Accident Scenario

Neutron shielding is again not an issue, for the reasons stated above. Gamma shielding in the NAC LWT is provided by a 5.75-inch thick layer of lead sandwiched between the inner and outer steel shells of the package body and a 3-inch thick lead billet encased in the steel base of the package. In the severe conditions of the Caldecott Tunnel fire scenario, the process of raising the peak temperature of the lead to its melting point requires more than half of the total 40-minute duration of the fire. Once the fire is over, temperatures of the gamma shielding material begin to decrease, and the peak temperature falls below the melting temperature of lead in less than 3 hours. Detailed analyses of the response of the NAC LWT package to the conditions of the Baltimore tunnel fire scenario, in which the duration of the fire was approximately 7 hours, showed that complete melting of the lead gamma shielding requires more than 8 hours of exposure to the intensely hot fire environment. Therefore, a large portion of the lead is not expected to change phase in the Caldecott Tunnel fire scenario. A careful analysis was completed of impact on dose for any potential localized thinning of the gamma shielding in the Baltimore tunnel fire scenario and gamma dose was found to remain within regulatory limits for accident conditions. That analysis bounds any impact that would occur in the Caldecott Tunnel fire accident scenario.

NRC staff evaluated the potential for a release of radioactive material from the NAC LWT transportation package analyzed for the Caldecott Tunnel fire scenario. The analysis indicates that the possibility of a release cannot be entirely ruled out for this package because temperatures in the drain and vent port seal regions during the transient exceed the continuous-use temperature limits for the hydrocarbon seals (TFE or Viton®). Although the package lid peak temperature remains significantly below the continuous-use temperature limit for its metallic seal, it exceeds the continuous-use temperature limit for its TFE seal. A simple "pass/fail" criterion is used for evaluating seal performance in this study. If the manufacturer's maximum recommended service temperature was exceeded at any time during the transient on any portion of the sealing surfaces, the seal was assumed to fail. Therefore no credit is taken in the release calculation for the presence of any seals. This is considered to be a highly conservative approach.

The thermal analyses conservatively show fuel cladding temperatures are not high enough to expect fuel rod failure as a consequence of exposure of an SNF package to this fire scenario. Therefore, any potential release would not involve a release of spent fuel or fission products, but could possibly result from CRUD detaching from the fuel rods. Rather than addressing all

radionuclides that could be contained in such CRUD particles, most of which have relatively short half-lives, and are therefore unlikely to be present in significant quantities on fuel old enough to be eligible for dry storage, (see reference [Sandoval et al. 1991], Table I-7), the radionuclide of the greatest concern was used as the basis of the release calculation. For shipments consisting of fuel that is 5 years old or older, Co^{60} is the most important radionuclide to be considered. (For fuel that is less than 5 years old, other short-lived isotopes, such as Mn^{54} and Co^{58} should be considered as well [Sandoval et al. 1991].) For PWR fuel, the total activity decreases to 3% of that at discharge in 5 years, and drops to 1% after 13 years. Co^{60} accounts for 92% of the activity at 5 years and 99% at 8 years (see page I-50, Sandoval et al. 1991). Based on this data, the average CRUD activity for five-year-cooled PWR fuel rods is about 0.006 curies per rod, based on a surface area of 1200 cm^2 per rod. The average CRUD activity for a 17x17 PWR assembly is therefore about 1.73 curies.

The amount of CRUD that could flake or spall from the surface of a PWR rod due to temperatures calculated for the fuel rods in the thermal analysis is estimated to be a maximum of 15% (Sandoval et al. 1991, Table I-10). The major driving force for material release is due to the increased gas pressure inside the package as a result of increases in internal temperature. The temperature change in the package is bounded by the difference between the maximum gas temperature predicted during the fire transient and the gas temperature at the time the package is loaded. For this analysis, the loading temperature is defined as 100°F (38°C), based on the value reported in the SAR (NRC 2001b). The maximum gas temperature is assumed to be the maximum peak clad temperature predicted during the transient. This yields a conservative estimate of the maximum possible temperature change.

To estimate the potential release from the NAC LWT package, a methodology similar to that developed at Sandia National Laboratory (for NUREG-6672 [Sprung et al. 2000]) was used (see [NUREG/CR-6894 2007]). The result of that analysis was that the potential release from the NAC LWT package based on five-year cooled fuel is estimated to be approximately 0.01 curies of Co^{60}. Since the A_2 value for Co^{60} is 11 curies (0.41 TBq), the potential release is about 0.001 of an A_2 quantity. Regulatory guidelines require the assumption of 100% spalling of CRUD from the rod surfaces HAC, but the release estimate based on the Sandia studies show that the amount that could be released is very small. Even if the estimated release fraction is increased to 100% (from the 15% used in this estimate), which constitutes a factor of 7, the activity that could potentially be released would be only 0.07 curies (0.0026 TBq), or 0.006 of an A_2 quantity for this radionuclide.

Therefore, the potential radiological hazard associated with an accident similar to the Caldecott Tunnel fire, if it were to involve an SNF package in close proximity to the fire source, is small. The probability of such an occurrence, based on tunnel accident frequency, flammable materials trucking accident statistics, and radioactive material shipment statistics, has been estimated as one such accident every million years (Larson 1983).

7.3 Consequences of MacArthur Maze Fire Accident Scenario

As in previous fire scenarios there are no adverse consequences related to loss in shielding in the MacArthur Maze accident scenario. The overarching concern is with the potential consequence of radioactive material release. Unlike the previous cases (Baltimore and Caldecott Tunnel fires), this accident scenario could result in fuel failure.

Based on the predicted fuel cladding temperatures from the COBRA-SFS modeling, fuel performance was evaluated using the burst rupture model in the FRAPTRAN-1.4 code (NUREG/CR-7023 2011). In the FRAPTRAN code, cladding rupture is evaluated with a burst stress/strain model developed from test data obtained for loss of coolant accident analysis and reactivity insertion accident evaluations. Burst rupture is the expected mechanism of failure for fuel rods in the reactor core when subjected to severe accident conditions, and is a potential failure mode for spent fuel at high temperatures.

Creep rupture is considered a possible alternative mechanism of failure for spent fuel rods. To evaluate this possibility, a separate analysis was performed with a creep rupture model, using the FRAPCON-3.4 code (NUREG/CR-7022 2011) in conjunction with the DATING code (Simonen and Gilbert 1988). The version of the code used in this analysis has been updated with creep coefficients from creep tests on irradiated cladding (Gilbert et al. 2002), for the temperatures in the range predicted for the hottest rod in the MacArthur Maze fire scenario.

The cladding temperatures from the fire, as calculated with COBRA-SFS, and rod pressures calculated by FRAPCON-3.4 (NUREG/CR-7022 2011) assuming the spent fuel had been subjected to normal reactor operation at 5.7 kW/ft, were input into FRAPTRAN-1.4 to calculate the cladding stresses. The FRAPTRAN-1.4 cladding burst model was also used to calculate the rupture temperature during the fire. The calculated cladding temperatures during the fire from the COBRA-SFS analysis, and the calculated hoop stresses obtained from FRAPTRAN-1.4 for the fire conditions were input into FRAPCON-DATING to calculate cladding rupture based on the out-of-reactor creep relationship in the DATING subroutine.

The peak cladding temperatures calculated with COBRA-SFS for the MacArthur fire were 293°F (145°C) at the start of the fire and reached a peak cladding temperature of 1388°F (753°C) in the fire transient. Based on these temperatures, the calculated cladding hoop stress is 50 MPa at the start of the fire and reaches a peak of 121 MPa just prior to predicted cladding rupture at 1098°F (592°C), as predicted with the burst strain model in FRAPTRAN-1.4. This relatively low rupture temperature reflects the conservatism in the cladding temperature history predicted in the thermal analysis, and the uncertainty in the FRAPTRAN predictions at the relatively low heating rate for the cladding in this fire scenario.

Based on the validation range of the models in FRAPTRAN, and the conservative assumptions in the thermal modeling that impose an extraordinarily severe temperature transient on the fuel rods within the GA-4 package in this fire scenario, the predicted cladding rupture at 1098°F (592°C) obtained in the FRAPTRAN analysis can be considered an extremely conservative result. However, the predicted peak cladding temperature obtained in the thermal modeling is 1388°F (753°C) in this fire scenario. The specific temperature value for burst rupture predicted with FRAPTRAN for these conditions may be quite conservative, and may have a fairly large uncertainty, but there is little uncertainty that the cladding would at some point fail by burst rupture if subjected to the severe conditions predicted for the fuel in the GA-4 package in the MacArthur Maze fire scenario.

The cladding failure temperature predicted with the creep model in the DATING code is 1229°F (665°C), which is significantly higher than the burst rupture temperature of 1098°F (592°C) obtained in the FRAPTRAN analysis. The DATING code is a more general creep prediction tool than FRAPTRAN, with its ballooning and rupture models, which are effectively high temperature creep models. However, it must be noted that, as with FRAPTRAN, the DATING code is being applied outside its validation databases when used to evaluate cladding response to the conditions of the MacArthur Maze fire scenario. However, the results obtained with both

modeling tools show that although there might be some uncertainty as to the exact temperature at which it would occur, fuel cladding could and probably would fail, if subjected to the severe conditions postulated for the MacArthur Maze fire scenario.

The burst rupture and creep rupture models predict cladding failure at a single location along the axial length of a fuel rod. Based on the temperature predictions obtained with the COBRA-SFS model, which omits the impact limiters, the fuel performance models predict rod rupture in the end region of the rod. The peak fuel cladding temperatures predicted with the ANSYS model are somewhat higher than the peak temperatures on the rod ends predicted with COBRA-SFS. Temperature distributions obtained with the ANSYS model, which assumes the impact limiters remain in place throughout the transient, result in the highest temperatures occurring near the axial center of the fuel region, and rod rupture would be expected near the middle of the rod for this package configuration. Since the design-basis fuel for the GA-4 is low burnup (i.e., no more than 45 GWd/MTU), the degree of pellet-clad interaction would be relatively limited, and a single rod breach would be expected to effectively depressurize the fuel rod. Therefore, no additional ruptures are predicted on a given rod, and potential release calculations are based on the assumption of one rupture per rod.

The rod temperatures in both analyses remain much higher than the predicted rupture temperatures for an extended period of time. Table 7.1 summarizes the elapsed time and time duration that the hottest rod peak temperatures are predicted to exceed the calculated burst rupture temperatures.

Table 7.1. Time above Predicted Rod Rupture Temperatures in the MacArthur Maze Fire Scenario

		COBRA-SFS Model		**ANSYS Model**	
		Max PCT in fire transient	1388°F (753°C)	**Max PCT in fire transient**	1433°F (779°C)
Rod Condition	**PCT at Time of Rupture**	**Elapsed Time (hours)**	**Time Above Rupture Temperature (hours)**	**Elapsed Time (hours)**	**Time Above Rupture Temperature (hours)**
rod rupture (burst strain model)	1,098°F (592°C)	0.8	16	0.69	>14.5
rod rupture (creep model)	1,229°F (665°C)	1.15	10.5	0.97	11.5
PCT = Peak Cladding Temperature					

Based on the burst strain model, the fuel rods are expected to rupture before the end of the fire. Based on the creep rupture model, the fuel rods would also be expected to begin rupturing before the end of the fire, but slightly later in the transient. Furthermore, the peak temperatures remain significantly above these predicted rupture temperatures for more than 10 hours. The fuel rod temperatures continue to increase even after the end of the fire, because of thermal inertia and build-up of decay heat that is not removed from the package during and immediately after the fire.

By the time of the secondary peak of 1348°F (731°C) in cladding temperature predicted with the COBRA-SFS model, which occurs at 250 minutes elapsed time (142 minutes after the end of the fire), the peak temperature on every rod in the package exceeds the highest temperature

predicted for rod rupture (1229°F [665°C]). The peak temperature of 1343°F (728°C) predicted with the ANSYS model is at essentially the same value as that predicted with the COBRA-SFS model at this point in the cooldown transient. More significantly, at this time the lowest peak rod temperature is 1285°F (696°C) in the COBRA-SFS model results, and the lowest axial peak temperature predicted in the fuel region in the ANSYS model is approximately 1134°F (612°C). Based on these results, it must be assumed that all of the rods in each of the four assemblies in this package would rupture in the MacArthur Maze fire scenario and release some fraction of their radioactive content into the canister. The integrity of the containment boundary then becomes the controlling factor in any release.

Package seal locations are shown to exceed all seal material temperature limits for long periods of time. Although experiments with the same material used in these seals suggest survival at temperatures well above design limits is possible (see discussion in Section 4.3), considerable additional work is needed to fully characterize seal performance at temperatures above their rated operating temperatures. In the evaluations of the potential consequences of the MacArthur Maze accident scenario, failed seals are assumed to simply vanish. Therefore estimating the leakage rates without seals was key to estimating material release, as was an estimate of the activity sources present in the package cavity. Because the peak fuel temperature exceeds the value where burst rupture of the zircaloy cladding can occur, the potential exists for a release involving fission products and spent fuel particles, as well as particulates resulting from CRUD detaching from fuel rod surfaces.

To estimate the potential release, source terms were generated with ORIGEN-ARP (Gauld et al. 2009) for two design-basis fuel configurations, WE 14x14 fuel at 35 GWd/MTU burnup and 10-years cooling and WE 15x15 at 35 GWd/MTU and 10-years cooling. Allowable release fractions in the *Standard Review Plan for Transportation Packages for Spent Nuclear Fuel; Final Report,* NUREG-1617 (2000) and in *Containment Analysis for Type B Packages Used to Transport Various Contents,* NUREG/CR-6487 (1996), were then used to calculate bounding A_2 fractions released into the GA-4 package.

There is little information upon which to base leakage rate from failed seals. Ultimately it was treated as being analogous to fluid flow through fractured material with an equivalent gap. Leakage between the closure lid and body flange was assumed to be the dominant leak path. Since a detailed finite-element analysis of the bolt tension showed that a positive clamping force is maintained throughout the fire and cooldown transient, the only gap will be due to the surface roughness and clamping force. The flow rate through a very small gap is proportional to pressure difference and to the cube of the gap thickness. The equivalent gap was estimated using literature values of conduction contact resistance for a range of contact pressure and related to the GA-4 using results of the bolt tension analysis. This analysis gives a maximum gap at the time seal failure occurs, which decreases as lid bolt tension increases during the cooldown transient until the gap is essentially closed. This window is estimated at less than 3 hours, which has the effect of greatly reducing the potential for a substantial release of radioactivity in this accident scenario.

Release estimates were completed using the estimated release fractions into the package at a conservative upper bound pressure, the leak rate model with a number of conservative assumptions (no particulate settling, no filtration of particulate by the gap). The total release from the package is estimated as 21 Ci (0.78 TBq) for the higher burnup fuel, and as 24.5 Ci (0.91 TBq) for the lower burnup fuel. Expressed as an A_2 fraction, relative to the mixture A_2 for each configuration, these release rates are 0.24 and 0.17, respectively. Therefore, the bounding estimate of the total release from the package is 0.24 of the mixture A_2 calculated

assuming WE 15x15 fuel at 45 GWd/MTU, 15 years cooling. As mentioned above, if the effect of particulate settling and the restriction of large particulate from passing through a small gap were taken into account, the release estimate would be significantly reduced.

In summary, the estimated consequence of this extremely challenging fire accident scenario is a potential release that would still be within regulatory limits.

7.4 Consequences of Newhall Pass Fire Accident Scenario

As in previous fire scenario analyses, loss of shielding in the GA-4 is not an issue in the Newhall Pass fire scenario. The concern is whether or not a release of radioactive material could occur. Like the MacArthur Maze fire accident scenario, this is another accident scenario that could result in failed fuel.

A cladding performance analysis was completed for the assumed fuel and burnup in similar fashion to that done for the MacArthur Maze fire scenario. In the burst rupture analyses, initial conditions for the hottest fuel rod were determined from a steady-state calculation using FRAPCON-3.4 for the design-basis fuel in the GA-4 package, WE 14x14 (standard) fuel with average burnup of 33 GWd/MTU, and initial room temperature pressurization of 460 psig. The FRAPCON calculation essentially “ages” the assembly to the internal pressure corresponding to its final burnup. The rod in this condition was then subjected to the time history of the maximum cladding surface temperatures predicted with the thermal models for the various bounding cases defining the Newhall Pass fire scenario, using FRAPTRAN1.4.

Table 7.2 summarizes the results of the burst rupture analyses as applied to the five cases evaluated for the Newhall Pass fire scenario. These results are also illustrated graphically in Figure 7.1. For the peak fuel region temperature histories predicted with the ANSYS model, the FRAPTRAN analysis predicts burst rupture at 1038°F (559°C). For the more realistic peak fuel cladding temperature histories predicted with the COBRA-SFS model, the FRAPTRAN analyses predict that burst rupture would not occur for the conditions postulated for these bounding cases, although clad ballooning is predicted to occur for the most severe case (NIST-06-A).

Creep rupture modeling evaluations were also performed for the fuel rods in the Newhall Pass fire scenario, using the FRAPCON-3.4 code in conjunction with the DATING code. The creep rupture modeling evaluations showed that fuel would not fail at the temperatures predicted for the Newhall Pass Tunnel fire scenario. This is consistent with the results obtained for the MacArthur Maze fire scenario, in which the creep rupture model predicted a rupture temperature of 1229°F (665°C). This temperature is not exceeded in any case of the Newhall Pass Tunnel fire scenario.

The burst rupture model predicts rupture at a single location along the axial length of a fuel rod. The temperature predictions obtained with both the COBRA-SFS model and with the ANSYS model show that the highest temperatures occur near the axial center of the active fuel region, and therefore rod rupture would be expected near the middle of the rod. As described in consequences for the MacArthur Maze accident scenario, a single rod breach would be expected to effectively depressurize the fuel rod. Therefore, potential release calculations are based on one rupture per rod.

Table 7.2. Results of Fuel Performance Analyses in the Newhall Pass Fire Scenario

Case	ANSYS Model Results		COBRA-SFS Model Results	
	Peak Fuel Region Temperature (°F [°C])	Fuel Failure Predicted?	Maximum Peak Cladding Temperature (°F [°C])	Fuel Failure Predicted?
NIST-01-A	1081 (583)	yes	882 (472)	no
NIST-01-B	954 (512)	no	767 (408)	no
NIST-02-A	1010 (544)	no	818 (436)	no
NIST-02-B	1020 (549)	no	834 (445)	no
NIST-03-A	921 (494)	no	742 (395)	no
NIST-03-B	913 (490)	no	745 (396)	no
NIST-04-A	1074 (579)	yes	853 (456)	no
NIST-04-B	867 (464)	no	693 (367)	no
NIST-06-A	1217 (659)	yes	994 (534)	no
NIST-06-B	881 (472)	no	702 (372)	no

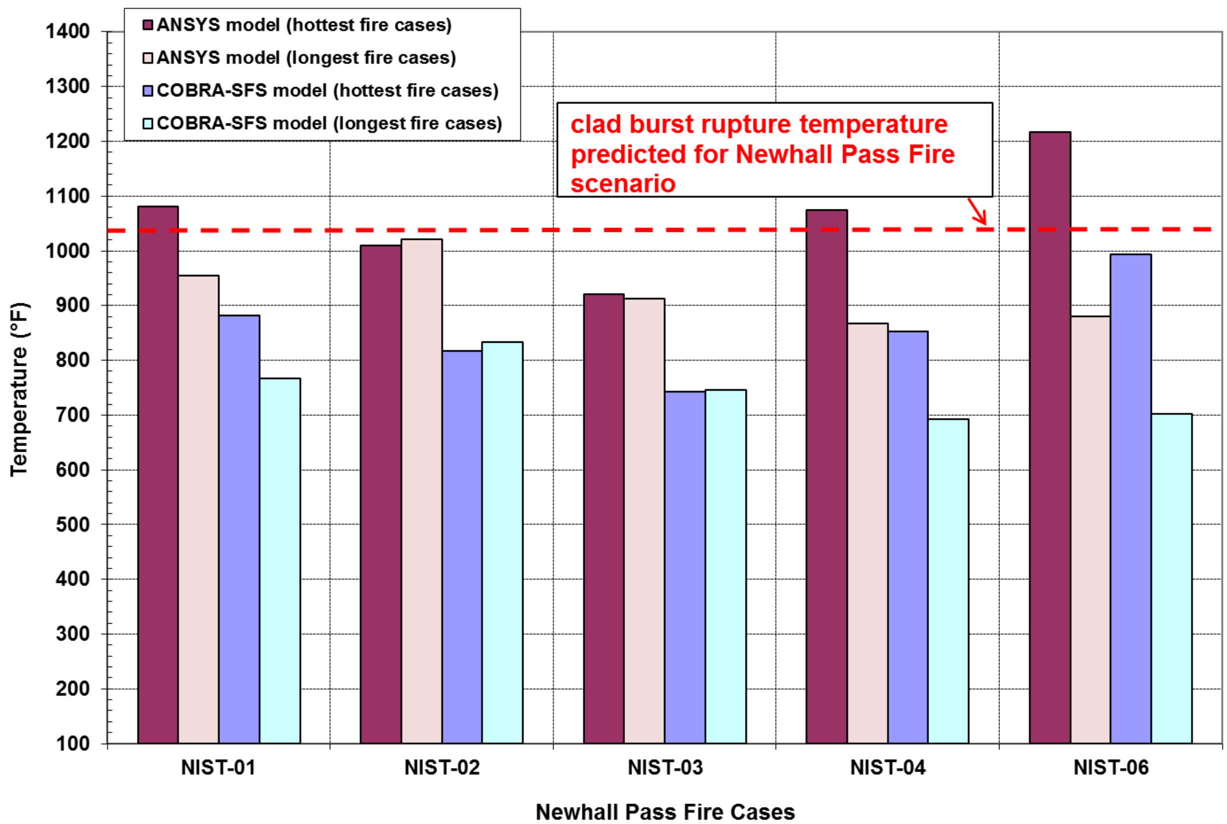

Figure 7.1. Predicted Burst Rupture Temperature Compared to Maximum Fuel Rod Temperatures from Thermal Analysis Models – Newhall Pass Fire Accident Scenario

Based on the ANSYS model results, predicted maximum fuel region temperatures exceed the calculated burst temperature obtained in the FRAPTRAN analysis for three of the five cases evaluated with the package at the hottest location in the tunnel (near the center of the tunnel). Predicted maximum fuel region temperatures do not exceed the calculated burst temperature in

any of the five cases with the package at the "longest fire" location (near the tunnel entrance). For the COBRA-SFS results, the predicted maximum fuel cladding temperature does not exceed the calculated burst temperature in any of the cases considered.

The ANSYS model shows only a limited portion of the fuel reaching the burst rupture temperature for the indicated cases. However for the purpose of calculating the potential release from the GA-4 package in the Newhall Pass Tunnel fire scenario, it is assumed that all rods in the package fail. This is consistent with the assumptions for the HAC fire in NRC guidance, and effectively bounds the maximum possible release from the package.

The thermal model results indicate that the highest temperatures reached in the seal regions are in the range that the seal material would be expected to withstand for up to 10 to 20 minutes without exceeding the documented temperature limits. However, in the Newhall Pass Tunnel fire scenario, the seal regions on the GA-4 package would be expected to experience elevated temperatures for several hours, not just a few minutes. Table 7.3 summarizes the peak temperatures predicted for the lid seal region for the various cases evaluated. This table reports the peak temperatures during the fire portion of the transient and also in the cooldown portion of the transient, which is when the highest seal region temperature occurs in all cases. Table 7.3 also includes the length of time the seal region is above the 30-minute exposure, 5-hour exposure, and long-term exposure temperature limits.

Table 7.3. Summary of Peak Lid Seal Temperatures during Phases of Transient in the Newhall Pass Fire Accident Scenario

ANSYS lid seal temperatures summary:				**Total Time Above 30-minute Exposure Limit of 520°F (hours)**	**Total Time Above 5-hour Exposure Limit of 400°F (hours)**	**Total Time Above Long-term Limit of 302°F (hours)**
	peak seal temperature during:					
Case	**"Hottest" Fire (°F)**	**"Longest" Fire (°F)**	**Post-fire Cooldown (°F)**			
NIST-01-A	499		630	2.62	7.25	>7.5
NIST-01-B		486	626	2.17	5.25	>5.7
NIST-02-A	505		586	1.80	5.2	>8.4
NIST-02-B		583	649	2.50	6.1	>7.7
NIST-03-A	411		533	0.67	3.5	7.4
NIST-03-B		494	578	1.5	4.9	>8.5
NIST-04-A	455		583	1.83	5.0	>7.7
NIST-04-B		429	552	1.17	4.4	>5.8
NIST-06-A	527		668	2.8	6.2	>6.8
NIST-06-B		447	545	1.2	4.1	>5.9

The time-at-temperature results for the drain valve seal and gas sample port seal are similar to the results for the lid seal. The heat-up and cooldown curves for these seals slightly lag the corresponding time values for the lid seal, due to their more protected locations within the closure lid and package base, respectively. The peak temperatures on the valve seals are essentially the same or slightly lower than the values predicted for the lid seal, and therefore the temperature response of the lid seal can be considered as bounding of the behavior of all seals in the package.

The results in Table 7.3 show that the highest seal temperatures occur during the cooldown phase of the transient, rather than during the period of fire exposure for the GA-4 package. The impact limiters shield the seal regions from direct exposure to the fire, and therefore limit the temperature rise on these components during the fire. In the post-fire cooldown of the package, however, the insulating effect of the impact limiters slows the rate of heat removal from the ends of the package, and the high temperatures developed in the central region of the package during the fire result in heat flowing toward the cooler ends. The temperature in these regions continues to increase long after the end of the fire portion of the transient.

In all cases evaluated, the seals would be expected to maintain their sealing function through the local vehicle fire, and do not reach temperatures that exceed the seal material performance limits until sometime into the cooldown portion of the transient. This behavior has important consequences to be considered in the evaluation of potential release from the package. But regardless of the time it takes to reach seal performance limits, the predicted temperatures show that potential release estimates for the GA-4 package must assume that the seals fail in all cases considered in this fire scenario.

Potential release from the GA-4 package in the Newhall Pass fire scenario can be estimated using the leak rate model and equivalent gap width relationship previously discussed in Section 7.3, to obtain a conservative bounding estimate for potential release of radioactive material from the same package in the MacArthur Maze fire scenario. The leak rate obtained with that model is a function primarily of the cavity gas pressure developed during the transient and the bolt temperature history. The conditions of pressure and temperature in the MacArthur Maze fire scenario effectively bound the conditions of the Newhall Pass Tunnel fire scenario. This is illustrated in Figure 7.2, with a comparison of the bounding cavity gas pressure calculated for the MacArthur Maze fire scenario, compared to the cavity gas pressure predicted for the bounding cases defining the Newhall Pass Tunnel fire scenario. The calculated cavity gas pressures conservatively neglect the effect of mass loss due to leakage, and the pressure is calculated based on the average cavity gas temperature, using the ideal gas law.

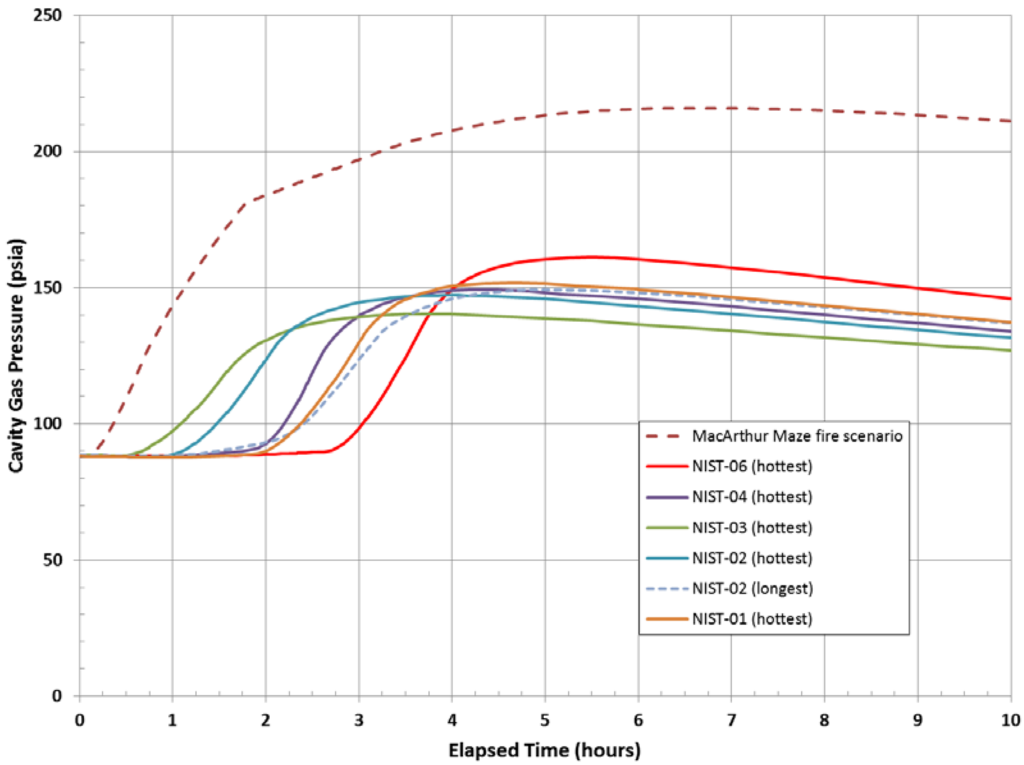

Figure 7.2. Cavity Gas Pressure for Bounding Cases for Newhall Pass Tunnel Fire Scenario Compared to Bounding Value from the MacArthur Maze Fire Scenario

The plot in Figure 7.2 clearly shows that for the bounding conditions defined to model the Newhall Pass Tunnel fire scenario, the cavity gas pressure is significantly lower than that predicted for the MacArthur Maze fire scenario. Similarly, the gas temperature and the package component temperatures (including the lid and lid closure bolts) are lower in the results obtained for the Newhall Pass Tunnel fire scenario. The results obtained with this leak rate model for the MacArthur Maze fire are bounding for the Newhall Pass Tunnel fire scenario.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The NRC has completed studies of truck and rail transport accidents involving fires relative to regulatory requirements for shipment of commercial SNF. NRC conducted case studies for accident scenarios involving four of the most severe of these fires and the results have been compared with existing regulatory requirements for SNF containers. Summaries of analyses of package response and potential consequences from these fire accident case studies are provided in this report.

The case study NRC conducted specifically for rail transport was the Baltimore tunnel fire accident scenario. As concluded in that study (NUREG/CR-6886 2009), the incidence of accidents on railways involving fires, coupled with regulatory (e.g., limit 2-track tunnels to single train with SNF) and planned procedural actions to minimize or exclude involvement of transportation of other hazardous materials, make accidents such as the one analyzed in this scenario a very low probability event. Therefore, specific to rail transport of SNF, the findings summarized in this report support the recommendations in a recent U.S. Department of Energy study (DOE 2009) on planned rail use for a majority (possibly even greater than 90%) of future SNF transport.

The three other case studies performed by NRC addressed truck transport of SNF on public roadways. These include the Caldecott Tunnel fire accident scenario (NUREG/CR-6894 2007), the MacArthur Maze accident scenario (NUREG/CR-7206 2015), and the Newhall Pass accident scenario (NUREG/CR-7207 2015). For roadway transport of SNF, it is recommended that route selection and approval should be completed in accordance with Federal requirements and include consideration of preplanned administrative controls (e.g., temporary lane closure) and alternate routes to address the impact of the current status (e.g., including seasonal weather changes, tunnel activity, or construction activity) that may impact the severity of an accident involving fire.

The severe fires case studies summarized in this report showed that the main factor driving a potential release is not the fire itself, but rather the impediment to getting decay heat out of the package during the fire and post-fire cooldown.

Regarding the adequacy of the current HAC fire test specifications, findings of response analyses for severe (extra-regulatory) fires include:

- These analyses confirmed that failure of shielding is not an issue in fire accident scenarios for SNF packages. Packages are designed to meet regulatory requirements in any credible loss-of-shielding scenario, including fire accidents.

- Packages are shown to be extremely robust in their response to severe, real-world accident scenarios.

- Analyses of conservative, bounding representations of severe fire accident scenarios are predicted to have less than an A_2 quantity release.

Results of NRC conducted seal testing (NUREG/CR-7115 2015) show some continued sealing effectiveness at elevated temperatures and are encouraging from the standpoint of lower potential releases in the event of an accident. However, the sealing function demonstrated at elevated temperatures has not shown consistent performance; therefore for the purpose of

safety analysis, when temperatures in the area of the seal exceed the rated values provided by the seal manufacturer, the seal must be assumed to have failed as part of the containment analyses.

The combined summary of work on fire accidents demonstrates that current NRC regulations and packaging standards provide a high degree of protection to the public health and safety against releases of radioactive material during real-life transportation accidents.

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[1] Draft version (i.e., the PNNL report) will be posted by NRC for public comment on the Federal Register; final NUREG/CR will be released by NRC, after resolution of public comments and other internal reviews.
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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This document summarizes studies of truck and rail transport accidents involving fires, relative to regulatory requirements for shipment of commercial spent nuclear fuel (SNF). These studies were initiated by the U.S. Nuclear Regulatory Commission in response to a 2006 National Academy of Sciences review of procedures and regulations. The fire accident scenarios were based on the most severe historical railway and roadway fires in terms of their potential impact on SNF containers.

While no such accidents involving SNF have ever actually happened in shipments either by rail or roadway, accidents resulting in fires do occur in both modes of transport and, however unlikely, plausible arguments can be made for the possibility of SNF containers being involved in such accidents. A regulatory framework for SNF containers is in place in the United States (10 CFR 71) and internationally (International Atomic Energy Agency) to ensure that risk due to such accidents is small and that the danger to the public is within accepted standards. The history of this regulatory framework is briefly summarized.

The combined summary of this work on fire accidents demonstrates that current U.S. Nuclear Regulatory Commission regulations and packaging standards provide a high degree of protection to the public health and safety against releases of radioactive material in real-world transportation accidents, were such events to involve SNF containers.

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