FACTORS AFFECTING PROBABILISTIC RISK ASSESSMENT OF TRANSPORTATION OF HAZARDOUS MATERIAL BY RAIL

BY

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THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Nuclear, Plasma, and Radiological Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

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Abstract

Transportation of hazardous material by rail is a fundamental infrastructural operation performed on a large scale within the United States yearly. Material release is a possibility associated with shipment failure that incurs large costs, and thus minimizing probability of release is of high importance. The approach to minimize this risk varies based on the type of material being transported. This thesis focuses on a comparison of risk analysis, risk perception, and regulation of highly radioactive material (spent nuclear fuel / high level radioactive waste) and flammable liquid material (with an emphasis on crude oil due to the high yearly volume of transport) being transported by rail.

In this thesis, a probabilistic risk assessment of the hazardous material transportation operations by rail is performed. This assessment yields risk importance measures for major failure (here meaning material release). The results indicate that prevention of derailment itself is the most important risk reduction measure, followed by preservation of the structural integrity of containers, should derailment occur. However, various factors affect the perception of operational risk. These factors depend on the type of hazardous material being transported, thereby affecting the perceived failure probability and associated costs of failure. Four factors affecting risk perception are identified, and their effects on parameters within the risk assessment are analyzed. These factors are natural versus industrial risks, chronic versus catastrophic risks, familiar versus unfamiliar risks, and risks managed by trustworthy versus untrustworthy sources. Improving risk perception can be done by implementing a consent-based approach and by educating the public about the transported hazardous materials.

Regulation of transportation operations is one approach by which risk can be minimized. In this thesis, an analysis of rail regulations is made with a focus on comparing the relative regulatory stringency for radioactive material and flammable liquid material shipments. The regulations analyzed are those that differ between the two material classes. The regulations affecting standard operation, such as speed, train size, and brake systems, are more stringent for flammable liquid carrying trains. Regulations concerning hypothetical accident conditions (drop, puncture, thermal, and immersion) are stricter for containers of radioactive material. A more integrated probabilistic risk assessment would likely strike a different balance between regulatory requirements for flammable liquids and radioactive materials, but implementing any such approach would need to account for how factors affecting risk perception affect the rulemaking process.
Acknowledgements

I would like to thank my internship mentors, particularly Matthew R Feldman and Dr. Kevin J. Connolly of Oak Ridge National Lab, for introducing me to the topic and issues of hazardous material transportation during my two internships in the summers of 2014 and 2015. They provided invaluable guidance to the writing and research process, particularly for this subject material. I would like to acknowledge my two academic advisers, Dr. Clifford Singer and Dr. William Roy, for providing guidance in the thesis writing process and introducing me to suggestions and material I would not have otherwise been aware of. In addition, I would like to thank other members of the NPRE department for guiding me through my academic years. I would like to acknowledge my friend and colleague, Robert Geringer, who has provided encouragement and input through my undergraduate and graduate years. I would also like to acknowledge another two of my colleagues, Kathryn Mummah and Joseph Rajchwald, with whom I have collaborated on papers from which I have borrowed material to include in this thesis. I would like to acknowledge the National Academy for Nuclear Training for providing me with a fellowship for financial support for much of this thesis-writing period.
1. Introduction

Transportation of hazardous material (i.e. hazmat) occurs on a large scale in the United States. On average, over 7,600 railroad cars carrying hazmat are transported via U.S. railways yearly [1]. The purpose of this thesis is to analyze the risk of this transportation of hazardous material by rail, and to use this analysis to identify pathways by which risk can be reduced. One pathway that already exists is regulation of railroad transport. Several regulations will be analyzed in terms of how they affect the risk analysis. The results of the analysis do not provide the entire picture, as various factors affect the perception of risk, leading to a difference between the perceived risk and the risk as calculated in the analysis. These factors will also be discussed in detail based on how they affect the risk analysis.

1.1 Hazardous Materials

The hazardous materials of focus in this report are radioactive material and flammable liquid. Radioactive material is one focus because of the upcoming need for large-scale transportation of spent nuclear fuel (SNF) and high level radioactive waste (HLRW), sometimes referred to together as high level radioactive material (HLRM). The United States has 99 operating nuclear power reactors at 65 sites, as well as 13 shutdown reactor sites, and thus has a high rate of SNF production. Existing U.S. reactors have produced and are estimated to produce a combined total of 140,000 metric tons of heavy metal waste (MTHM) [3], all of which will likely require transportation to a possible interim storage facility (ISF) and/or eventual repository site. Many nuclear power plant sites already have nearby railhead access, and those without functioning railheads can have them installed at relatively low cost, making rail one of the most efficient modes of HLRM transportation.

Railroads are an integral part of the U.S. shipment infrastructure for cargo other than SNF/HLRW because of the routing flexibility and speed at which shipments of vast quantities of material can take place. Near 40% of domestic transport, in ton-miles, is made via rail yearly. [4] With over 140,000 miles of track, the rail system is expansive and essential for U.S. domestic infrastructure. [5] However, despite the extensiveness of the rail system, its safety and reliability can be called into question. Train accidents such as derailments do not always draw considerable attention, but, when those trains are carrying hazardous material, the accidents can evolve into larger scale events, potentially leading to skepticism regarding the general safety of railroad shipments.

The discovery of crude oil in the Bakken Formation of North Dakota has caused a spike in domestic transport of crude by rail (CBR) in recent years. The Bakken Formation contains shale oil that
has recently become more accessible due to the development of hydraulic fracturing (fracking) technology. The oil found in the Bakken Formation, however, is sweet (i.e. low in sulfur) and light \[6\], which causes it to have a more volatile nature than typical crude oil. So, when trains transporting this oil derail, large-scale events are more likely to occur. The incidents related to transportation of this oil can lead to skepticism in the reliability in the rail network for any hazardous material transportation. A result of this thesis is an analysis of differences in risk of transporting material by rail based on the type of material being transported, and the containers that they are transported in.

1.2 Risk

Risk is involved in any activity that involves the potential for failure. It is quantified by the product of the probability of failure and the consequence of that failure.

\[
Risk = \text{Probability} \times \text{Consequence}
\]  

Risk is quantified in whichever units the consequence is described by. This can be money, lives, time, or any other source of loss. Risk assessment is an important tool in assessing large-scale operations prior to performing them in order to minimize consequences and failure frequency. A probabilistic risk assessment (PRA) of hazardous material transportation by rail is performed in Chapter 2 of this thesis, including information on the tools used to perform the assessment and a risk importance measure analysis for all failure modes. All cost values are in U.S. dollars (USD) at face value at the time the data was reported.

Risk as calculated in the PRA is not always the same as risk perceived, especially by those who do not fully understand or similarly assess the values factors involved in the PRA \[7\]. Various factors affect risk perception, which can cause a misappropriation of efforts to risk reduction, or a misrepresentation of relative risk between various activities, compared to a PRA approach with a different risk consequence evaluation. In Chapter 3 of this report, four risk perception factors will be identified and related to the topic of hazardous material transportation by rail. In particular, a comparison of risk perception between SNF/HLRW and CBR will be made based upon these factors. These factors do not typically affect the risk calculation results directly, but rather affect individual identifiable parameters within the PRA, which then affect the final risk calculation result. For each factor, the affected parameters within the PRA are identified, and their effect on the final risk calculation is determined.
1.3 Regulation

Chapter 4 of this thesis will focus on a comparison of regulation for transport of radioactive material and flammable liquid material by rail. The regulations that rail shipments are subject to can be found in Title 49 (Transportation) of the Code of Federal Regulations (CFR). The primary Parts in that title relevant to this analysis are Part 173 (Shippers – General Requirements for Shippers and Packagings), Part 174 (Carriage by Rail) and Part 179 (Specifications for Tank Cars). Regulations differ in these Parts depending on the classification of hazardous material cargo that the train is carrying. As seen in Table 1.1, crude oil is classified as a Class 3 (flammable and combustible liquid) material. SNF/HLRW is classified as a Class 7 (radioactive) material. Though Class 7 refers to any kind/level of radioactive material, this report will focus on transportation of SNF and HLRW. Regulations in Chapter II of Title 49 (Parts 200-279), composed by the Federal Railroad Administration (FRA) and Department of Transportation (DOT), are also relevant to rail transport of all materials.
Table 1.1: Hazardous material classification for crude oil and SNF/HLRW as per 49 CFR 173.2 [8]

<table>
<thead>
<tr>
<th>Class No.</th>
<th>Division No. (if any)</th>
<th>Name of class or division</th>
<th>49 CFR reference for definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td>Forbidden materials</td>
<td>173.21</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>Forbidden explosives</td>
<td>173.54</td>
</tr>
<tr>
<td>1</td>
<td>1.1</td>
<td>Explosives (with a mass explosion hazard)</td>
<td>173.50</td>
</tr>
<tr>
<td>1</td>
<td>1.2</td>
<td>Explosives (with a projection hazard)</td>
<td>173.50</td>
</tr>
<tr>
<td>1</td>
<td>1.3</td>
<td>Explosives (with predominately a fire hazard)</td>
<td>173.50</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>Explosives (with no significant blast hazard)</td>
<td>173.50</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>Very insensitive explosives; blasting agents</td>
<td>173.50</td>
</tr>
<tr>
<td>1</td>
<td>1.6</td>
<td>Extremely insensitive detonating substances</td>
<td>173.50</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>Flammable gas</td>
<td>173.115</td>
</tr>
<tr>
<td>2</td>
<td>2.2</td>
<td>Non-flammable compressed gas</td>
<td>173.115</td>
</tr>
<tr>
<td>2</td>
<td>2.3</td>
<td>Poisonous gas</td>
<td>173.115</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Flammable and combustible liquid</td>
<td>173.120</td>
</tr>
<tr>
<td>4</td>
<td>4.1</td>
<td>Flammable solid</td>
<td>173.124</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>Spontaneously combustible material</td>
<td>173.124</td>
</tr>
<tr>
<td>4</td>
<td>4.3</td>
<td>Dangerous when wet material</td>
<td>173.124</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>Oxidizer</td>
<td>173.127</td>
</tr>
<tr>
<td>5</td>
<td>5.2</td>
<td>Organic peroxide</td>
<td>173.128</td>
</tr>
<tr>
<td>6</td>
<td>6.1</td>
<td>Poisonous materials</td>
<td>173.132</td>
</tr>
<tr>
<td>6</td>
<td>6.2</td>
<td>Infectious substance (Etiologic agent)</td>
<td>173.134</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Radioactive material</td>
<td>173.403</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Corrosive material</td>
<td>173.136</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Miscellaneous hazardous material</td>
<td>173.140</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>Other regulated material: ORM-D</td>
<td>173.144</td>
</tr>
</tbody>
</table>

A Final Rule (80 FR 26643-26750) regarding amendments to regulations of Class 3 material was released on 1 May 2015, and went into effect beginning on 7 July 2015. Those changes are made to regulations defined in 49 CFR Parts 171-180, and any amendments will be noted as such throughout this paper. Both the previous and the new regulations will be discussed for Class 3 materials. The new regulations apply to trains known as high-hazard flammable trains (HHFTs), which are defined in the Rule as trains composed of either 20 or more tank car loads of a Class 3 flammable liquid in a continuous block, or 35 tank car

4
loads of a Class 3 flammable liquid across the entire train. [9] Crude oil is typically shipped in a railcar tank known as the DOT-111, which has a Canadian equivalent known as the CTC-111A. “The DOT-111A, called a CTC-111A in Canada, make up about 69 per cent of the American tanker car fleet and up to 80 per cent of the Canadian fleet.” [10] SNF/HLRW is shipped in a cask, which is then typically placed on a heavy load flatbed railcar.

Because SNF/HLRW is shipped via container and flatbed, the container requires its own regulations as well, which can be found in Title 10 (Energy) CFR Part 71 (Packaging and Transportation of Radioactive Material), as prepared by the Nuclear Regulatory Commission (NRC). This Part also provides regulations for general transport of radioactive material, so the cask-bearing railcar is subject to both groups of regulations when applicable.

Restrictions imposed by the Association of American Railroads (AAR) will be taken into account as well. The primary AAR regulations relevant to this analysis are Circular No. OT-55-N (Recommended Railroad Operating Practices For Transportation of Hazardous Materials), which applies to both Class 3 and Class 7 HLRM shipments, and AAR Standard S-2043 (Performance Standard for Trains Used to Haul High Level Radioactive Material).
2. **Probabilistic Risk Assessment**

The purpose of this section is to set up a PRA analysis for the transportation of hazardous material by rail. This analysis has the value of identifying the primary sources of risk during the transportation operation. It also provides a quantitative baseline by which to analyze the more qualitative effects of both risk perception phenomena and regulatory actions, which are performed in later sections of this thesis. The assessment in Chapter 2 is for generic hazardous material transportation, and not for any particular material classification. Comparisons of Class 3 and Class 7 will be made in Chapters 3 and 4 using this PRA as a reference to show how each classification differs in terms of risk quantification.

The primary tool used in this analysis is the event tree. An event tree represents a series of events that must occur to reach a certain end state of an operation. These events are referred to as “top events,” as they are identified as the events listed along the top of the event tree (as in Fig. 2.2). The end states are those listed on the right side of the event tree. For every event tree, there exists an initiating event (IE), which is the leftmost event.

An event tree is read as follows: beginning with the initiating event, one moves along the first branch of the tree until an intersection (black dot) is reached. The top event corresponding to that intersection (the top event directly above the intersection) is checked for success or failure. Should the top event be a success, one then continues to the upper fork of the intersection (directly to the right, in the case of the event tree used here). Should the top event be a failure, one moves to the bottom fork of the intersection (down, in for the event tree used in this analysis). Figure 2.1 is provided as an example.

```
Top Event

  (Event Success)

  (Event Failure)
```

**Figure 2.1: Event tree key: success moves right, failure moves down and right**

This process is repeated until the end state is reached for the given sequence of top event successes or failures.
2.1 Event Tree

The event tree for the transportation of hazardous material by rail will now be developed. Assumptions will be noted as they are made. The event tree will first be formulated and presented, and then each top event will be discussed in more detail.

The first step of the event tree formulation is defining the initiating event (IE). After defining the IE, each of the top events can follow: Operational failure/Derailment, Derailment of Hazmat, Hazmat Release, End State. In this analysis, it is given that there is hazardous material on the train, and thus the presence of hazardous material on the train is not checked for in a top event. With these top events, the event tree is created as follows:

![Event Tree Diagram]

**Figure 2.2: Hazardous material transportation by rail risk event tree**

2.2 Initiating Event

In this case, the IE is a shipment of hazardous material by rail. A shipment must occur in order for the event tree to be relevant (without any shipments, there can be no successes or failures). Initiating events are typically quantified in terms of frequency of occurrence. In this case, the number of transportation attempts (shipments) per year would be the relevant frequency for risk determination. Frequency varies based on the type of hazardous material being transported by rail. For example, radioactive material (particularly SNF/HLRW) has a very low frequency of shipment by rail at the time of this thesis, while flammable liquids (Class 3 hazardous material) have a relatively high frequency. Frequencies of crude oil
shipments in particular have experienced a large increase in the past decade, including an increase of over 500% from 2011 to 2014 [11].

To determine the total number of trains per year that carry hazardous material, it was necessary to find a ratio of hazmat-carrying trains to the total number of freight trains. The total number of freight train-miles per year can be multiplied by this ratio to get the total number of hazmat train-miles per year. From the FRA Office of Safety Analysis, it was found that in the most recent three complete years of available data (2012 to 2014, at the time of this thesis), there were a total of 1.632 billion freight train miles traveled in the United States. Also in this period, there were 5046 total freight train accidents, 1622 of which involved trains carrying hazardous material. (All data from the FRA Office of Safety Analysis used in this thesis can be found in Appendix A.) Assuming all freight trains have an approximately equal probability of derailing, the accident ratio can be used to approximate the number of train miles per year traveled by trains carrying hazmat.

\[
\frac{1.632 \text{ billion freight train miles} \times \frac{1622 \text{ hazmat train accidents}}{5046 \text{ freight train accidents}}}{3 \text{ years}} = 525 \text{ million hazmat train miles}
\]

By this estimate, hazmat-carrying trains travel approximately 175 million miles per year. This frequency can be used as the IE with units of miles per year, or the IE frequency can be converted to a unit of trips per year, by arbitrarily defining a trip as 1,000 miles long. By using trip frequency, risk of a single trip can be more easily calculated using top event frequencies. For the calculations made in this report, it is assumed that a train takes one trip of 1,000 miles. The initiating event frequency is then the following:

\[
\frac{175 \text{ million hazmat train miles}}{\text{year}} \times \frac{1 \text{ trip}}{1000 \text{ miles}} = 175,000 \text{ trips per year}
\]
2.3 End States

It is important to establish the end states to understand the value of each of the top events. There are three possible end states for this event tree: success, minor failure, and major failure. Failure levels vary with monetary and environmental damage. They are defined as such:

- **Success** – The success end state is associated with a successful shipment of hazardous material. There are no accidents or derailments that threaten the container. The only way for this end state to exist is if top event one, derailment/operation, is a success. Then, by definition, the initiating event is a success. A success end state leads to zero equipment or track damage, and does not require any down time for repairs or cleanup.

- **Major failure** – The major failure end state occurs when there is a release of hazardous material to the environment. Major failure requires failure of all three top events. A hazardous material release is considered a major failure because of the extra level of cost associated with equipment and track damage, as well as the environmental cleanup costs not associated with non-release failures. Data was collected from the FRA Office of Safety Analysis [1] regarding the costs of accidents on trains containing hazardous material from the past 36 months. Table 2.1 below can be used to compare the costs of accidents during which a release occurred to those for which there was no material release. All costs in Table 2.1 are in units of million USD.


Table 2.1: Average monetary damage by end state definition, 2012-2014. Damage values in units of millions of dollars.

<table>
<thead>
<tr>
<th></th>
<th>Number of accidents</th>
<th>Equipment Damage</th>
<th>Track Damage</th>
<th>Total Damage</th>
<th>Damage per accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release</td>
<td>55</td>
<td>55.623</td>
<td>25.635</td>
<td>81.258</td>
<td>1.477</td>
</tr>
<tr>
<td>No release</td>
<td>1516</td>
<td>154.256</td>
<td>90.391</td>
<td>244.647</td>
<td>0.161</td>
</tr>
</tbody>
</table>

\[
\frac{Cost_{Release}}{Cost_{NoRelease}} = \frac{1.477}{0.161} = 9.17
\]

(5)

Cost per accident for a major failure is $1.477 million on average. As seen above, cost of an accident with release is over nine times the cost of an accident with no release. This major failure cost does not include environmental cleanup or other associated post-accident management costs, such as evacuation or decontamination, if applicable. For example, the major failure of a Class 3 train at Lac Mégantic, Quebec, during which an explosion occurred in an urban area, incurred costs of $200 million for cleanup and decontamination. [12]

- Minor failure – The minor failure end state occurs when there is a derailment/operational failure, but there is no release of hazardous material to the environment. Minor failure is mechanical and requires a relatively low amount of cleanup and repair compared to Major failures. There are down time costs associated with minor failure, just as there are with major failures. As seen in the table above, average costs for minor failures are approximately $161,000 per accident. Note also that minor failures have a higher frequency than major failures (and therefore historically more likely to occur). The PRA will determine the probabilities of each level of failure and the associated monetary risk.
2.4 Top Event: Operational Failure

The first top event checks the status of the train operation, including the chance of derailment due to any cause. Given the IE has occurred (i.e. a shipment is taking place), the train must derail or there must be an operational failure for there to be a shipment failure. Operational failures include side-on collisions and other failure modes during which derailment does not necessarily occur. Risks due to failure modes such as violent attacks are not within the scope of this analysis.

To provide insight as to approximate derailment probability, data was collected from the FRA Office of Safety Analysis [1] to determine the total number of accidents since January, 2012. Data was then found for the total number of train-miles traveled in the same time period. Dividing the former number by the latter yields a per-mile train accident rate. This rate is for all freight trains, as opposed to just those carrying hazardous materials.

Table 2.2 displays the number of accidents from January, 2012 through December, 2014 by accident cause:

<table>
<thead>
<tr>
<th>Cause of Accident/Event</th>
<th>Number of Incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>610</td>
</tr>
<tr>
<td>Human Factors</td>
<td>1,950</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>754</td>
</tr>
<tr>
<td>Signal</td>
<td>148</td>
</tr>
<tr>
<td>Track</td>
<td>1,584</td>
</tr>
<tr>
<td><strong>Total Events</strong></td>
<td><strong>5,046</strong></td>
</tr>
</tbody>
</table>

Each accident consisted of one of the following events: derailments, head-on collision, rear-end collision, side collision, raking collision, broken train collision, highway-rail impact, obstruction impact, fire/violent rupture, other impacts, other events.

As found previously, the total number of train miles found for the same three-year time period was $1.632 billion.

This yields a relative train accident frequency of the following:
To put this into perspective and more into probability terms, resume the assumption that a typical train trip is 1,000 miles long. On a per-trip basis, there would be 0.0031 accidents per trip, or a 0.31% chance of an accident on a 1,000 mile train trip, based on the historical data.

\[
\frac{5,046 \text{ accidents}}{1,632,000,000 \text{ miles}} = \frac{1 \text{ accident}}{323,000 \text{ miles}}
\]

(6)

2.5 Top Event: Hazmat Car Involvement

The next top event checks whether the hazardous material-carrying cars were the ones that derailed, given that some part of the train derailed. When a derailment occurs, there are usually only a few railroad cars off the rails. In the event of failures such as side-on collisions, often only one or two cars are involved in the accident. Therefore, there is some probability that should an accident occur, none of the hazmat cars are involved, and there is thus no chance of material release. There are several complicated steps in the analysis of this top event. For example, factors such as the overall train composition, number of hazmat-carrying cars on the train, location of hazmat-carrying cars in the train, and location of accident, all need to be considered to accurately determine this probability.

It is useful to have an approximate value of this probability in order to determine its relative contribution to the probability of each end state. Several assumptions must be made for this approximation and will be noted as such.

The first assumption is homogeneity among trains containing hazardous material. This is not the case in reality, as some trains may contain only a few hazmat-carrying cars, as is expected to be done with spent nuclear fuel. Some trains may contain only a few hazmat-carrying cars among several other non-hazmat cars, and some may be large unit trains, carrying up to 120 hazmat-carrying cars on the same train, as is often done with crude oil shipments.

The first step in establishing the homogeneity assumption is to determine the expected number of cars that derail should an accident occur. Based on Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation by Liu, Saat, and Barkan [13], the median number of railroad cars that derail per derailment event is five. It is thus assumed that for each incident, five consecutive cars in the train derail.

The second step in homogeneity establishment is to determine the expected number of hazmat-carrying cars on the train experiencing an accident. To obtain this value, the FRA Office of Safety
Analysis database will again be used. From the database, data was gathered from the most recent 36 months available (October, 2015 to November, 2012), detailing the total number of cars involved in accidents as well as the number of hazmat-carrying cars involved in those accidents. With this data [1], a simple ratio can be made to determine the probability that a given car is carrying hazmat on an accident-involved train. The ratio is as follows:

\[
P_{HazmatCar} = \frac{\text{number of cars carrying hazmat}}{\text{total number of cars}} = \frac{24561}{110943} = 0.2214
\]

(7)

In other words, this ratio assigns the value 22.14% to the probability that any given car on a train is carrying hazardous material, given already that 1) the train has experienced an accident/derailment and 2) there is at least one car on the train carrying hazardous material.

Thus far, it is assumed that on a hypothetical homogeneous train for which an accident occurs, five cars are involved in the accident and 22.14% of the cars on the train contain hazardous material. With this information, the probability that a hazmat-carrying car is involved in the accident can be found. One final assumption is needed in this step, which is that the hazmat-containing cars are randomly distributed among the train. In reality, hazmat-carrying cars are typically grouped together, but data for these car distributions is not readily available or practical to use in this analysis, because point of derailment is also unknown in this scope.

The probability \( p \) that a given car contains hazmat is 22.14%, and the probability \( q \) that it does not contain hazmat is the compliment of this, or 77.86%. The probability of having \( k \) cars with hazmat out of the five that derail can be calculated with the following binomial equation:

\[
p_k = \binom{n}{k} p^k q^{n-k}
\]

(8)

\[
q = 1 - p
\]

where \( n \) is five. The binomial distribution is shown in the Fig. 2.3 below.
The probabilities of each of the six values of $k$ are provided in Table 2.3.

### Table 2.3: Probability of $k$ derailed hazmat cars versus $k$, using binomial equation

<table>
<thead>
<tr>
<th>$k$ (number of hazmat cars derailed)</th>
<th>$p_k$ (probability of $k$ derailed hazmat cars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2861</td>
</tr>
<tr>
<td>1</td>
<td>0.4068</td>
</tr>
<tr>
<td>2</td>
<td>0.2314</td>
</tr>
<tr>
<td>3</td>
<td>0.0658</td>
</tr>
<tr>
<td>4</td>
<td>0.0094</td>
</tr>
<tr>
<td>5</td>
<td>0.0005</td>
</tr>
<tr>
<td>$&gt;0$</td>
<td>0.7139</td>
</tr>
</tbody>
</table>

This shows that if five cars derail, the probability that zero of them contain hazmat is 28.61%. This is the definition of a success of this top event. The probability that at least one of them contains hazmat is 71.39%, which defines failure of this top event. The most likely number of hazmat cars to derail is one, at 40.68%.
If this top event occurs, the event tree proceeds directly to the minor failure end state. If this top event fails ($k>0$), then at least one hazmat car has derailed, and the event tree proceeds to the third top event.

### 2.6 Top Event: Hazardous Material Release

The third top event to consider is the failure of the container of the hazardous material. Container failure leads to material release, which is the precedent for the major failure end state. There are two ways to represent this probability. The first is through use of a fault tree. A fault tree is another PRA tool; it is used to quantify the probability of a top event based on the probabilities of multiple basic events. In the case of container failure, the total probability that the container fails is equal to the sum of the probabilities of its failure modes. The fault tree method ties in well with the hypothetical accident condition tests required by the Code of Federal Regulations for hazardous material containers. Although these test requirements differ based on the contents of the container, (which will be discussed thoroughly in a Chapter 4), the failure modes for each container type are the same. A fault tree for this top event would look like the following in Fig. 2.4:

![Fault Tree Diagram]

**Figure 2.4:** Theoretical fault tree for Top Event 3 failure featuring hypothetical accident conditions as failure modes
Any of the four hypothetical accident condition failure modes in the fault tree (drop, puncture, thermal, immersion) occurring beyond the container limits would lead to container failure. The probabilities of each of these modes vary depending on environmental factors, such as the existence of nearby thermal or immersion sources. For example, probability of immersion failure when moving near a river or over a bridge is larger than immersion failure probability during transportation through a desert. Similarly, probability of thermal failure is larger when driving with or alongside fuel sources. Probabilities also vary based upon the specifications of the container, the hazardous material within, and the method by which it is attached to the train, in addition to several other parameters. Probability of container failure, however, can be calculated by the following equation, after probabilities of each basic event are determined:

\[
P(\text{container failure}) = P(\text{drop}) + P(\text{puncture}) + P(\text{thermal}) + P(\text{immersion})
\]  

(9)

This is an approximate formula, adequate when the probabilities on the right hand side of the equation are sufficiently small. Determining the values for each of these individual probabilities is beyond the scope of this thesis, but this equation will be used to determine how regulations qualitatively affect risk of container failure.

The probability of Top Event 3 can also be found by using a relative frequency from FRA data. Instead of using a theoretical approach using a fault tree, past data for hazmat releases can be used to approximate a probability of release for future accidents. The source of data (FRA Office of Safety Analysis), from which Top Event 2 probability was obtained, also provided information on the number of hazmat releases involved in the cars that derailed. It is from this data that the probability for failure of top event three can be approximated.

The probability in question can be represented with the following binomial equation:

\[
P(\text{Hazmat release|train derail } \cap \text{ hazmat derail}) = \binom{k}{z} a^z (1 - a)^{k-z}
\]  

(10)

- \(k\): number of hazmat cars derailed
- \(z\): number of hazmat cars releasing contents
- \(a\): probability of any given car releasing, given that it has derailed

The value of \(a\) can be determined using by obtaining a ratio of number of hazmat cars released to the total number of hazmat cars damaged or derailed using FRA data [1]. This ratio is the probability of a single car releasing contents given that it has derailed:
The value of $k$ ranges from zero to five, as determined in the previous section. However, the probability of this top event assumes that at least one hazmat car has derailed, and thus $k$ cannot be zero for this top event. Table 2.4 shows the normalized probabilities of $k$, given $k>0$.

**Table 2.4: Normalized probabilities of $p_k$, given $k>0$**

<table>
<thead>
<tr>
<th>$k$ (number of hazmat cars derailed)</th>
<th>$p_k$ (probability of $k$ derailed hazmat cars</th>
<th>$k&gt;0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5698</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.3241</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.0922</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.0132</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.0007</td>
<td></td>
</tr>
</tbody>
</table>

The median value of $k$ is 1, while the mean is 1.55. The probabilities are skewed towards smaller values of $k$, which means the median is a better estimate of the data. The value of $z$ can range from zero to $k$. Success for top event three is defined as zero containers releasing material ($z = 0$). Failure is defined as the compliment of this probability ($z > 0$). Table 2.5 reports the success and failure probabilities for each value of $k$.

**Table 2.5: Success and failure probabilities for top event three for each $k$ value**

<table>
<thead>
<tr>
<th>$k$ (number of hazmat cars derailed)</th>
<th>$P_3$ (success) $z = 0$</th>
<th>$P_3$ (failure) $z &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9239</td>
<td>0.0761</td>
</tr>
<tr>
<td>2</td>
<td>0.8536</td>
<td>0.1464</td>
</tr>
<tr>
<td>3</td>
<td>0.7886</td>
<td>0.2114</td>
</tr>
<tr>
<td>4</td>
<td>0.7286</td>
<td>0.2714</td>
</tr>
<tr>
<td>5</td>
<td>0.6732</td>
<td>0.3268</td>
</tr>
</tbody>
</table>

Success of containment leads to a minor failure end state. Containment was not breached, and thus consequences are minimized. If containment failed, then there was a release of hazardous material to the environment, which is a major failure end state.
2.7 Probability and Risk Calculations

For completion, the probabilities of each end state will now be calculated based on the probabilities found in each of the top events. To estimate a monetary risk value, the average costs associated with each end state will then be included in the calculations. Success and failure probabilities are straightforward for top events one and two, but for the third, it is necessary to know the number of hazmat cars that derailed. The median value was 1 car and the mean was 1.55 cars, so for an estimate, it will be assumed that $k = 1$ hazmat car derailed per hazmat derailment for the calculations. Results will also be provided using the other values of $k$ for comparison.

The event tree in Fig. 2.5 is the same as that in Section 2.1 above, but with added values for each of the top event success and failure probabilities, IE frequency, and end state monetary costs.

![Event Tree Diagram]

**Figure 2.5**: Hazardous material transportation by rail risk event tree with probability, frequency, and end state cost values

Table 2.6 below shows probability and frequency results for each end state.
Table 2.6: Final event tree end state calculations, with probability, frequency, and risk due to each end state

<table>
<thead>
<tr>
<th>End State</th>
<th>Probability</th>
<th>Calculated Frequency (yr(^{-1}))</th>
<th>Risk per trip ($)</th>
<th>Risk per year (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>0.9969</td>
<td>174458</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Minor Failure</td>
<td>2.932*10(^{-3})</td>
<td>513</td>
<td>472</td>
<td>82.59</td>
</tr>
<tr>
<td>Major Failure</td>
<td>1.684*10(^{-4})</td>
<td>29</td>
<td>248</td>
<td>42.83</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>175,000</td>
<td>720</td>
<td>125.42</td>
</tr>
</tbody>
</table>

Risk of minor failure is nearly double the risk of major failure, while the probability of minor failure is approximately 17 times that of major failure, assuming \(k=1\). Comparing the table above to the data found in the end states section, the expected frequencies of minor and major failure closely resemble the data from 2012 to 2014, which is expected because most of the probabilities in the event tree are derived from this data set.

Table 2.7 provides risks and frequencies for all values of \(k\) for comparison. Major failure probability and risk are proportional to the number of hazmat cars expected to derail.

Table 2.7: End state risks and frequencies for all assumed values of \(k\)

<table>
<thead>
<tr>
<th>(k) value</th>
<th>Minor Failure Frequency (yr(^{-1}))</th>
<th>Major Failure Frequency (yr(^{-1}))</th>
<th>Risk per Trip ($)</th>
<th>Risk per year (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>513</td>
<td>29</td>
<td>720</td>
<td>125.42</td>
</tr>
<tr>
<td>2</td>
<td>486</td>
<td>57</td>
<td>928</td>
<td>162.44</td>
</tr>
<tr>
<td>3</td>
<td>461</td>
<td>82</td>
<td>1,116</td>
<td>195.34</td>
</tr>
<tr>
<td>4</td>
<td>437</td>
<td>105</td>
<td>1,288</td>
<td>225.44</td>
</tr>
<tr>
<td>5</td>
<td>416</td>
<td>127</td>
<td>1,455</td>
<td>254.56</td>
</tr>
</tbody>
</table>

Note that all risk values account only for risk due to equipment and track damage, as reported in the FRA database. These values do not include risk associated with costs resulting from environmental damage, down time, clean up, or other large-scale operations such as evacuation or decontamination. Sources of risk vary based on the type of hazardous material being transported, since different hazardous materials have different environmental effects. These sources also vary based on location of shipment. For example, risk due to evacuation cost would be higher in an urban area than in a rural area.
2.8 Risk Importance Measures

One of the primary benefits of performing the final risk calculations is to determine which parts of the event sequence have the greatest effect on the overall risk values. The events with the highest relative risk importance can then be identified and targeted for improvement. Risk importance measures provide a path to the most efficient use of resources for risk reduction.

One way to reduce risk is to implement rules and regulations regarding operation and safety standards for the equipment used in hazardous material transportation. Risk reduction worth (RRW), or similarly, Fussell-Vesely importance (FV), can be used to determine which segment of operation needs to be focused on with stricter standards, should there be a call for regulation increase, to have the maximum effect of reducing risk. The equations for RRW and FV are below.

$$RRW = \frac{R(base)}{R(p_x=0)} = \frac{1}{1-FV}, \quad FV = \frac{R(base) - R(p_x=0)}{R(base)}$$  \hspace{1cm} (12)

- $R(base)$: present risk level
- $R(p_x=0)$: risk with top event $x$ with probability zero

For this event tree, however, RRW and FV are not very useful tools for determining effects of top events for the major failure end state. This is because the reduction of any of the top event probabilities to zero will cause a major failure probability of zero. Because all three events must fail for the major failure end state, $R(p_x=0)$ equals zero for all events, and all events will have the same FV of 1. The minor failure top event has a similar issue, where FV of top event one is 1, and FV for all other top events are equal.

Conversely, certain risk importance measures can be used to determine maximum risk achievement to determine which factors would increase overall risk the most. Because of the nature of this event tree, risk achievement will be the most useful tool in determining the risk-related value of each top event. This is because setting the risk achievement does not automatically disallow any failure end states (but rather the success end state). The measurement term used here is risk achievement worth (RAW), and is defined by the following equation.

$$RAW = \frac{R(p_x=1)}{R(base)}$$  \hspace{1cm} (13)

- $R(p_x=1)$: risk with top event $x$ with probability one
By assuming a top event will fail with probability 1, it is possible to determine which top event has the greatest effect on causing the failure end states. Rather than determining which top event probability should be reduced, as with RRW or FV, it is instead determined which top event probability should not be increased. These are similar approaches, and RAW provides better data in this case. Table 2.8 shows the RAW for each top event for the minor and major failure end states.

**Table 2.8: Risk achievement worth for failure end states**

<table>
<thead>
<tr>
<th>Top Event</th>
<th>Minor Failure RAW</th>
<th>Major Failure RAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>322.5806</td>
<td>322.5806</td>
</tr>
<tr>
<td>2</td>
<td>0.9770</td>
<td>1.4008</td>
</tr>
<tr>
<td>3</td>
<td>0.3025</td>
<td>13.1406</td>
</tr>
</tbody>
</table>

Top event 1 (Derailment/Operation) has the greatest RAW for both failure levels, ranging from one to three orders of magnitude greater than the other RAW values. This is logical based on the structure of the event tree, where derailment must occur for either failure mode to occur.

For the minor failure end state, Top Event 2 has a larger RAW than Top Event 3. This is because of the high likelihood of Top Event 3 being a success based on its baseline probability. Guaranteeing Top Event 2 failure will most likely lead to a Top Event 3 success state, leading to the minor failure end state.

The major failure end state has a larger RAW for Top Event 3 than Top Event 2. This is expected, because Top Event 2 already has a high probability of failure originally, so guaranteeing Top Event 3 failure, where baseline probability is much lower, has a much larger effect on major failure probability.
2.9 Takeaways from the PRA and Risk Importance Measures

A takeaway from this risk importance measurement is that the derailment/operation top event has by far the greatest impact on the frequency of both minor and major failures, by default, since derailment/operational failure is a precursor to any failure end state. Derailment/operation also has the same RAW for both failure levels. Based on the risk importance measure, it is seen that the best way to reduce the probability of shipment failure is to reduce the probability of derailment/operational failure. This is a difficult task, however, since derailment/operation already has a very low failure rate, and the law of diminishing returns suggests that incrementally lowering an already low failure rate can have a very high cost.

By assuming derailment has happened, the next best way to reduce cost is to reduce the probability of major failure. If derailment/operational failure occurs, then there is definitely a failure end state, and minor failure is the cheaper one. The RAW results indicate that Top Event 3, hazardous material release, has the greatest effect on major failure probability. Therefore, to reduce major failure probability, the best approach would be to reduce probability of hazmat release; this is done by having stronger, more durable containers of the material on the trains, and will be discussed greatly in Section 3 of this report.

The final way to reduce major failure probability is to reduce probability of Top Event 2, which is to reduce the probability that a hazmat-carrying car derailed. Potential solutions will also be discussed in Chapter 5, but based on the binomial used to calculate this probability, the most logical approach would be to reduce the number of hazmat-carrying cars in general. This is unlikely to happen, since successful hazmat car shipments are associated with large profits, and would not be a popular or plausible approach.

Several assumptions were made in this analysis, including homogeneity and fixed values for top event failure probabilities instead of distributions. Therefore, there is some uncertainty associated with the final calculation results. These results are used for the purpose of relative magnitudes and references for later Chapters, rather than for a full risk assessment of this operation. For that, a more in-depth analysis would be required, as will be discussed in Section 5.4: Future work.
3. Risk Perception

The purpose of Chapter 3 is to bring attention to the several factors that lead to a difference between the risk as calculated in Chapter 2 and the risk as perceived by the public. These factors can apply to any source of risk, so this chapter applies and explains the factors in terms of the risk due to the transportation of hazardous materials. The factors will be used to differentiate between the public view of risk of hazmat transportation based on the type of material being transported, notably between Class 3 (flammable liquid) material such as crude oil, and Class 7 (radioactive) material such as spent nuclear fuel. The discussion of each perception factor will then reference back to the event tree in Chapter 2. These factors do not directly change the perception of the calculated risk, but rather certain values within the calculation. The change in the value perceptions then effectively changes the calculation results.

As a reminder, the top events of the event tree are as follows:

- Initiating event (IE) – hazardous material shipment
- Top event one (TE1) – derailment or operational failure
- Top event two (TE2) – presence of hazardous material among the derailed/failed cars
- Top event three (TE3) – release of hazardous materials
- End states – success: successful shipment; minor failure: failure without hazmat release; major failure: failure with hazmat release

Each factor analysis will end with a speculation on how the factor affects parametric quantities within the PRA. The event tree (Fig. 2.5) and the final risk probability/frequency table (Table 2.6) will be reproduced with added visuals to show which parts of the PRA are affected by each risk perception factor.

3.1 Factors Affecting Risk Perception

Four factors that affect risk perception will be analyzed in this chapter. The factors are natural versus industrial risks, chronic versus catastrophic risks, familiar versus unfamiliar risks, and risks managed by trustworthy versus untrustworthy sources. Those factors in consideration are the ones considered to have the greatest effect on hazardous material transportation specifically and also have an effect on some parameter within the PRA calculation or results. Each factor is also identified by the Department of Health and Welfare of the state of Idaho in a report titled *Perceived Versus Actual Risk* [14], as well
as by risk perception expert Dr. Peter Sandman, former Rutgers professor and founder of the Environmental Communication Research Program. [15]

3.2 Natural versus Industrial

A risk due to a natural process is perceived to be lower than one caused by an industrial process [14, 16]. The classic example of this risk perception disparity can be seen in the following scenario: radiation dose from naturally occurring radon can be seen as lower (less risky) than that received by residing near a nuclear power plant or other nuclear industries. In actuality, dose from naturally occurring radon is much greater, as seen in Fig. 3.1 below, produced by Lawrence Berkeley Lab. Fig. 3.1 is based on data that does not include a large recent increase in medical radiation exposures averaged over the U.S. population, nor does it correct for the portion of radon exposure that is anthropogenic due to living and working in enclosed structures near ground level; but it nevertheless suffices to illustrate the point that radiation exposure from nuclear fuel cycles is a very small component of other radiation exposures.

![Sources of Exposure](image)

**Figure 3.1: Sources of annual radiation dose equivalent: Largest – Natural radon; Smallest – Nuclear fuel cycle [17]**

The maximum dose equivalent rate for a container of radioactive material being transported is 200 mrem/hr at the surface of the container [18]. Near cask radiation dose in incident free conditions
is estimated to be 0.0004 mrem. [19]. This like takes into consideration some distance from the cask as well as a very short exposure time due to the cask moving at train speeds during shipment.

The natural versus industrial factor affects the event tree by varying the cost associated with the success end state. For the industrial risks, even the success end state has some associated cost; for the hazmat shipments, this cost is environmental, resulting from the feared radiation coming from the packaging. Even though this radiation is very small compared to other radiation exposures, it is perceived to be significant. There is no such cost associated with the natural risks. For example, the transportation of Class 3 material would have minimal perceived risk-based costs associated with a successful shipment compared to Class 7 transportation. Fig. 3.2 shows where the natural versus industrial factor affects the PRA.

<table>
<thead>
<tr>
<th>Perceived Type of Risk</th>
<th>Affected Factor</th>
<th>Perceived Effect on Factor</th>
<th>Perceived Effect on Total Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>Success Cost</td>
<td>Remains $0</td>
<td>None</td>
</tr>
<tr>
<td>Industrial</td>
<td>Success Cost</td>
<td>Becomes &gt;$0</td>
<td>Increased Total Risk Cost</td>
</tr>
</tbody>
</table>

**Figure 3.2: Effect of natural versus industrial risk perception factor on the PRA**

Associating a cost with the success end state has two effects. First, it greatly increases the perceived overall risk of operation, since the success state is the most frequent, and giving it a small cost has a large
total value. Second, it weakens the concept of a success end state, and essentially provides the idea that every shipment is a failure. This is very detrimental to the planning and operation of shipment of the industrially-perceived materials, since money is spent on reducing these success end state costs, even though those costs are negligible.

3.3 Chronic versus Catastrophic

Risks with large infrequent consequences (catastrophic) are perceived as riskier than those with smaller consequences with high frequency (chronic) [14, 16]. The typical example of this phenomenon is the perception of risk of flying in an airplane versus risk from driving in a car. While an airplane crash has a high cost of failure (catastrophic), it has a probability orders of magnitude less than that of a car accident, which has relatively low individual failure cost [20]. Multiplying the probability by the consequence yields the risk, and risk per mile of driving a car is much greater than that of flying.

The issue here is with the perception of frequency of catastrophic failures. Because the catastrophic failures are highly publicized through the media, the public perceives them to have a much larger frequency than they actually do. Associating a high cost event with a high frequency leads to a huge increase in perceived total risk. Similarly, the low profile failures, such as car accidents, are not as publicized, and the success state frequency for lesser consequence actions is so high that total risk is perceived as low. Even if chronic failures are publicly known to have larger frequency than catastrophic failures, the relative difference is not typically understood.

As calculated in Chapter 2, the minor failures contribute most to the total risk, due to their much higher frequency of occurrence. Although major failures have greater consequences per incident (~$1.477 million), minor failures contribute nearly double the risk to the total yearly risk value. There is a similar situation with chronic and catastrophic failures.

This consequence size factor has a parallel in the realm of shipment of different hazardous materials. Risk involving Class 7 material is historically associated with catastrophic consequences, notably due to the incidents at Chernobyl, Fukushima, Hiroshima and Nagasaki. All accidents or destructive uses of Class 7 material have had large negative consequences and are highly publicized for extended periods of time, so now any interaction or involvement with Class 7 material is perceived to have a high failure frequency. On the contrary, Class 3 material accidents, such as gas explosions or oil fires, are associated with a lower relative major failure frequency, and thus lower contribution to total risk from major failure. Inclusion of the consequences of use of nuclear weapons in the above list can be significant, particularly if one compares the casualties from a1984 methyl isocyanate release in India in
the chemical hazards. This is because perceptions of the consequences of possible future nuclear explosions far outweigh those from chemical hazards and thus by association may considerably influence risk perceptions concerning radioactive materials more generally.

The effect on total risk can be explained with use of the event tree from Chapter 2. For catastrophic failure, the frequency of incident is perceived to be higher than is calculated by several orders of magnitude. This increases the total perceived risk over all end states by a large amount, even with the low relative frequency of major failure, particularly for Class 7 material. For the chronic failures, such as release of Class 3 material, the major failure end state has a higher probability of occurrence but a lower cost per incident. As will be discussed in Chapter 4, containers of Class 7 material have a much lower probability of release than containers of Class 3. Fig. 3.3 shows where the chronic versus catastrophic factor affects the PRA.
<table>
<thead>
<tr>
<th>Perceived Type of Risk</th>
<th>Affected Factor</th>
<th>Perceived Effect on Factor</th>
<th>Perceived Effect on Total Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chronic</td>
<td>Major Failure</td>
<td>Decreases or remains unchanged</td>
<td>Decrease or unchanged</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Major Failure</td>
<td>Increases significantly</td>
<td>Increased Total Risk Cost</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3: Effect of chronic versus catastrophic risk perception factor on the PRA

3.4 Familiar versus Unfamiliar

Risk due to causes familiar to the subject appears lower than risks due to unfamiliar causes [14, 16]. Transportation of hazardous material, and hazardous materials themselves, provide an excellent example of this risk perception phenomenon. Hazardous material classes such as flammable gas and flammable liquids feel more familiar to the public than radioactive material. Many deal with flammable gases and liquids in their everyday lives in the form of gas stoves and automobile gasoline, while very few manage radioactive material. Thus, management of familiar hazardous materials is perceived to have a lower risk than management of radioactive materials.
This perception phenomenon is explained by a feeling of understanding of the failure states for familiar materials, and by a lack of understanding for failure states of the unfamiliar materials. An unfamiliarity with transportation of some material drives up the perceived cost of the failure end states, particularly the major failure end state as defined by this thesis. Because of past large scale radioactive release events, such as nuclear plant meltdowns, any release is perceived to have the potential of causing a similar level of damage [21]. Therefore, perceived cost of major failure for a radioactive material shipment is closer to the levels of the past-publicized events, even though failure in this case would be much more manageable.

Contrarily, familiarity with materials can drive down the perceived cost of major failure from what it is calculated to be. Familiar materials are perceived as more manageable, and they sometimes may be, however major failure can still incur very large cost. Fig. 3.4 shows where the familiar versus unfamiliar factor affects the PRA.
The difference between the familiar versus unfamiliar factor and the natural versus industrial factor is the following: the familiar/unfamiliar factor affects the perceived failure costs, while the natural/industrial factor affects the perceived success costs. Unfamiliar materials have a large perceived major failure cost due to its effects and properties being poorly understood. An industrial material, however, is often misunderstood to cause problems even when no failure occurs. Note that it is possible to have multiple factors affecting the same scenario, as is the case with Class 7 material.

### 3.5 Trustworthy versus Untrustworthy

A risk controlled by an untrustworthy source is perceived to be greater than the same risk controlled by a trustworthy source [14, 16]. The best example of this is in the nuclear power and radioactive waste management industry, particularly the experiences at Yucca Mountain in the United States versus those
of Osthammar in Sweden. The Yucca Mountain Project has been unsuccessful thus far. Part of the cause is resulting from the risk to the State of Nevada being involuntary, and part of the effect has led to a lack of trust in the U.S. Department of Energy (DOE) to manage radioactive waste. One consultant for Lincoln County, Nevada, Mike Baughman, stated for the Las Vegas Review Journal that “the political approach to resolving this very technical issue results in a significant erosion of trust,” [22] and a report for the State of Nevada Agency for Nuclear Projects states that their task is to research “the DOE's track record in nuclear materials handling and trustworthiness.” [23] Trustworthiness is acknowledged to be a factor in the decision-making process for the Yucca mountain project, and this is so because it affects the perception of the magnitude of risk involved in allowing the project to proceed. The trustworthiness factor is similar for all risk-based analyses, such as the transportation of hazardous material. Because DOE is also responsible for this process, the reputation of trustworthiness (or lack thereof) of DOE stemming from the Yucca Mountain Project and earlier Cold War era management of radioactive materials has an effect on its trustworthiness for transporting radioactive material.

Trustworthiness affects the PRA through the event tree by changing the perception of success and failure probabilities. A trustworthy source will have a higher perceived probability of success (and lower probability of failure). This drives down the perceived risk by reducing the frequency of failure states, and thus the cost contribution of the failure states to the total risk. Contrarily, an untrustworthy source will have a higher perceived probability of failure (and lower probability of success). This has the effect of increasing total risk by increasing the failure state frequency and cost contribution to the total risk. Fig. 2.5 displays where the trustworthy versus untrustworthy factor affects the PRA.
<table>
<thead>
<tr>
<th>Perceived Type of Risk</th>
<th>Affected Factor</th>
<th>Perceived Effect on Factor</th>
<th>Perceived Effect on Total Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trustworthy</strong></td>
<td>Success/Failure Probability</td>
<td>Decreases</td>
<td>Decreased Total Risk Cost</td>
</tr>
<tr>
<td><strong>Untrustworthy</strong></td>
<td>Success/Failure Probability</td>
<td>Increases</td>
<td>Increased Total Risk Cost</td>
</tr>
</tbody>
</table>

**Figure 3.5: Effect of trustworthy versus untrustworthy risk perception factor on the PRA**

To decrease the perceived risk, a good strategy is openness and cooperation. This strategy both makes the risk a voluntary one, thereby establishing the IE frequency, and builds trust, thereby increasing the perceived success probability. Trustworthiness is a large part of why the approach for building an SNF repository in Sweden was successful when compared to the attempt made by the United States in Nevada.

### 3.6 Risk Perception Summary and Future Work

Bringing together risk as perceived by the public and risk as calculated by experts is a vital step in the efficient appropriation of efforts for reducing risk. For each of the four factors discussed in Chapter 3, there is some cause for transportation of Class 7 material to have a higher perceived risk than calculated.
High perceived risk has the effect of potential of very expensive regulation or altogether inability to perform the transportation operation out of fear of that risk. For maximum efficiency of operation, these factors should be addressed. For most of the factors, cooperation and transparency may have some influence, but overlap of concerns about nuclear weapons and non-weapons effects may be only partially amenable to such approaches. Discrepancies between risk as perceived and as calculated PRA differently weighted with respect to risk assessment of the transportation procedure and hazard, lead to an increased failure probability and overall monetary and environmental risk, as perceived by non-experts. Risk from Class 7 shipments is likely perceived as much higher than risk due to Class 3 shipments due to these factors.

Each of the factors can be addressed to reduce the perceived risk. A more in-depth analysis on which factor quantitatively affects overall risk the most would have to be performed in order to best allocate resources for education or participation in decision making, if only one or two could be addressed at a time. Chapter 5 of this thesis will present some approaches for addressing each of these factors.
4. Risk Reduction by Regulation

The purpose of this chapter is to outline the rules and regulations governing train operation, particularly those for trains carrying hazardous material. Regulations are set in place in order to reduce the risk of railroad transportation. This chapter will outline several regulations that have an effect on the PRA performed in Chapter 2, and will explain the parts of the PRA affected by each regulation. This chapter is divided into two sections; the first discusses regulations that affect standard operation of the train, and the second discusses regulations regarding hypothetical accident conditions. Each section has a unique effect on the PRA.

Some work shown in this chapter was performed by the thesis author during an internship at Oak Ridge National Lab. [52]

4.1 Accident Prevention and Mitigation Parameters

This section provides an overview of some of the regulations that affect standard train operation and setup. Generally, these regulations have the purpose of reducing probability of TE1 (derailment/operational failure) and TE2 (hazmat car involvement) from the PRA in Chapter 2. The risk importance measures analysis indicated that TE1 had the greatest effect on each of the failure probabilities. Therefore, the regulations affecting TE1 are among the most important in reducing total transportation risk.

The following regulations are set in place in an attempt to reduce probabilities of Top Events 1 and 2. The event tree structure is set up so that both of these events must fail in order for major failure to occur. It is therefore beneficial to attempt to reduce the likelihood of each. Likelihood reduction must be done while still maintaining some efficiency in the transportation network; for example, speed limits can be set very low to avoid accidents, but this would cause a large operation cost. This section aims to demonstrate the differences in railroad operation standards among cargo of different material classifications, primarily for crude oil (which is in Class 3) and radioactive material (which is in Class 7), that will alter either the likelihood or the consequence of an accident should one occur. Many operational parameters are shared among rail transport of materials of all classes, but some differ from class to class. The parameters that both differ and have a significant effect on accident cause/consequence are the ones that will be discussed. They are the following: train speed, train size (weight and length), and brake systems.
4.1.1 Speed

The first way to control potential accident occurrence or consequence is by regulating train speed. Speed is an important factor in train operations because of the effect it has on many of the other regulated parameters; it affects braking systems, routing, and hypothetical accident conditions. Trains are also limited to a certain speed when performing a turn based on track curve radius and grade (incline).

Train speed has an effect on all three Top Event probabilities within the event tree in Chapter 2, as shown in Fig. 4.1. It affects the probability of accident or derailment based on stopping distance for obstructions and other abilities for navigating obstacles, as will be discussed later in this section. Train speed has an effect on TE2 probability as well. Based on Liu, Barkan and Saat, “Analysis of Derailments by Accident Cause”, the predicted number of train cars derailing can be obtained as a function of train speed, using the following equation [24]:

\[
N_c = A_c \cdot S^{B_c}
\]  

- \(N_c\): number of cars derailed
- \(A_c\): given constant (average value of 1.852)
- \(S\): Train speed
- \(B_c\): Given constant (average value of 0.486)

Recall that the probability of TE2 is found using a binomial expression with parameter \(n\) representing the number of derailed cars, which can be found in this case using \(N_c\). As \(n\) increases, TE2 failure probability increases.

Train speed also has an effect on TE3 probability. From “A Risk Assessment Study of the Transportation of Hazardous Materials over the U.S. Railroads” by Raj, the predicted probability of hazardous material release given derailment of a hazmat-carrying car can be found as a function of train speed using the following equation:

\[
q(U) = a \cdot U^{0.5}
\]  

- \(q(U)\): probability of release, in percent
- \(a\): constant obtained from data
- \(U\): train speed, in m.p.h. [25]
Figure 4.1: PRA parameters directly affected by train speed regulations

The standards for speed of Class 7 SNF/HLRW-carrying tank cars can be found in AAR Circular No. OT-55-N, which are the following:

Definition: A “Key Train” is any train with: …One or more car loads of Spent Nuclear Fuel (SNF), High Level Radioactive Waste (HLRW)…

Maximum speed -- "Key Train" - 50 MPH [26]

Speed limitations were placed on speed of Class 3 railcars in the recently passed legislation regarding speed in high threat urban areas (HTUA). (HTUAs are defined in 49 CFR 1580, in Section 3 and Appendix A.) The new regulation mandates the following:

All trains are limited to a maximum speed of 50 mph. The train is further limited to a maximum speed of 40 mph while that train travels within the limits of high-threat urban areas (HTUAs) as defined in §1580.3 of this title, unless all tank cars containing a Class 3 flammable liquid meet or exceed the DOT Specification 117 standards, the DOT Specification 117P performance standards, or the DOT Specification 117R retrofit standards provided in part 179, subpart D of this subchapter. [27]

The justification provided for this level of reduction is to decrease the kinetic energy of a train traveling through HTUAs. A 10 mph decrease in speed from 50 mph to 40 mph would decrease kinetic energy, defined by KE=0.5*m*v^2 where m is mass and v is velocity, by a factor of:
A speed decrease will also increase the likelihood of a train operator to apply brakes successfully and avoid a potential cause of danger should one present itself in front of the train. Braking distance is also dependent on speed based on the following equation:

\[
v^2 = v_0^2 + 2a\Delta x
\]  

(17)

- \(v\): final velocity
- \(v_0\): initial velocity
- \(a\): acceleration
- \(\Delta x\): stopping distance

For the case of a freight train needing to stop, final velocity is zero, \(v_0\) is either 50 mph or 40 mph, depending on the location, and acceleration is an assumed constant depending on the quality of the brakes and other operating conditions. To compare stopping distance for trains moving at 40 mph and 50 mph, the following ratio analysis can be used:

\[
\frac{\Delta x_{40\text{mph}}}{\Delta x_{50\text{mph}}} = \frac{2a \cdot 40^2}{2a \cdot 50^2} = \frac{40^2}{50^2} = 64\%
\]  

(18)

\[
\text{Reduction in } \Delta x = 1 - \frac{\Delta x_{40\text{mph}}}{\Delta x_{50\text{mph}}} = 36\%
\]

The stopping distance is also reduced by 36% because of the speed limitation. Decreasing speed in critical areas can reduce probability and consequence of an accident in multiple ways.

The speed reduction was not made greater as a result of the safety concerns caused by increased rail traffic and congestion in HTUAs. HHFTs may be required to reduce speed in an HTUA, but other trains would not necessarily need to, and thus train dispatching and management and use of track sidings would increase, thereby increasing risk of collisions and cost of commerce due to time delays. [9]

The cost and benefit of this speed regulation change was estimated in 80 FR 26643-26750 based on a 20 year total and at a 7% discount rate. Cost was estimated at $180 million, while benefits range from $56 – 242 million. Costs are based on the time lost by traveling through HTUAs at slower speeds,
while benefits are calculated based on the avoidance of low to high consequence incidents, thereby providing a range of potential monetary benefit.

Based on speed regulations, Class 3 and Class 7 had been regulated equivalently, but after 80 FR 26643-26750, certain Class 3 trains, notably those typical of carrying crude oil, now have increased regulations because of the speed restriction in HTUAs. The overall magnitude of this difference in regulation depends upon the relative frequency at which SNF/HLRW carrying railcars travel through HTUAs when compared with HHFTs.

4.1.2 Train Size

The second parameter potentially affecting incident likelihood or consequences is train size. This section will be divided into regulations and effects of both train length and car weight. Generally, the larger a train is, the more mass it has, thereby increasing its kinetic energy and severity of accident should one occur. Long trains also take longer so stop due to communication from car to car when brakes are applied. If a defect on a train track exists, a long train will inherently take a longer time to bypass the defect, thereby increasing the likelihood of the defect causing an event. Weight of individual train cars is also considered, since weight increase leads to an increase in force required to flip the train on its side or raise it off the track, which are the general processes by which derailment occurs. This section will compare regulations regarding size parameters where applicable, as well as compare typical train dimensions, for Class 3 and Class 7 (HLRM) material trains.

4.1.2.1 Train Length

A train carrying HLRM can be one of three types: regular trains, key trains, or dedicated trains. A regular train operates under standard regulations, including those that apply for the various hazardous material classifications that are on the train. Regular trains can be any length and have any combination of cargo classifications. Key trains are similar to regular trains but operate under additional restrictions that improve safety by altering security, operation, and routing procedures. Dedicated trains are specifically constructed to transport SNF/HLRW by providing specially built heavy-load flatcars and buffer cars. SNF/HLRW is the only cargo on a train dedicated to it. Dedicated trains also operate under increased restriction to decrease risk [19].

Although the use of dedicated trains requires increases in regulatory restriction, economic and safety benefits arise from using shorter dedicated trains. The shorter dedicated trains are also able to reach their destinations more quickly since all of the cargo is destined for a single location, which also provides
greater predictability in train movement and location along the route. The use of dedicated trains allows for a smaller train fleet, since there is minimal down time associated with dedicated train cars traveling longer routes to accommodate other cargo destinations. Dedicated trains are also able to incorporate the optimal configurations of flatcars, buffer cars, and locomotives to decrease risk during transport. According to an FRA Report to Congress from 2005 in support of the use of dedicated trains for SNF/HLRW rail transport, safety benefits also arise from dedicated train usage. “Non-incident risk from the entire future shipping campaign is estimated to be on the order of approximately one (1) latent cancer fatality (LCF) for every 40,000 shipments in non-dedicated trains and approximately one (1) LCF for every 50,000 shipments in dedicated trains.” [19] The DOE also required the use of dedicated trains for SNF/HLRW shipments to the Yucca Mountain facility when the project was active. [28] Though this requirement may not yet officially apply for SNF/HLRW transport to a future repository site, it will be assumed that dedicated trains will be the type in use for the purpose of comparison with typical Class 3 carrying trains.

A dedicated train for SNF/HLRW transport is constructed in a fashion similar to that shown in the Fig. 4.2. Locomotive car(s) drive the train, two buffer cars surround the cask cars, and an escort car trails at the end. Though there is no limitation to the actual length of the train, there is a limitation on the amount of radioactivity that can be transported at once which can be found in 49 CFR 174.700 (b): “The number of packages of Class 7 (radioactive) materials that may be transported by rail car or stored at any single location is limited to a total transport index and a total criticality safety index (as defined in §173.403 of this subchapter) of not more than 50 each. [29]” Therefore the number of cars with casks on them is limited by the amount and composition of used fuel within. For this discussion, assume a train with a range of three to eight cask cars.
There is no regulatory train length limit for trains carrying Class 3 material, but rather a mechanical limit of the locomotives and the couplers holding the train together. Typical unit trains, or trains carrying only one type of material, for crude oil are within the range of 70-120 tank cars [31]. At about 54 feet of length per car [32], this can lead to train lengths of 3780 to 6480 feet, not including the lengths of the locomotives and buffer cars. Trains of this length, which are significantly longer than dedicated trains carrying Class 7 SNF/HLRW, are more likely to derail.

In the case of a damaged length of track, it is possible for a train to navigate it without derailing. This becomes less and less likely as more of the train passes it, both based on a constant probability of a given car derailing at that point, and based on the increase of damage to the track as a cyclical load is placed on it by the passing train. Take as an example the derailment that occurred in Cherry Valley, Illinois on 19 June 2009, where there was a washed out length of track that derailed part of a train carrying 114 tank cars of Class 3 material. The conductor was unaware of the track wash out (track flooding), and the train proceeded over the endangering length of track. The train traversed the hazardous track, and after two locomotives and 56 train cars had already passed the washed out zone, the following 19 cars derailed. According to the accident report, the washout, originally 17 feet long, likely widened due to the passage of the train. It then failed at the 57th car due to unsupported track after widening of the washout [33]. Longer trains both take longer to pass a damaged length of track, and cause that length

Figure 4.2: Typical dedicated SNF/HLRW transportation train consist [30]
of track to lessen its condition and ability to support the rest of the train. A short train, such as the dedicated trains used to transport SNF/HLRW that are 8-13 cars long, would potentially be able to traverse the washout based on the number of cars that were able to pass on the Class 3 train. The 8-13 cars would likely have caused less damage to the track than the 56 tank cars that passed on the long train.

Although shorter trains require more trips across a given amount of track to transport the same amount of cargo, this analysis assumes that track damage would be discovered and reported by a train traversing the damage, and would be repaired by the next trip.

Train length affects the probabilities of failure for Top Events 1 and 2. It affects TE1, derailment and operational failure, based on the brief analysis above. It also affects TE2 probability by limiting the number of cars that could potentially derail. A shorter train, such as a SNF/HLRW unit train, is far less likely to have several cars derail than a 120-car-long Class 3 material unit train. Thus, there is a smaller failure probability for TE2 as \( n \) decreases. Lastly, train length can also have an effect on IE frequency. If length is limited, more trips are required to transport the same amount of material. Higher IE frequency leads to higher frequency of all end states. Fig. 4.3 shows the parameters of the PRA affected by train length.

Figure 4.3: PRA parameters directly affected by train length regulation
4.1.2.2 Car Weight

SNF/HLRW cars weigh about 394,500 pounds; 250,000 pounds are from the cask and its contents, while the other 144,500 pounds are from the heavy-haul flat car. “Like other cars constructed to carry heavy loads, cask cars use additional axles and span bolsters to distribute the weight over a larger portion of the track structure.” [19] Class 3 tank cars, such as the DOT-111, are limited to 286,000 lbs. by regulation. [9] The benefits of heavy cars are that they are more stable and require more torque to flip over or derail. The downsides include the placement of more stress on the track, which could cause problems if the track is damaged already, which is why the heavy cars have the additional axles and equipment for load distribution. Thus, car weight affects TE1 probability, but it is a function of multiple variables depending on the operation and track conditions.

4.1.3 Brake Systems

Brake systems are a major method by which to prevent or mitigate accident consequences. Brakes can either decrease the kinetic energy of a train before a collision or derailment, or they can stop the train in time to avoid an accident altogether. In general, train brakes are regulated by 49 CFR 232, and it to this extent that Class 7 material-carrying railcars are officially regulated. The AAR, however, requires the use of additional braking systems on railcars carrying HLRM, by requesting the use of Electronically Controlled Pneumatic (ECP) brakes on railcars in Standard S-2043. [34] The FRA supported this request in its 2005 Report to Congress. [19]

Brakes of Class 3 trains were formerly regulated solely by 49 CFR 232 until the Final Rule (80 FR 26643-26750) passed on 1 May 2015, which added regulation to the brake systems required by HHFTs. The regulation is split into five parts, the first three of which are as follows:

(i) Each rail carrier operating a high-hazard flammable train (as defined in §171.8 of this subchapter) operating at a speed in excess of 30 mph must ensure the train is equipped and operated with either a two-way end-of-train (EOT) device, as defined in 49 CFR 232.5, or a distributed power (DP) system, as defined in 49 CFR 229.5.

(ii) By January 1, 2021, each rail carrier operating a high-hazard flammable unit train (HHFUT) comprised of at least one tank car loaded with a Packing Group I material, at a speed exceeding 30 mph must ensure the train is equipped with ECP brakes that meet the requirements of 49 CFR part 232, subpart G, except for buffer cars, and must be operated in ECP brake mode as established in 49 CFR part 232, subpart G.

(iii) By May 1, 2023, each rail carrier operating a high-hazard flammable unit train (HHFUT) not described in paragraph (a)(3)(ii) of this section, at a speed exceeding 30 mph must ensure the train is equipped with ECP brakes that meet the requirements of 49 CFR part 232, subpart G, except for
buffer cars, and must be operated in ECP brake mode as established in 49 CFR part 232, subpart G. [9]

The final two Parts, not reproduced here, provide exceptions and alternative brake system approval processes. The first of these regulations, (i), requires the installation of two-way EOT or DP devices. The reason for this is the length of typical Class 3 unit trains. If the brakes needed to be applied in an emergency, it took too long for the cars in the rear to receive the braking signal, since it must travel through the train car by car starting at the front. This meant it took a long time for all brakes to be applied. The EOT and DP devices provide additional signals to the train so that all of the brakes may be fully activated sooner than if it was using the traditional systems. The delay is not as relevant in Class 7 HLRM dedicated trains since they are only up to 15 cars long, and the signal travel time is negligible compared to that of the Class 3 unit trains which can be up to 120 cars long.

The second and third of these regulations, (ii) and (iii), require the installation of ECP brakes by 2021 and 2023, respectively, on HHFUTs that travel in excess of 30 mph, which is a majority of them when considering typical operating conditions. ECP brakes are an upgrade to the traditional air braking technology which effectively allow all of the brakes on the train to be activated simultaneously, similar to the effect of the EOT and DP devices. This brings the level of restriction on brake systems of Class 3 trains beyond the Class 7 brake system restrictions imposed by AAR Standard S-2043, but not until 2021 at the latest. Note that this regulation only applies to HHFUTs, which are defined in the 80 FR 26643-26750 as “a train comprised of 70 or more loaded tank cars containing Class 3 flammable liquids traveling at greater than 30 mph.” [9]

Brake system quality primarily affects TE1 of the event tree. Better brakes decrease the probability of an accident or derailment. The other top events are not directly affected, but can be affected indirectly through the effects brake systems have on train speed.
4.2 Hypothetical Accident Conditions

Hypothetical accident condition regulations work under the assumption that Top Events 1 and 2 fail, and they determine how well prepared each type of rail transport car needs to be to withstand the stresses expected during an accident. There are four tests that each rail container can be subjected to by regulation. The first is a drop test, simulating the railcar or container falling some distance onto a surface. The second is a puncture test, which involves applying a concentrated force to the container. The third is a thermal test, which involves subjecting the container to a pool fire and/or a torch fire for the required amount of time. The fourth test is an immersion test, which involves placing the container underwater and checking for breaches in containment.

Class 3 and Class 7 material containers are subject to different regulations of hypothetical accident scenario testing. Class 7 HLRM containers are subject to all four types of testing, and in sequence, meaning the same cask must pass all four in the given order to be certified for operation. Class 3 containers, such as the DOT-111, are subject to only the puncture and thermal tests. This section outlines these tests and provides analysis on the differences in requirements that each must pass by regulation.

Each of these tests affects the failure probability of TE3 (material release) of the Chapter 2 PRA. As stated in Chapter 2, TE3 failure probability can also be represented by a fault tree, with basic events representing each of the four failure modes addressed by the hypothetical accident condition regulatory tests. The sum of the failure probabilities for each of these basic events is equal to the total theoretical Top Event 3 failure probability. Thus, increasing regulatory requirement for these conditions leads to a decreased failure probability. The primary areas of effect in regards to the PRA are shown in Fig. 4.4.
4.2.1 Drop Test

Class 7 HLRM containers are subject to a drop test as per 10 CFR 71.73, which states that the container must undergo “A free drop of the specimen through a distance of 9 m (30 ft.) onto a flat, essentially unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected.” [35] In the case of the free drop, the orientation that would cause the most damage is generally regarded as the following in Fig. 4.5:
Based on the following kinetics equation, in which $g$ is acceleration due to gravity and $h$ is height of the container before the drop, the speed of the cask upon impact is approximately 13 meters per second, or 30 miles per hour. This can also simulate a 30 mph impact as part of a train system. The drop test is the first of four required of a SNF/HLRW container. It is not required for a Class 3 container.

$$v = \sqrt{2gh} = 13.2 \text{m/s} = 29.7 \text{ mph}$$ \hspace{1cm} (19)

### 4.2.2 Puncture Test

The first test common to containers of both material classes is the puncture test. The puncture test investigates the ability of the packaging container to withstand a concentrated force in a hypothetical accident scenario. Puncture test procedures for each container type vary but have a similar concept: application of a large force over a small area at the weakest points of the container. For the Class 7 container, this involves dropping it onto an upright metal rod, while for the Class 3 HHFT container, it involves hitting the container from the side with a ram.

The full puncture test requirements for the Class 7 container can be found in 10 CFR 71, and are reproduced below.
A free drop of the specimen through a distance of 1 m (40 in) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15 cm (6 in) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6 mm (0.25 in), and of a length as to cause maximum damage to the package, but not less than 20 cm (8 in) long. The long axis of the bar must be vertical. [35]

In the case of the puncture test, the orientation that causes the most damage is considered to be perpendicular to the side of the cask, as shown in Fig. 4.6 below.

Figure 4.6: Puncture test orientation for maximum damage for Class 7 SNF/HLRW containers

The setup is different for a Class 3 container. The puncture test is performed by setting the tank car up in a stationary position and then striking it with a ram car. The full requirements can be found in 80 FR 26643-26750 for the side-on puncture test. Prior to that Rule, only a head-on puncture was required, which was not necessarily the orientation that would inflict the maximum damage, as is required in the SNF/HLRW container regulations. The new regulation for the HHFT tank car is as follows, with the orientations shown in Fig. 4.7:
The tank car must be able to withstand a minimum side impact speed of 12 mph when impacted at the longitudinal and vertical center of the shell by a rigid 12-inch by 12-inch indenter with a weight of 286,000 pounds. [9]

![Head - Code of Federal Regulations (CFR) § 179.16](image)

![Shell - Ongoing Research](image)

[Orientation now required by 80 FR 26643-26750]

**Figure 4.7: Class 3 tank car puncture test orientations [36]**

The required specifications for the tests of the SNF/HLRW container and the crude oil railcar differ in each of impact force, indenter size, and impact speed. To obtain the relative magnitude of the tests, the specifications will be normalized to a quantity that exemplifies the puncture intensity. This quantity is represented by the variable $I$ in the following equation:

$$ I = \frac{F \cdot v}{A} $$

(20)

- $F$: force of impact
- $v$: relative velocity of container and indenter on impact
- $A$: impact area (or area of indenter face)

Puncture intensity is proportional to both impact force and velocity because as either increases, the more difficult it becomes for the material to remain intact upon impact. Puncture intensity is inversely proportional to impact area since a smaller contact area concentrates the given applied force (increases the pressure), thereby causing a higher stress on the shell contact area.
Because the quantity of impact force divided by impact area is impact pressure, $P$, the puncture intensity can also be written as follows:

$$I = P \ast v$$  \hspace{1cm} (21)

The units for this puncture intensity quantity are watts per square meter, which have a physical meaning of energy flux, or the amount of energy transferring through a given area per unit time. In the case of the puncture test, the energy is transferred by the impact, the area is that of the container that is in contact with the indenter, and the time is the duration of the impact.

The force of impact for the SNF/HLRW puncture test is limited by the strength of the mild steel bar upon which the container is dropped. The calculations of the limiting impact force below were obtained from the NAC-UMS Safety Analysis Report (Docket No. 71-9270) [37].

“The transfer cask is loaded with a pressure load equal to the dynamic yield stress (flow stress), $S_yD$, of the bar, which is related to the static yield stress by:

$$S_{yD} = S_y \left(1 + \frac{E}{D}\right)^\frac{1}{2} = 47,000 \text{ psi} = 324 \text{ MPa}$$  \hspace{1cm} (22)

where

- $S_y$ = static yield stress of bar material, SA-36, 36,000 psi
- $E$ = strain rate of bar material during drop = 100 sec$^{-1}$
- $\rho$ = material constant for mild steel = 5
- $D$ = material constant for mild steel = 40"

Note that this calculation pertains only to the mild steel bar universally used for SNF/HLRW container testing, and is valid for any SNF/HLRW container puncture test.

From the pressure and the impact area of the mild steel bar, which as per regulation is a 15-centimeter diameter (7.5 cm radius) circular rod, the impact force can be found:

$$F = 324 \text{ MPa} \ast \pi \ast 7.5\text{cm}^2 = 5.7 \ast 10^6 \text{ N}$$  \hspace{1cm} (23)

Finally, the impact velocity can be found with the information that the container is dropped from a height of one meter onto the steel rod. Based on energy conservation principles and assuming negligible drag forces during the drop, the velocity upon impact is:
Then, puncture intensity can be found as:

$$I_{SNF/HLRW} = P \times v = 324 \text{ MPa} \times 4.4 \text{ m/s} = 1425 \frac{MW}{m^2}$$

A majority of the information used for the next puncture intensity calculation is based on the DOT-111 puncture test data from the full-scale test of a DOT-111 tank car performed by the Federal Railroad Administration on 18 December 2013 [38]. The test conditions were approximately equivalent to those required by the new puncture resistance regulations and will be scaled accordingly. The test performed was a side-on puncture test as depicted in Fig. 4.7 with a 12” by 12” indenter as required by regulation, but with an impact speed of 14 mph and a ram car with weight 297,125 pounds, or 11,125 pounds (3.9%) more than required for the test. The car was filled to 97% capacity with water to simulate a typically crude-filled railcar. The primary results of the test were as follows:

- The railcar failed (was punctured) at the above impact conditions
- The peak measured impact force was 960 kips (4.3 x10^6 N)
- The energy to just cause puncture was calculated to be 1.45 million foot-pounds (1.97 MJ), or the energy of a 12.1 mph impact with the impact vehicle

From sensors on the ram car, the following graph of force versus displacement was obtained. The impact energy curve is obtained by performing a cumulative integral of the force over the displacement.
For this particular test of the DOT-111 railcar, the puncture intensity can be calculated from the peak impact force, ram car velocity, and indenter area, and converted to metric units:

\[ I_{\text{rest}} = \frac{960 \text{ kips} \times 14 \text{ mph}}{1 \text{ ft}^2} = 287.7 \frac{MW}{m^2} \]  

(26)

The test result paper proposed that the energy at which the tank failed was the equivalent to that of the impact of the same ram car moving at 12.1 mph. This corresponded to a fail puncture intensity of the following:

\[ I_{\text{fail}} = \frac{960 \text{ kips} \times 12.1 \text{ mph}}{1 \text{ ft}^2} = 248.6 \frac{MW}{m^2} \]  

(27)

Returning now to the goal of determining the puncture intensity of the puncture test newly required by regulation for HHFT railcars, this quantity can be calculated using the impact force, impact velocity, and impact area. The latter two quantities are given within the regulatory requirement: the impact velocity...
is 12 mph and the impact area is 12” x 12”, or 1 square foot. Therefore, only the impact force must be obtained. This will be done using the results of the above test.

Given that the container fails at an impact energy of 1.45 million foot-pounds (1.97 MJ) based on the puncture test data, and that this is the impact energy associated with a 297,125 pound ram car moving at 12.1 mph (KE\text{test}), the impact energy for a ram car of the size and velocity of that required by regulation can be determined. The impact energy is kinetic, and kinetic energy is given by:

\[ KE = \frac{1}{2} mv^2 \]  

where \( m \) is mass. The energy of the ram car as described in the puncture test regulation (KE\text{reg}) can be found by using the following scaling procedure, where force is in units of pounds of force (lbf):

\[ KE_{\text{reg}} = KE_{\text{test}} \times \left( \frac{m_{\text{reg}}}{m_{\text{test}}} \right) \left( \frac{v_{\text{reg}}^2}{v_{\text{test}}^2} \right) \]

\[ KE_{\text{reg}} = 1.45 \times 10^6 \text{ ft lbf} \times \left( \frac{286000}{297125} \right) \left( \frac{12^2}{12.1^2} \right) \]

\[ KE_{\text{reg}} = 1.37 \times 10^6 \text{ ft lbf} \]  

The impact energy of a ram car with the specifications as described by the DOT-111 puncture test regulations is 1.37 million foot-pounds (1.86 MJ). To find the impact force associated with this impact energy, refer to the solid line added in the figure below to denote the impact energy associated with regulatory requirement at 1.37 million foot-pounds.

Since impact energy is found by integrating the impact force over the displacement, the impact force associated with the 1.37 million foot-pound impact energy can be found by determining the force at which the integrated impact energy curve reaches the desired value. This is also shown in the below figure. By drawing a vertical line at the displacement at which energy is 1.37 million foot-pounds from the impact energy curve to the force curve, the force required by the test can be determined.
Figure 4.9: Impact forces associated with test conditions (960 kips) and regulatory requirements (dashed line, 910 kips)

This method yields a regulatory impact force of 910 kips (4x10^6 N). The regulation puncture intensity for CBR is:

\[
I_{CBR} = \frac{910 \text{ kips} \times 12 \text{ mph}}{1 \text{ ft}^2} = 233.7 \frac{\text{MW}}{\text{m}^2}
\]  

(30)

The puncture test specifications for side-on impact for each of SNF/HLRW containers and CBR containers were taken and normalized to a single quantity, referred to as the puncture intensity, to allow for comparison of the level of regulation for each transportation system. The puncture intensity for the SNF/HLRW containers was found by multiplying the pressure limit of the metal rod upon which the container is dropped, by the relative velocity of the container to the rod upon impact. This yields a puncture intensity of 1425 MW/m^2. The required puncture intensity that a container carrying CBR (DOT-111) must withstand was found using the impact force corresponding to the predicted impact
energy and the required impact velocity and indenter area. This yields a puncture intensity of 233.7 MW/m². It is also calculated that a DOT-111 would fail at a puncture intensity of 248.6 MW/m².

Four primary observations can be drawn from these calculations:

1) Federal puncture test requirement regulations of SNF/HLRW rail transport containers have 6.1 times the puncture intensity of those now implemented for CBR rail transportation containers.

2) Federal regulations for puncture test requirements of rail transport containers for SNF/HLRW are 5.73 times greater than the failure puncture strength of a typical DOT-111 railcar.

3) DOT-111 railcars can be cleared for operation with a puncture resistance safety factor of 1.06.

4) Probability of failure of the puncture basic event of the TE3 fault tree is greater for the DOT-111 than for a SNF/HLRW cask.

Note that the data from this single test performed on the DOT-111 is not necessarily representative of all DOT-111 tank cars, and that the contents of the tank during the test (water) are not necessarily representative of the standard contents of the railcar during typical operation (Class 3 material) during puncture conditions.

### 4.2.3 Thermal Test

The thermal test is the second hypothetical accident condition that both Class 3 and Class 7 packages are tested to withstand. Thermal tests consist of subjecting the containers to a fire for a specified temperature and duration. For Class 7 (SNF/HLRW) containers, the specific conditions are found in 10 CFR 71, and the orientation is shown in Fig. 4.10. The information from that regulation relevant to this analysis is given below.

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…and the specimen must be positioned 1 m (40 in) above the surface of the fuel source. [35]
The procedures and requirements for tank cars used to carry Class 3 material differ from the radioactive material container tests, and they can be found in 49 CFR 179, Appendix B. The tank cars are subject to two different thermal tests: a pool fire, similar to that described above, and a torch fire, which is a more concentrated flame at a hotter temperature. However, for this thermal test, tank cars are not tested, but rather metal plates of the same material, thickness, and thermal properties as the tank car shell with thermal shielding equivalent to that on a full-size tank car.

The thermal test procedure for the tank car pool and fire tests are each two step processes. The first step demonstrates that heat will flow through the metal plate in the absence of a thermal protection system. The procedure consists of exposing a metal plate to the fire conditions described by regulation (reproduced in the Table 4.1 below) with nine thermocouples in the required arrangement on the unexposed side of the plate. The thermocouples must indicate temperatures between 0° and 37.8° Celsius prior to fire exposure. One side of the plate is then exposed to the fire in a fashion where the only heat transfer path is through the plate. A minimum of two thermocouple devices must indicate 427 °C (800 °F) after 13 minutes, plus-or-minus one minute, of simulated pool-fire exposure. A minimum of two thermocouples must indicate 427 °C (800 °F) in four minutes, plus-or-minus 30 seconds, of torch simulation exposure. [39]

This portion of the test ensures that the fire is providing enough heat to adequately test the thermal protection system by serving as an experimental control. For example, if the thermocouples remained at low temperatures after fire exposure without a thermal protection system, then they would certainly remain at low temperatures in the test with the thermal protection system, in which case the thermal protection system performance would be unclear.
The second portion of the test is similar to the first, except the plate has a thermal protection system on the side exposed to the fire. The other side has the thermocouples arranged as in the first portion, with the same pre-fire exposure temperature minimum and maximum (0° C to 37.8° C). The protected plate is then exposed. For both the pool fire and torch fire tests, the thermal protection system must retard the heat flow to the plate so that none of the thermocouples on the non-protected side of the plate indicate a plate temperature in excess of 427 °C. The pool fire test requires a minimum of three consecutive successful simulation fire tests for each thermal protection system. The torch fire test requires a minimum of two consecutive successful tests for each thermal protection system. [39]

After determining that heat would indeed flow through the plate without a thermal protection system in the first portion of the test, the second portion demonstrates the ability of the thermal protection system to sufficiently retard heat flow.

Table 4.1: Class 3 tank car thermal test specifications [39]

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Fire Temperature (°C)</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool</td>
<td>871</td>
<td>100</td>
</tr>
<tr>
<td>Torch</td>
<td>1204</td>
<td>30</td>
</tr>
</tbody>
</table>

Higher temperature and duration standards for Class 3 tank cars are logical, since Class 3 materials (flammable liquids) are a fuel source for a thermal incident. Should the contents of a tank car ignite somehow, the adjacent tank cars should be able to withstand the resulting thermal load as long as there exists fuel to burn. SNF/HLRW containers do not have flammable contents, and a dedicated train would not have other containers with flammable contents, so a thermal load of the magnitude of 25,000+ gallons of burning crude oil would have to come from an outside source.

In an attempt to minimize the likelihood of subjecting HLRM containers to extensive thermal stress, the AAR passed, as part of Circular No. OT-55-N, a “no-pass” restriction regarding the movement of trains carrying HLRM into a tunnel simultaneously occupied by a Class 2 (flammable gas) or Class 3 train. This is in light of the Howard Street Tunnel fire in Baltimore, MD in 2001 [40], during which a derailed train carrying tripropylene and hydrochloric acid, Class 3 materials, led to a chemical fire that burned in a tunnel for five to six days before it could be extinguished. It is unknown whether a HLRM container could withstand this level of thermal stress, but to avoid the risk altogether, the restriction was implemented. It is as follows:
When a train carrying SNF or HLRW meets another train carrying loaded tank cars of flammable gas, flammable liquids or combustible liquids in a single bore double track tunnel, one train shall stop outside the tunnel until the other train is completely through the tunnel. [26]

This no-pass restriction has the effect of further reducing the failure probability of the thermal failure basic event within the fault tree representative of TE3. By reducing the availability of a thermal source, the probability of thermal failure is reduced, and thus the probability of hazardous material release is reduced.

A potential issue lies within the setup of the Class 3 tank car thermal test. The test determines the ability of a plate of the same thermal properties and thickness to withstand the given thermal load, but this does not capture the other potential effects stemming from a tank car being subject to a thermal load, such as expansion of the contained liquid and the resulting pressure buildup within the tank. Pressure buildup can cause a tank rupture, even if the tank hull is able to withstand the external thermal load.

A report by AAR written to the Pipeline and Hazardous Materials Safety Administration (PHMSA) regarding Recommendations to Improve the Safety of Railroad Tank Car Transportation in November 2013 [41] provides an overview of the ability of different variations of DOT-111 tank cars to withstand a 1500° F (815° C) pool fire. This analysis was performed using the AFFTAC model, which is the model typically used to perform an analysis of fire effects on tank cars. Results are shown in Table 4.2 below. The study shows that tank cars carrying ethanol without jackets failed the thermal test in fewer than 100 minutes, which is the minimum survival time required by regulation. The tank cars that were carrying diesel fuel or that were jacketed were able to withstand the fire for the required length of time. Though definitive conclusions cannot be drawn regarding tank cars carrying crude oil from this study, it can still be concluded that the thermal test of a bare metal plate required by regulation does not fully encompass the effects of a thermal load on an enclosed tank car.
Table 4.2: Thermal test model of DOT-111 variations subjected to 1500° F pool fire [41]

<table>
<thead>
<tr>
<th>Tank Car Features</th>
<th>Survival Time in Pool Fire (min.) Ethanol</th>
<th>Survival Time in Pool Fire (min.) Diesel Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-CPC 1232</td>
<td>None</td>
<td>51</td>
</tr>
<tr>
<td>DOT 111</td>
<td>JKT</td>
<td>72</td>
</tr>
<tr>
<td>CPC-1232 DOT-111</td>
<td>with HHS, additional</td>
<td></td>
</tr>
<tr>
<td>1/16” shell thickness, TFP</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>CPC-1232 DOT-111</td>
<td>with JKT, FHS, TFP all lading expelled at 623</td>
<td></td>
</tr>
</tbody>
</table>

CPC-1232 – AAR tank car standard effective 1 Oct 2011; JKT – Jacketed; HHS – Half-height head shield; FHS – Full height head shield; TFP – Top fittings protection

4.2.4 Immersion Test

Two different immersion tests are required of Class 7 containers. The first is the fourth and final test in sequence after the drop, puncture, and thermal tests on the same cask. This immersion tests requires “For fissile material subject to §71.55, in those cases where water in-leakage has not been assumed for criticality analysis, immersion under a head of water of at least 0.9 m (3 ft) in the attitude for which maximum leakage is expected. [35]” A separate immersion test, this time for a package not previously subjected to the drop, puncture, and thermal tests, is to be performed on “A separate, undamaged specimen must be subjected to water pressure equivalent to immersion under a head of water of at least 15 m (50 ft). [35]” No radioactive material should be released from the packages to pass each immersion test. The basic orientation is shown in Fig. 4.11.

An immersion test is not required for Class 3 tank cars.
This immersion test requirement reduces the basic event failure probability of immersion failure in the TE3 fault tree, further reducing the overall TE3 failure probability.

4.3 Regulation Summary

Regulations are implemented in the transportation industry for the purpose of reducing risk. All three top events of the PRA are targeted. TE1 and TE2 are targeted by operational regulations, and TE3 is targeted by hypothetical accident condition regulations, in general. These regulations differ based upon the class of hazardous material being transported. It is seen that Class 3 material is more restricted in its operation considering train speed and brake systems, but note also that SNF/HLRW trains are typically restricted to being dedicated trains with fewer cars and more security. SNF/HLRW trains are far more regulated based on hypothetical accident condition requirements, requiring tests of all four failure modes in sequence, whereas Class 3 containers require only separate puncture and thermal tests.

From a risk-based standpoint, Class 7 containers have a lower TE3 failure probability than Class 3 containers. In all accident condition cases, Class 7 containers have more stringent regulations, and a claim can therefore be made that it has lower probability of failure. A comparison of probabilities of TE1 and TE2 failure between the two classes is less clear. Multiple factors require consideration. It is quantitatively unknown how much each factor reduces failure probability of the top events. Questions such as the following need to be addressed in order to form a complete comparison of risk due to shipments of the two material classes:
• Does a reduction in train speed of Class 3 trains in HTUAs or use of fewer cars in Class 7 dedicated trains reduce risk and failure probability more?

• Will ECP brake systems leave Class 3 unit trains and Class 7 dedicated trains on par in terms of braking ability?
5. Approaches to Risk Reduction and Future Work

A PRA was performed here, factors affecting risk perception were identified, and regulatory attempts at risk reduction were analyzed. It is thus now appropriate to suggest further approaches to a reduction in risk for the transportation of hazardous material by rail. The purpose of this chapter is to address solutions to risk perception and regulation issues based on the results of the PRA performed in Chapter 2. Existing factors and regulations and their effects on the PRA will be summarized, and approaches to improve them will be provided. Since Class 7 transportation by rail has not yet occurred on a large scale, there is still time to make this analysis and potentially implement some of the suggestions made.

5.1 Risk Perception Sensitivity and Analysis

Table 5.1 summarizes the factors affecting risk perception and the corresponding effects they have on the PRA results.

Table 5.1: Summary of factors affecting risk perception and their corresponding effect on PRA parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Affected PRA Parameter</th>
<th>Effect on PRA Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural/Industrial</td>
<td>Success Cost</td>
<td>Increased</td>
</tr>
<tr>
<td>Chronic/Catastrophic</td>
<td>Major Failure Frequency</td>
<td>Increased</td>
</tr>
<tr>
<td>Familiar/Unfamiliar</td>
<td>Major Failure Cost</td>
<td>Increased</td>
</tr>
<tr>
<td>Trustworthy/Untrustworthy</td>
<td>Success Probability</td>
<td>Decreased</td>
</tr>
</tbody>
</table>

Although it is unknown how much the listed in Table 5.1 affect the total risk in their present state, it is possible to consider the sensitivity of the total risk to each factor. This discussion of sensitivity provides insight regarding the rate of risk change per change in PRA parameter, but not the current effect level on those parameters. Additional research is required to determine which of the factors affects risk perception the most presently. Much like the risk importance measure analysis in Chapter 2, this sensitivity analysis is useful for providing a path towards efficient risk reduction methods.

The sensitivity analysis is performed by varying the value of a parameter and observing the change in total risk. By plotting total risk versus parameter change, the sensitivity of risk to the given parameter is obtained; sensitivity is given by the slope of the resultant curve. Fig. 5.1 shows results of analysis of the sensitivity of risk to each of the four risk perception factors. The risk is most sensitive to
the factor with the greatest slope, which in this case is the trustworthy/untrustworthy factor, which affects the perception of success probability, or alternatively, failure probability, since the probabilities are dependent. In this plot, a change in success probability is a *decrease* in success probability while maintaining the same proportions of failure probabilities. A change in failure probability is an increase, while decreasing the success probability to maintain complementarity. The remaining parameters all have similar sensitivity, and Chronic versus Catastrophic sensitivity and Familiar versus Unfamiliar sensitivity are overlapping, or essentially equivalent.

Figure 5.1: Sensitivity of risk to risk perception factors and corresponding PRA parameters

Because risk associated with the success end state is $0$, it was not possible to address the sensitivity of the natural/industrial factor by using percent changes. The following figure displays the change in total yearly risk as a function of cost associated with the success end state.
Figure 5.2: Sensitivity of risk to cost associated with success end state

In this figure, the y-intercept is the present value of risk. To put this in perspective with the other parameters, a $5000-cost associated with the end state has a similar effect to increasing the failure probabilities by approximately 180%.

The sensitivity analysis demonstrates that the best approach for reducing perceived risk is to address the trustworthy versus untrustworthy and the natural versus industrial risk perception factors. The factors can be addressed with cooperation and education, respectively. Cooperation with the public tends to build trust, while a lack of cooperation diminishes it. This can be seen historically with the attempts of establishing long-term HLRM repositories in Sweden and the United States. As stated by the U.S. Secretary of Energy Advisory Board, “public trust and confidence is generally essential for agencies to carry out effectively missions assigned to them.” [42] In the Environmental Impact Statement of SKB, the company responsible for managing Sweden’s nuclear waste, it is stated among “Key factors for progress in the Swedish nuclear waste management programme” that “Building of trust in affected municipalities creates the necessary public acceptance.” [43] Establishing trust decreases the perceived risk, which is what makes it so vital to actions such as hazardous material transportation and storage. Establishing trust through public cooperation also helps to reduce perceived risk when addressing the...
familiar versus unfamiliar factor. By introducing cooperation into the hazardous material management procedure, the public has the ability to become more familiar with the materials in question. Take again as an example the approach taken by SKB during the repository establishment process up to the present time of this thesis. All of the SKB facilities are open to visitor tours, including the ISF, canister laboratory, and Aspō Hard Rock Laboratory, each of which are essential to the development of the repository. [44]. The transparent approach taken by SKB provides a way for the public to become familiar with the materials and provides a path for establishing trust, both of which decrease perceived risk. In the United States, a consent-based approach was not taken for siting Yucca Mountain, and that project has since stalled due largely in part to public opposition. The State of Nevada vetoed the attempt of DOE to send waste to Yucca, and then took action to prevent the construction of railways to get the waste to Yucca subsequently. [45] Following the support withdrawal from the Yucca Mountain project, the Obama Administration formed a panel of experts to formulate a plan for an alternative repository solution. This panel, known as the Blue Ribbon Commission on America’s Nuclear Future (BRC), presented a report in 2011 to the Secretary of Energy regarding their suggestions to an approach for future potential repository. The basis of the siting process recommended in the report was to follow a consent-based approach. [46, 47]

A cooperative approach is relevant to hazardous material transportation as well. Among the causes of the Yucca Mountain project failure was the Walker River Paiute Tribe withdrawal of permission to ship nuclear waste through its reservation. [46] This inhibited the transportation of Class 7 material to a final repository destination. There is also opposition to the operation as a whole, including shipment along current rail lines. Since “the potential for an accident and subsequent release of radioactive materials has generated considerable opposition to transporting large amounts of radioactive waste,” [48] there is still room for improvement regarding the public perception of the shipments. A potential approach would be to work with local authorities to support emergency response training, as provided by Section 180(c) of the Nuclear Waste Policy Act, as amended in 1987. [49] This approach would have several effects on risk and risk perception, such as making the material more familiar, lessening the likelihood of a catastrophic incident, and establishing trust with local communities, thereby addressing three of the risk perception factors. Another approach is to develop cooperation programs such as the “Commercial Vehicle Safety Alliance, which seeks uniformity in commercial vehicle inspections and enforcement activities,” and the FRA Safety Assurance and Compliance Program, which works “to identify systemic safety issues, including issues pertaining to hazardous materials transportation, and to develop and implement plans to address them.” [50] These programs develop trust between the public and those responsible for handling the hazardous materials.
The second approach to reducing perceived risk is through providing knowledge about the subject. This approach addresses the natural versus industrial and chronic versus catastrophic factors, and also helps address the familiar versus unfamiliar factor. Radiation has a high outrage factor, and providing knowledge about natural radiation and a comparison to levels of industrial radiation may be useful to decreasing the sense of risk due to the natural versus industrial factor. However, this is more difficult to effectively implement than the cooperation approach since reaching out to the masses with this type of knowledge is challenging and can be taken as an attempt of disinformation. Because the knowledge is provided to reach some goal for the providers benefit, such as permission for hazmat transportation or the development of a HLRM storage facility, the legitimacy of the information can be questioned. Therefore, this approach is secondary to cooperation, as attempting to educate the public before establishing trust can cast doubt upon the authenticity of the information conveyed.

5.2 Regulatory Effects and Reduction Approaches

Unlike risk perception factors, regulation affects the probabilities of individual top events within the PRA event tree. Table 5.2 below summarizes the regulations discussed in this thesis and the corresponding affected top events for each.

Table 5.2: Affected top events for each regulated train system feature

<table>
<thead>
<tr>
<th>Regulated Train System Feature</th>
<th>Affected Top Event (TE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>TE1, TE2, TE3</td>
</tr>
<tr>
<td>Train Length</td>
<td>TE1, TE2</td>
</tr>
<tr>
<td>Car Weight</td>
<td>TE1</td>
</tr>
<tr>
<td>Brake Systems</td>
<td>TE1</td>
</tr>
<tr>
<td>Hypothetical Accident Conditions</td>
<td>TE3</td>
</tr>
</tbody>
</table>

The sensitivity analysis for these regulations is essentially identical to the risk importance measures analysis performed in Chapter 2 of this thesis. The sensitivity of risk to each is proportional to the sum of the risk importance of the affected top events. Therefore, risk is most sensitive to the operational regulations, which all include TE1 as an affected top event. TE1 is currently the most affected top event by regulation, which is one of the causes of the low failure probability it currently has. Because TE1 has the greatest risk importance, it is the most targeted by regulatory measures. However, hypothetical accident condition regulations are also vital, since, as discussed previously, the cost of reducing derailment failure is likely very high due to its already very low probability. TE3 had the
second greatest risk importance measurement and has a much higher failure probability than operation/derailment, which is what hypothetical accident condition regulations are intended to reduce.

One way to reduce risk through use of regulation is to increase the level of hypothetical accident regulations required for containers of Class 3 material. The puncture test required of Class 3 containers has a very small safety factor, and the speed required to cause puncture is much less than the average train speed, leading to a very high likelihood of TE3 failure during a collision. The thermal test requirements can also be improved to account for the effects of thermal expansion and bursting, rather than just the thermal load abilities of the container material. Since Class 3 materials are flammable by definition, the thermal test is one of the most relevant tests for those containers. It is possible to add a drop and immersion test requirement for Class 3 containers as well, but those are much less relevant for Class 3 than for Class 7 because Class 7 containers are lifted off the train during standard operation, making a drop scenario much more likely.

The probability of TE2 failure is a function of two parameters: $n$, the number of cars that derail per derailment, and $p$, the ratio of hazmat cars to non-hazmat cars on trains. To reduce the failure probability, either $n$ or $p$ must be reduced. Reducing $n$ is done by addressing TE1 and decreasing the probability of derailment on a car-by-car scale rather than a train-by-train scale. Speed regulations are partly intended to achieve this effect, and other potential regulations of car connections may have an effect on car-to-car derailment magnitude. Train length also affects $n$ by limiting the number of cars on a train, which thus limits the maximum number that can derail in an event. Requiring the use of key or dedicated trains is one way to reduce $n$. The other approach is regulating $p$, which can be done by limiting the number of hazmat-carrying cars per train. While this approach may reduce the probability of hazmat derailment, it will cause efficiency issues, as unit trains are a major part of hazmat transportation. Requiring diversity in train cargo would also cause the train to travel a longer distance to get cargo to all destinations, thereby increasing probability of TE1 failure. Therefore, if TE2 must be addressed via regulation, then reducing $n$ is the best approach.
5.3 Conclusions

The risk of hazmat railroad transportation was analyzed in this thesis for two primary reasons. One was to perform an analysis in preparation for an upcoming increase of radioactive material transport by rail in the form of shipments of SNF/HLRW to an eventual ISF and repository site. This analysis can potentially shed some light on the risk, risk perception, and regulatory issues regarding Class 7 railroad transport. The second reason was to provide insight on the differences between Class 3 and Class 7 material transport in terms of risk perception and regulation. The probabilistic risk assessment (PRA) in Chapter 2 was an assessment of hazardous material transport by rail in general (i.e., for all material classes). The analyses of Chapters 3 and 4 then provided insight toward the differences between classes in terms of the PRA.

The PRA in Chapter 2 was performed at a basic level to obtain point estimates of hazmat rail transportation failure probabilities. From these estimates, a risk importance measures analysis was made to identify which top events have the greatest impact on risk. The derailment/operational failure event and the material release top events had the greatest importance. After further analysis of regulation in Chapter 4, it was found that these top events were the most targeted by regulation. Each of the operational regulations target derailment/operational failure, and the hypothetical accident condition regulations target the material release failure. Regulations serve to reduce failure probability.

The regulations selected for analysis in this thesis were those in which regulation levels differ between trains carrying Class 3 and Class 7 material. The comparison of regulatory stringency in Chapter 4 resulted in a deduction that Class 3 material rail transport has more stringent operational regulations. This does not necessarily lead to the conclusion that Class 3 trains have a lower TE1 failure probability, but rather that the probability contributions from those regulated factors are smaller. Though use of dedicated trains for SNF/HLRW transport for future repositories is not officially mandated by regulation, including this feature can greatly reduce TE1 failure probability for Class 7 trains.

Hypothetical accident condition regulations are more stringent for Class 7 trains than for Class 3 trains. The only possible exception is the thermal test, for which the flammable liquid-carrying trains have higher temperature and duration requirements for the fires in the test. This exception is still questionable, however, since some problems were found with the comprehensiveness of the Class 3 thermal test procedure. For all other hypothetical accident condition tests (drop, puncture, and immersion), Class 7 trains have stricter requirements. Each test addresses a failure mode for TE3, and each requirement reduces the probability of TE3 failure.
In addition to regulation, risk perception plays a role in creating an acceptable level of risk needed for the performance of tasks such as hazardous material transportation. Several factors affect both risk perception and some quantity in the PRA, such as failure probability or cost. Four factors were analyzed in this thesis: natural versus industrial risks, chronic versus catastrophic risks, familiar versus unfamiliar risks, and trustworthy versus untrustworthy risks. From the sensitivity analysis for these factors, it was found that risk was most sensitive to the trustworthiness of those responsible for the risk. It is suggested that cooperation was the best way to address this factor, since cooperation increases trust, and thus decreases the perceived risk. Another approach to reduce perceived risk is to provide knowledge to the public and educating them about any risks involved in hazmat transportation, but this is secondary to cooperation because issues may arise regarding suspicions about the quality of information provided.

5.4 Future Work

Several assumptions were made within this thesis that can be expanded upon for a more accurate analysis of hazmat transportation risk. Beginning in Chapter 2, various assumptions were made regarding the PRA top events, including multiple homogeneity assumptions and a simple event tree with only three top events. This is a target for improvement in a future analysis. For example, a similar risk assessment was made by Liu, Saat, and Barkan, in which point of derailment was taken into account and probability distributions were carried through the analysis, yielding a distribution for failure state probabilities. [13] In the Chapter 2 PRA, the amount of available data led to a low uncertainty level, but a distribution yields a more accurate failure state probability and is more characteristic of a complete risk assessment. Assumptions were made regarding tank car placement, point of derailment, and train length homogeneity in this thesis, which can be represented more accurately with additional data to obtain a more accurate failure probability distribution.

A second possibility for future work is with a more in-depth analysis of the risk perception factors and their relative effects on the PRA and risk perception in general. As stated within the sensitivity analysis section, sensitivity provides information on the rate of risk change per change in risk perception factor, but does not provide the current level of effect of the factor on the risk. A potential approach to solve this problem is to conduct surveys of the public to determine which factors have the largest effect on their perception of risk from hazardous materials. A similar approach was taken by Fischoff et al. in 1978 to determine the perceived risk of nuclear power compared to x-rays and “electric power”, in which nuclear power had higher average risk ratings than the others. [51]
A comparison like this could be made for transportation of different hazardous material classes, such as Class 3 and Class 7, or a comparison could be made between transportation of hazardous material and some other risky activity. The factors with the highest mean rating would have the greatest effect on risk perception of hazmat transportation. This comparison may provide some quantitative insight as to effects that the risk perception factors have on PRA quantities, such as success probability and major failure cost, to potentially back up the claims made in this thesis regarding the factor effects on PRA parameters.

A third possibility for future work is to perform a more quantitative analysis of the transportation regulations to determine if there is possible underregulation or overregulation of hazmat containers, since failure probabilities are so different for each. Class 7 transportation has an excellent record with few to zero release incidents [48], whereas Class 3 transportation has had several release incidents, but a much longer and larger-volume record of shipments. Whether or not this difference can be explained by regulation stringency differences or just small Class 7 shipment volume should be investigated.

A possibility for future work would be to implement changes based on the analysis made within the risk perception factors chapter and the sensitivity analysis section regarding cooperation and voluntary risk taking. The changes would serve to decrease the perceived risk of hazardous material management and create a more efficient hazardous material management process. Based on lessons learned from the Yucca Mountain repository project, cooperation is important to implement from the start of long-term operations, which is upcoming once again when a repository is established and large quantities of Class 7 hazardous material are shipped nationwide. To best avoid public risk perception issues, a cooperative approach should be taken, and taking steps toward public education about the relevant hazardous materials is another advantageous endeavor that may assist in completing the task.
6. References


## Appendix A: Data used from FRA Office of Safety Analysis

Table A1: Accessed through "Accident Detail Report" query at Reference [1]

<table>
<thead>
<tr>
<th>month</th>
<th>total accidents with hazmat car</th>
<th>total # cars on hazmat trains</th>
<th>total # hazmat cars</th>
<th># hazcars derailed</th>
<th># releases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-15</td>
<td>35</td>
<td>2965</td>
<td>684</td>
<td>26</td>
<td>2</td>
</tr>
<tr>
<td>Sep-15</td>
<td>34</td>
<td>1942</td>
<td>500</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>Aug-15</td>
<td>46</td>
<td>2728</td>
<td>623</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>Jul-15</td>
<td>54</td>
<td>3610</td>
<td>820</td>
<td>65</td>
<td>8</td>
</tr>
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