Development of Rail Accident Rates for Spent Nuclear Fuel Rail Shipments

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ABSTRACT

A key factor in evaluating the safety of rail shipments involving the transport of commercial spent nuclear fuel (SNF) is the development of transportation accident rates that are reflective of the unique characteristics associated with these train operations. Typical rail freight operations may involve consists of a hundred cars or more, which may pass through multiple rail yards for trains to be decoupled and reassembled. In contrast, trains carrying SNF are anticipated to be operated in consists of considerably fewer cars. Moreover, they could be operated in a dedicated fashion, thereby avoiding yard decoupling and reassembling activities in transiting from shipment origin to destination. This paper and presentation describes the methodology developed to estimate rail accident rates for future commercial SNF shipments and presents the corresponding results. The analysis utilizes the Federal Railroad Administration accident database, and takes into consideration accidents whose root causes are independent of the size of the consist, as well as those that are associated exclusively with yard activities.

INTRODUCTION

The U.S. Department of Energy (DOE) is planning for an integrated system to store and dispose of the nation's nuclear waste, which will require transporting SNF from existing sites to eventual storage and disposal locations. As part of creating a safe, secure and efficient transportation system, DOE is developing a rail transport capability through its Office of Integrated Waste Management, within the Office of Nuclear Energy.

To support this effort, development is underway to design and build new railcars capable of moving heavy, rail-sized SNF casks (see Figure 1). A typical consist will include locomotives, buffer cars, rail cask cars, and an escort car. The illustration below depicts this configuration for a single cask transport. As additional casks are added to the consist, additional buffer cars will also be included. However, it is unlikely that more than seven casks will be moved on a single train due to operational and security considerations.

Figure 1. SNF Train Configuration for a Single Cask Shipment

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The design of these railcars must meet the Association of American Railroads' (AAR) performance specification for trains used to carry high-level radioactive material (standard S-2043). This standard was developed to ensure safe rail transport of SNF casks through the use of best available technology to minimize the probability of derailments during transport. The standard requires a modern and robust safety monitoring system, real-time monitoring of several performance parameters, timely notification of off-normal events to prevent derailments caused by equipment degradation or failure, electronically controlled pneumatic brakes to improve stopping distances and detect any malfunctions, special operating and maintenance standards and practices, enhanced inspections and maintenance, and special crew training (AAR, sourced 2016).

Of particular interest is the extent to which an SNF train configuration, operating in accordance with AAR S-2043, can be expected to function from a safety perspective. The following distinctions are notable when compared to cargo transported as part of a general freight train carrying a variety of commodities:

- The typical size of a general freight train is comprised of many more cars than an SNF configuration, often consisting of 100 cars or more.
- SNF shipments are not expected to go through yards and be subject to decoupling and reassembling; rather yard activity is likely to be limited to possible refueling, crew changes and periodic inspections/repairs.
- Speed restrictions (i.e., maximum of 50 mph) would be imposed on an SNF train in accordance with AAR's Recommended Railroad Operating Practices for Transportation of Hazardous Materials (AAR, 2016).
- Trains would preferentially operate on tracks with positive train control, where available.
- SNF shipments will be accompanied by armed security personnel.

Due to these considerations, as well as the S-2043 requirements, rail carriers may opt to perform these shipments by operating a train that is dedicated to moving SNF exclusive of any other cargo in the consist. This would be consistent with a recommendation made by the National Academy of Sciences in its report, entitled *Going the Distance: The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States* (NAS, 2006).

The purpose of the study described herein was to factor these considerations into determining an appropriate accident rate for rail shipments of SNF under a dedicated train arrangement[3].

ANALYSIS METHODOLOGY

The primary source for analyzing rail accident/incident data is maintained by the Federal Railroad Administration (FRA)[4]. This database is an electronic version containing each Rail Equipment Accident/Incident Report, which every railroad is required to file if the event exceeds a monetary threshold of damages to infrastructure of rolling stock (Liu, et al., 2012)[5]. Information contained in each report includes a description of the railroad involved, accident type, location, track type, cause, severity and other related circumstances (FRA, 2011). The reporting format has remained stable over time, enabling researchers to analyze accident frequency over multiple years of consistent recordkeeping.

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[3] This is a technical report that reflects research and development efforts to explore technical concepts which could support future decision making by DOE. No inferences should be drawn from this report regarding future actions by DOE.

[4] Hereafter, the term "accidents" will be used to refer to accidents and incidents.

[5] This threshold is adjusted over time to account for monetary inflation.

This is significant when performing accident studies, where expanding the sample size supports a more rigorous analysis.

It is important to recognize that the primary cause of failure in rail accidents can be either a particular car in the train that creates the initiating event, or it can be attributed to a problem associated with how the train is being operated. As noted by Schafer and Barkan (2008):

> *Car mile-related causes are those for which the likelihood of an accident is proportional to the number of car miles operated. These include most equipment failures for which accident likelihood is directly proportional to the number of components (e.g., bearing failure) and also include most track component failures for which accident likelihood is proportional to the number of load cycles imposed on the track (e.g., broken rails or welds)……Train mile-related causes are those for which the accident likelihood is proportional to the number of train miles operated. These include most human error failures for which accident likelihood is independent of train length and depends only on exposure (e.g., grade crossing collisions).*

Consequently, when developing rail accident rates, one must determine whether the recorded accident is car mile-related (CM) or train mile-related (TM). This leads to a rail accident rate expression of:

Rail Accident Rate (per mile) = train-mile accident rate per mile + [(car-mile accident rate per mile) x (number of cars in train)]

Accident Frequency

The FRA report allows for the designation of an accident cause from among several hundred eligible entries. A study performed by ICF (2003) aggregated these classifications into fifty-one accident cause groups, and designated each cause group as being either car mile-related or train mile-related. A subsequent effort by Schafer and Barkan (2008) re-assigned certain cause groups to one or the other category based on findings from performing a statistical analysis. This resulted in the assignment of cause groups to categories as shown in Figure 2.

The FRA report also allows for distinguishing the type of track where the accident occurred (i.e., main, yard, siding, industry). In this analysis, an SNF shipment was assumed to move as a dedicated train, such that decoupling and reassembling the train in yards as well as pulling into sidings to allow other freight trains to pass would be unlikely. As it is assumed that the railroad would only take custody once an SNF shipment has been loaded onto a rail car, accidents occurring on industrial property were also not considered. Consequently, only accidents taking place on main track were examined.

Accident types were classified into three categories (ICF, 2003): 1) derailments, 2) train-to-train collisions, and 3) other; this latter category includes highway-rail crossing accidents. An effort was also made to distinguish among accidents associated with Class I railroads and those attributed to non-Class I railroads (i.e., short line and regional railroads).

It is customary in performing rail accident rate analyses to segment rates by rail track class. The FRA divides track into seven classes that are commonly used by the freight railroad industry. Higher track class values correspond to greater maximum permissible operating speeds, which are typically strongly correlated with track quality, including the presence of signaled track, wayside detection, and more frequent inspections and maintenance (Liu et al., 2017).

Group	CM/TM	Cause Description	Group	CM/TM	Cause Description
01E	CM	air hose defect (car)	06H	TM	radio communications error
02E	CM	brake rigging defect (car)	07H	TM	switching rules
03E	CM	handbrake defects (car)	08H	TM	mainline rules
04E	CM	UDE (car or loco)	09H	CM	train handling (excl. brakes)
05E	CM	other brake defect (car)	10H	TM	train speed
06E	CM	centerplate/carbody defects (car)	11H	TM	use of switches
07E	CM	coupler defects (car)	12H	TM	misc. track and structure defects
08E	CM	truck structure defects (car)	01M	TM	obstructions
09E	CM	sidebearing, suspension defects (car)	02M	TM	grade crossing collisions
10E	CM	bearing failure (car)	03M	CM	lading problems
11E	CM	other axle/journal defects (car)	04M	CM	track-train interaction
12E	CM	broken wheels (car)	05M	TM	other miscellaneous
13E	CM	other wheel defects (car)	01S	CM	signal failures
14E	CM	TOFC/COFC defects	01T	TM	roadbed defects
15E	CM	loco trucks/bearings/wheels	02T	TM	nontraffic, weather causes
16E	TM	loco electrical and fires	03T	TM	wide gauge
17E	TM	all other locomotive defects	04T	TM	track geometry (excl. wide gauge)
18E	TM	all other car defects	05T	CM	buckled track
19E	TM	stiff truck (car)	06T	CM	rail defects at bolted joint
20E	CM	track/train interactions - hunting (car)	07T	CM	joint bar defects
21E	CM	current collection equpment (loco)	08T	CM	broken rails or welds
01H	CM	brake operation (main line)	09T	CM	othe rail and joint defects
02H	TM	handbrake oeprations	10T	CM	turnout defects - switches
03H	TM	brake operations (other)	11T	CM	turnout defects - frogs
04H	TM	employee physical condition	12T	TM	misc. track and structure defects
05H	TM	failure to obey/display signals			

Figure 2. Accident Cause Groups and Categories

The FRA accident data used in this analysis covered the period from January 2011 through August 2016. This represented the most recent events that were publicly available. The number of accidents observed during this period are shown in Figure 3, reported separately by Class I vs. non-Class I railroad, accident type, track class, and whether the accident was designated as car-mile or train-mile related.

Several interesting observations emerge when reviewing these results. For Class I railroads, a larger number of accidents are attributed to train-related rather than car-related causes. By contrast, for non-Class I railroads there is approximately an even split between accidents attributed to the train as opposed to a particular car. For both railroad types, however, over 90% of car-related accident causes resulted in a derailment. Train-related causes resulted in derailments roughly only 30% of the time for Class I railroads and roughly 60% of the time for non-Class I railroads. Another observation of interest is the number of Class I railroad accidents deemed as train-related that were classified in the “Other” accident category (approximately 60% of total). One possible explanation is the fact that highway-rail grade crossing accidents are included in this category, as prior studies have reported that highway-rail accidents comprise nearly 70% of these records (Liu, 2016).

ALL ACCIDENTS – CLASS I RAILROADS					**ALL ACCIDENTS – NON-CLASS I RAILROADS**			
Track Class	**CM**	**TM**	**TOTAL**		**Track Class**	**CM**	**TM**	**TOTAL**
X/1	73	88	161		**X/1**	139	146	285
2	126	122	248		**2**	140	93	233
3	178	266	444		**3**	47	63	110
4	429	686	1,115		**4**	42	53	95
5 & higher	99	227	326		**5 & higher**	1	0	1
TOTAL	905	1,389	2,294		**TOTAL**	369	355	724
DERAILMENTS – CLASS I RAILROADS					**DERAILMENTS – NON-CLASS 1 RAILROADS**			
Track Class	**CM**	**TM**	**TOTAL**		**Track Class**	**CM**	**TM**	**TOTAL**
X/1	73	65	138		**X/1**	137	132	269
2	120	76	196		**2**	135	57	192
3	167	71	238		**3**	45	21	66
4	378	146	524		**4**	37	7	44
5 & higher	86	57	143		**5 & higher**	1	0	1
TOTAL	824	415	1,239		**TOTAL**	355	217	572
COLLISIONS – CLASS I RAILROADS					**COLLISIONS – NON-CLASS I RAILROADS**			
Track Class	**CM**	**TM**	**TOTAL**		**Track Class**	**CM**	**TM**	**TOTAL**
X/1	0	8	8		**X/1**	0	1	1
2	2	13	15		**2**	3	9	12
3	0	27	27		**3**	0	6	6
4	6	61	67		**4**	0	4	4
5 & higher	2	15	17		**5 & higher**	0	0	0
TOTAL	10	124	134		**TOTAL**	3	20	23
OTHER – CLASS I RAILROADS					**OTHER – NON-CLASS I RAILROADS**			
Track Class	**CM**	**TM**	**TOTAL**		**Track Class**	**CM**	**TM**	**TOTAL**
X/1	0	15	15		**X/1**	2	13	15
2	4	33	37		**2**	2	27	29
3	11	168	179		**3**	2	36	38
4	45	479	524		**4**	5	42	47
5 & higher	11	155	166		**5 & higher**	0	0	0
TOTAL	71	850	921		**TOTAL**	11	118	129

Figure 3. Accident Frequency by Railroad, Accident Type, Track Class and Mileage Designation

Exposure

Accident rates are derived by utilizing the frequency of occurrence as the numerator and a measure of exposure as the denominator. For this study, car-miles and train-miles traveled commensurate with the accident reporting period are the denominators of interest. The Bureau of Transportation Statistics (BTS) compiles this information on an annual basis, with the most recent reporting period being the 2012 calendar year (BTS, sourced 2016). As the annual number of Class I train-miles and car-miles tends to fluctuate from year-to-year, average annual numbers were determined for the period from 2000-2012. This resulted in an average of 511 million annual Class I train-miles and 36 billion Class I car-miles.

BTS does not report similar information for non-Class I railroads. However, a study performed by ICF concluded that non-Class I railroad traffic amounts to 5.2% of Class I railroad traffic (ICF, 2003). Based on that finding, annual non-Class I railroad activity was estimated to be 26.57 million train-miles and 1.87 billion car-miles.

While this information provides an estimate of annual train-mile and car-mile activity by railroad type, there remained a need to assign exposure to various track classes. The most recently available survey in which the number of car and train-miles were reported by track class produced the results displayed in Figure 4 for Class I railroads (Anderson and Barkan, 2004). Unfortunately, estimates of annual activity by track class is not available for non-Class I railroads. By applying the respective percentages from Figure 4 to the average annual number of train-miles and car-miles for Class I railroads, estimates of annual car and train-miles traveled by track class were generated (see Figure 5).

Recall that the accident data used in this study covered the period from January 2011 through August 2016. As this represents 5.67 years of data, annual car-miles and train-miles were multiplied by 5.67 to normalize the accident rate numerator and denominator.

FRA Track Class	X/1	2	3	4	5&6
% Car-Miles	0.3	3.2	11.6	63.1	21.9
% Train-Miles	0.3	3.3	12.1	61.8	22.6

Figure 4. Percentage of Car and Train-Miles by Track Class

FRA Track Class	X/1	2	3	4	5&6
Annual Car-Miles (billions)	0.11	1.15	4.18	22.72	7.88
Annual Train-Miles (millions)	1.53	16.86	61.83	315.8	115.49

Figure 5. Annual Number of Car and Train-Miles by Track Class

Accident Rates

Accident rates by accident type and track class were produced by combining the accident frequency information in Figure 2 with the estimated number of car-miles and train-miles traveled over the same reporting period. The results appear in Figure 6 for Class I railroad car-mile accident rates, Figure 7 for Class I railroad train-mile accident rates, and Figure 8 for Non-Class I railroad accident rates (both car-mile and train-mile). It is important to note that the denominator for car-mile rates are reported in units of billions while train-mile rates are reported in units of millions.

In reviewing the results displayed in Figures 6-8, it can be seen that accident rates, regardless of railroad type or cause, decrease with higher track classes. In particular, for Class I railroads, there is a significant drop in accident rates when going from track class X/1 to higher rated track. This suggests that SNF shipments should avoid use of X/1 track if at all possible.

Also notable is that, with the lone exception of track class X/1 train-mile accident rates for Class I railroads, derailment rates far exceed those rates for other accident types. Railroads should therefore be encouraged to deploy risk mitigation strategies directed at preventing derailments, presumably a major reason why S-2043 was implemented.

Track Class	Derailment	Collision	Other	All
X/1	117.37	0	0	117.37
2	18.33	0.30	0.61	19.24
3	7.02	0	0.46	7.48
4	2.92	0.05	0.34	3.31
5 & higher	1.92	0.04	0.25	2.21

Figure 6. Class I Railroad Car-Mile Accident Rates (per billion car-miles)[6]

Track Class	Derailment	Collision	Other	All
X/1	7.5	0.92	1.72	10.14
2	0.79	0.13	0.34	1.26
3	0.20	0.07	0.48	0.75
4	0.08	0.03	0.26	0.37
5 & higher	0.09	0.02	0.24	0.35

Figure 7. Class I Railroad Train-Mile Accident Rates (per million train-miles)

Mileage Category	Derailment	Collision	Other	All
CM (per billion car-miles)	33.27	0.28	1.03	34.58
TM (per million train-miles)	1.43	0.13	0.78	2.34

Figure 8. Non-Class I Railroad Accident Rates

SAMPLE APPLICATION

The availability of these accident rates enables their use in performing safety analyses of SNF shipments under consideration by DOE. Using established railroad network databases and system analysis tools, it becomes possible to assign a specific accident rate to each segment of the network based on the railroad type and track class. Based on the type of SNF shipment, an estimate of the shipment accident likelihood can be derived. Below is a simple illustration of how this would be done.

Consider a hypothetical shipment involving SNF in which the total trip distance is 290 miles, with a composition of railroad type and track class as follows:

- Non-Class I railroad (short line): 20 miles
- Class I railroad – track class 2: 30 miles
- Class I railroad – track class 4: 180 miles
- Class I railroad – track class 5: 60 miles

The overall accident likelihood for a single cask shipment (i.e., 6 cars in train) would be:

$$20\ TM_{sl} + 120\ CM_{sl} + 30\ TM_{cl2} + 180\ CM_{cl2} + 180\ TM_{cl4} + 1080\ CM_{cl4} + 60\ TM_{cl5} + 360\ CM_{cl5}$$

where:

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[6] Some cells have reported accident rates of 0, because no observations of this type were observed in the accident database for the reporting period used in this study. This does not mean that such accidents have not occurred in the past, but rather it suggests that a larger accident reporting period should be examined when deriving corresponding rates.

TM = train-mile accident rate
CM = car-mile accident rate
sl = Non-Class I railroad
cli = Class I railroad track class i

In this illustration, the accident rate for "All" causes is used.[7] After converting accident rates into per mile unit values and multiplying by the corresponding distances, we arrive at:

Overall Shipment Accident Likelihood = 0.000185

This same approach was applied to trains comprised of 3 and 5 casks shipped, the results of which are displayed in Figure 9.

No. of Casks Shipped	No. of Cars in Train	Total Train-Miles	Total Car-Miles	Overall Accident Likelihood
1	6	290	1,740	0.000185
3	10	290	2,900	0.000194
5	14	290	4,060	0.000202

Figure 9. Accident Likelihood for Hypothetical Cask Shipments

One question that is likely to arise concerns the benefits that may be achieved by shipping multiple casks on the same train. For this hypothetical example, the results displayed in Figure 8 suggest that shipping multiple casks as part of the same train (rather than the same number of casks shipped in multiple trains) will provide a safety benefit in terms of the overall accident likelihood of the shipping campaign. However, it is important to note that whether such benefits can be achieved will depend on the proportion of track on the route associated with each track class. The extent to which such accommodations can be made may also be constrained in terms of the location and timing of casks that can be loaded where the SNF currently resides.

CONCLUSIONS

This paper describes an approach for estimating rail accident rates for SNF shipments based on likely operating characteristics of SNF trains and the most recent data available, with the intention of helping to inform policymakers and analysts in planning for future SNF transport. Accident rates were generated for different types of railroads, accidents and track classes, according to whether the primary cause was considered train-related or car-related. It is important to note that these calculations are based on data from regular freight trains. Therefore, due to the specialty design and monitoring features of S-2043, accidents in general and derailments in particular are expected to be even lower.

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[7] The rationale for using these rates is that any accident, regardless of its severity, could affect stakeholder perceptions of shipment risk. However, it is anticipated that under any accident scenario, the SNF cask would not breach, although the time required to restore normal railroad operations would differ.

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ACKNOWLEDGMENTS

This information was prepared as an account of work sponsored by the U.S. Department of Energy. Neither the DOE, nor any of its employees or contractors, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the DOE. The views and opinions of authors expressed herein do not necessarily state or reflect those of the DOE.