PROBABILITY OF PIPELINE OR RAILROAD FIRES AFFECTING SPENT NUCLEAR FUEL TRANSPORTATION CASKS

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ABSTRACT

This paper estimates the likelihood that a pipeline break or a train fire could occur in the immediate vicinity of a spent nuclear fuel cask during rail transit. U. S. Department of Transportation databases are examined for information that yields likelihood estimates for such accidents. The results presented are intended to provide details and information in a form that is useful reference for future risk studies. Probabilities are calculated for both pipeline fires caused by pipeline breaks and for hazardous materials fires caused by train accidents. As an illustration, the resulting probabilities are used to calculate typical probabilities for fire accidents during rail transportation of spent fuel casks. For a single1600 km (1000 mile) trip, the probability of a transportation cask being involved in a pipeline fire accident is about $9x10^{-22}$. Similarly, the probability of a cask being involved in a train fire accident during a single 1600 km (1000 mile) trip is estimated to be about $3x10^{-7}$. Because of the low likelihood but potentially severe thermal conditions caused by turbulent mixing of oxygen into the fire plume, pipeline accidents fall into the category of very low probability, high consequence accidents. For train transportation, the probability of a hazardous materials fire, assuming a typical freight train, is high enough to be considered in transportation risk assessments.

INTRODUCTION

Concerns about cask transportation accidents that might involve severe pipeline breaks or tank car fires have been expressed by stakeholders during recent shipping campaigns. Existing databases are available from the United States Department of Transportation that permit estimation of fire accident rates for both rail transport and rail-pipeline interactions. Databases from both the Federal Railroad Administration and the Office of Pipeline Safety are used in this study. In addition, Geographic Information System (GIS) data developed by the State of Texas allow estimation of the exposure of rail lines to pipeline ruptures. In this paper, these data are presented and then used in illustrative calculations that give estimates of the likelihood of such accidents.

PIPELINE FIRE PROBABILITIES

Pipelines Neighboring Railroads

To estimate the potential exposure of rail lines to pipeline breaks and fires, a quantitative appraisal of the incidence of pipelines neighboring railroads is needed. As a step toward such an appraisal, a representative group of five counties, Hardin, Jasper, Jefferson, Liberty, and Orange, near Houston, Texas was considered because the Railroad Commission of Texas had appropriate data in a computer format at the time this report was written. The counties chosen represent a geographical region where petroleum industries and pipelines are common. Geographically correlated databases for all of the pipelines in each county were purchased and added to the existing databases describing railroad locations and characteristics in Sandia's Geographic Information System for Transportation (GIS-T). The fractions of selected mainline rail routes (typically the only lines employed for large shipments of radioactive material, e.g. spent nuclear reactor fuel) intersected by or running close to pipelines were then tabulated with special software tools developed at Sandia for use with a commercial geographic information system (GIS).

Geographic information systems provide powerful software tools for studying geographically correlated information and comparing multiple sets of data (layers) with each other (e.g. population density with highway maps) to obtain data on relationships

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(e.g. population density along selected routes). Typically, the built-in software tools are best suited for studying data layer relationships over large areas: an entire route within a county or a metropolitan area. Because Sandia needs demographics associated with transportation routes on a detailed scale (kilometer by kilometer) for routes that are national in scope, a software tool was developed which could automatically tabulate population information (U.S. Census Blocks layer) along selected routes (digital atlas layer) for subsequent processing.

For the current application, selected mainline rail sections within three of the five counties for which pipeline data were purchased were divided into 200-meter lengths, and the occurrences of pipelines within 100 meters of either side of the rail line were tabulated for each of the 200-meter segments (by the automatic tabulation tool). With the built-in capabilities of the GIS, it was also possible to tabulate the occurrence of pipelines of specific sizes and fluid content (gases, liquids, or refinery products) within the selected proximity of the rail lines. For this evaluation, tabulations of all pipelines and of pipelines with 6 inch or greater diameters, within 100 meters of the selected rail mainlines, were compiled.

Rail mainlines were located in only three of the five counties for which pipeline data were purchased. Table 1 lists the three counties and the rail-line/pipeline correlation data for all pipelines/fluids in the Railroad Commission of Texas data. In the tables, each rail mainline in the county is listed separately. Table 2 lists similar information for pipelines of 6 inch or greater diameter and all fluids. A typical map of rail lines analyzed is shown in Figure 1. An example of the rail-line segmentation and pipeline intersections is shown in Figure 2.

Table 1. Rail-line/Pipeline Correlation Statistics for All Pipelines/Fluids

County	Total 200-m Rail Segments	Rail Segments Intersected by Pipelines	Fraction
Jefferson	176	20	0.114
	176	25	0.142
Liberty	289	58	0.201
	279	43	0.154
Orange	220	44	0.200
	273	54	0.198

Table 2. Rail-line/Pipeline Correlation Statistics for Pipelines 6 inch dia. or larger, All Fluids

County	Total 200-m Rail Segments	Rail Segments Intersected by Pipelines	Fraction
Jefferson	176	19	0.108
	176	23	0.131
Liberty	289	49	0.170
	279	40	0.143
Orange	220	36	0.164
	273	29	0.106

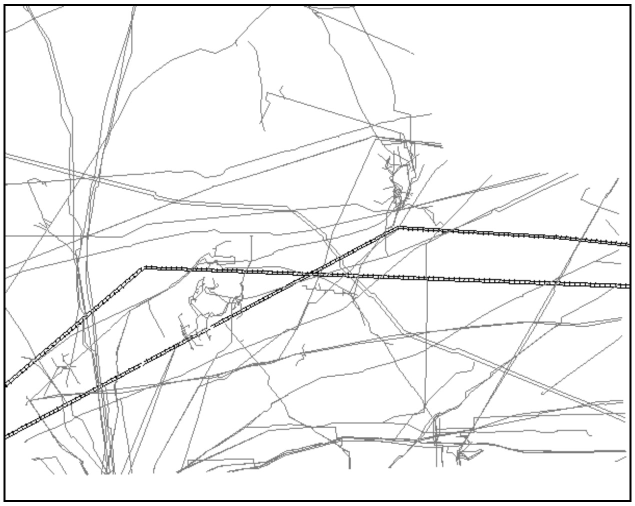

Figure 1. Rail mainlines and all pipelines in southern Liberty County, Texas. Thin lines are pipelines; hatched lines are rail mainlines.

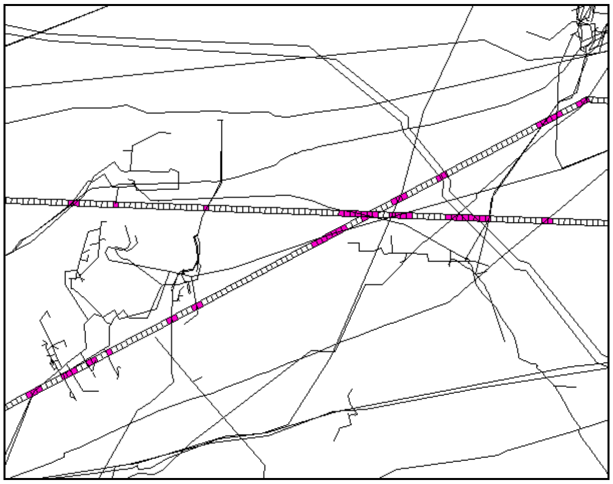

Figure 2. Example of analysis of 200-m mainline railroad segments in southern Liberty County, Texas. Thin lines are pipelines; shaded rail segments intersect one or more pipelines.

In this limited sample of data, the fraction of the mainline rail tracks within 100 meters of a pipeline is 20% or less. This is not surprising in view of the fact that in most of these cases, the pipelines did not parallel the rail lines but crossed them at varying angles. The fraction for 6-inch diameter or larger pipelines within 100 meters of the same rail lines is smaller, as expected from a casual examination of the pipeline-size distributions.

Pipeline Break Probabilities

The Office of Pipeline Safety (OPS), part of the U. S. Department of Transportation, keeps statistics on pipeline accidents in the United States. These data are available to the public for computer download (http://ops.dot.gov/), and are used here to estimate the annual probability that a pipeline breaks or is damaged and catches fire. The OPS divides pipelines into three categories: liquid transmission, natural gas transmission, and natural gas distribution. For estimation purposes, pipelines nominally 6 inches or larger are considered to have a significant potential to damage a spent fuel cask. The recent 14 year period from 1986 to 1999 was analyzed.

As shown in Table 3, for liquid pipelines, an average of about five fires per year occurred between 1986 and 1999 over a total pipe length of 240000 to 260000 km (150000 to 160000 miles). Assuming a one hour fire duration so that a joint probability of a cask being present can be estimated later, the annual probability that a fire will exist at a given liquid pipeline location within one meter at a given time is 2.3 x 10^{-12}. Total pipeline length for each of the pipeline categories is provided on the OPS web site for each year where statistics are kept. This calculation was facilitated by the field "FIRE" in the liquid pipeline database, which answered the question "Was there a fire? (y/n)."

Table 3. Calculation of Annual Fire Probability for Liquid Pipelines

Year	Number of Large Fires	Miles of Pipeline	Meters of Pipeline	Fires/m	Fraction of Year Fire Occurs	Probability of Fire at Location and Time
1986	9	153462	2.46974E+08	3.64411E-08	1.14077E-04	4.1571E-12
1987	6	152859	2.46003E+08	2.43899E-08	1.14077E-04	2.78233E-12
1988	4	152547	2.45501E+08	1.62932E-08	1.14077E-04	1.85868E-12
1989	4	150488	2.42187E+08	1.65161E-08	1.14077E-04	1.88411E-12
1990	2	149008	2.39806E+08	8.34009E-09	1.14077E-04	9.51413E-13
1991	2	150425	2.42086E+08	8.26153E-09	1.14077E-04	9.42451E-13
1992	4	152595	2.45578E+08	1.62881E-08	1.14077E-04	1.8581E-12
1993	1	165781	2.66799E+08	3.74814E-09	1.14077E-04	4.27577E-13
1994	10	155208	2.49784E+08	4.00347E-08	1.14077E-04	4.56704E-12
1995	4	153566	2.47141E+08	1.61851E-08	1.14077E-04	1.84635E-12
1996	8	154863	2.49228E+08	3.20991E-08	1.14077E-04	3.66177E-12
1997	5	155140	2.49674E+08	2.00261E-08	1.14077E-04	2.28452E-12
1998	7	156753	2.52270E+08	2.77481E-08	1.14077E-04	3.16542E-12
1999	3	157024	2.52706E+08	1.18715E-08	1.14077E-04	1.35427E-12
					Average	2.26722E-12

For natural gas transmission and distribution pipelines, Tables 4 and 5, show that the probabilities, based on an assumed one-hour fire duration, of a fire being present at any one-meter length of pipeline 6 inches and larger are 8.6 x 10^{-13} and 3.7 x 10^{-13} per year repectively. These probabilities represent three to four fires per year for 460000 to 490000 km (290000 to 300000 miles) of gas transmission pipeline, and about five fires per year for 1200000 to 1600000 km (780000 to 1000000 miles) of gas distribution pipeline. Searching for fires in these data was more difficult because the field "FIRE" is not included in the current natural gas transmission and distribution pipeline database. In order to determine the number of fires annually, the comment field of incidents with breaks or ruptures of pipes over 6 inches was searched for the words "fire", "burn" or "explo" to determine if a fire or explosion possibly occurred. The comments thus identified were then read to determine if there were false positive readings, i. e., if words such as "no fire occurred" or "the fire department responded" were present in the comments field. Summing the average probabilities for the pipeline types, total annual probability that a break in a pipe 6 inches or larger will lead to a fire with one-hour duration at any one-meter length of pipe is estimated to be 3.5 x 10^{-12}.

Routing Considerations and Example Calculation of Overall Probability

The probability that a pipeline breaks and that a fire will occur as discussed above is half of the problem. The probability that a cask is present when the break occurs must also be considered. The joint probability that a cask will be present when the fire occurs is

Table 4. Calculation of Annual Fire Probability for Natural Gas Transmission Pipelines

Year	Number of Large Fires	Miles of Pipeline	Meters of Pipeline	Fires/m	Fraction of Year Fire Occurs	Probability of Fire at Location and Time
1986	1	289958	4.66643E+08	2.14297E-09	1.14077E-04	2.44463E-13
1987	3	291857	4.69699E+08	6.38707E-09	1.14077E-04	7.28618E-13
1988	4	288160	4.63749E+08	8.62535E-09	1.14077E-04	9.83955E-13
1989	3	287926	4.63373E+08	6.47427E-09	1.14077E-04	7.38566E-13
1990	2	291990	4.69913E+08	4.2561E-09	1.14077E-04	4.85524E-13
1991	3	293862	4.72926E+08	6.34349E-09	1.14077E-04	7.23647E-13
1992	4	291468	4.69073E+08	8.52745E-09	1.14077E-04	9.72787E-13
1993	11	293263	4.71962E+08	2.3307E-08	1.14077E-04	2.65879E-12
1994	2	301545	4.85291E+08	4.12124E-09	1.14077E-04	4.70139E-13
1995	4	296947	4.77891E+08	8.37011E-09	1.14077E-04	9.54838E-13
1996	3	292186	4.70229E+08	6.37987E-09	1.14077E-04	7.27798E-13
1997	1	294304	4.73637E+08	2.11132E-09	1.14077E-04	2.40853E-13
1998	6	301700	4.85540E+08	1.23574E-08	1.14077E-04	1.40969E-12
1999	3	301079	4.84541E+08	6.19143E-09	1.14077E-04	7.06301E-13

Average 8.60427E-13

Table 5. Calculation of Annual Fire Probability for Natural Gas Distribution Pipelines

Year	Number of Large Fires	Miles of Pipeline	Meters of Pipeline	Fires/m	Fraction of Year Fire Occurs	Probability of Fire at Location and Time
1986	5	780401	1.25594E+09	3.98109E-09	1.14077E-04	4.54152E-13
1987	8	802335	1.29124E+09	6.19562E-09	1.14077E-04	7.06778E-13
1988	3	866639	1.39472E+09	2.15096E-09	1.14077E-04	2.45376E-13
1989	2	838237	1.34901E+09	1.48256E-09	1.14077E-04	1.69127E-13
1990	5	945964	1.52238E+09	3.28432E-09	1.14077E-04	3.74666E-13
1991	8	890876	1.43373E+09	5.57986E-09	1.14077E-04	6.36534E-13
1992	3	891984	1.43551E+09	2.08985E-09	1.14077E-04	2.38404E-13
1993	5	951750	1.53170E+09	3.26436E-09	1.14077E-04	3.72388E-13
1994	11	1002669	1.61364E+09	6.81688E-09	1.14077E-04	7.7765E-13
1995	2	1003798	1.61546E+09	1.23804E-09	1.14077E-04	1.41232E-13
1996	4	992860	1.59786E+09	2.50335E-09	1.14077E-04	2.85575E-13
1997	6	1002896	1.61401E+09	3.71745E-09	1.14077E-04	4.24076E-13
1998	4	1004373	1.61638E+09	2.47466E-09	1.14077E-04	2.82302E-13
1999	2	1007065	1.62072E+09	1.23402E-09	1.14077E-04	1.40774E-13

Average	3.74931E-13

$$P_{Fire\_damage} = P_{Fire\_present}\, P_{Cask\_present} \tag{1}$$

where,

$P_{Fire\_present}$ = The annual probability that a large fire will occur at a specific location along a railroad at a given time.

$P_{Cask\_present}$ = The annual probability that a cask will be present at the same specific location along the right-of-way when the pipeline fire occurs.

The first of these probabilities is presented in the previous section. Many different route models may be considered to estimate the second probability. One such model can be represented as

$$P_{Cask\_present} = P_{Cask\_location}\, P_{Cask\_time}\, P_{Pipeline\_present} \tag{2}$$

where,

$P_{Cask\_location}$ = The annual probability that a cask will be at a particular location along the railroad.

P_{Cask_time} = The annual probability that a cask will be at a particular location along the railroad at a given time.

$P_{Pipeline\_present}$= The probability that a pipeline will be present along the railroad right-of-way.

If the cask is equally likely to be at any location along the route, the first of these probabilities can be estimated from the cask length, the number of casks, and the route length.

$$P_{Cask\_location} = \text{(cask length)(no. of casks)/(route length)} \tag{3}$$

The second probability, P_{Cask_time}, can be estimated from maximum stop time at sidings along the route

$$P_{Cask\_time} = \text{(max. stop time)/(hours per year)} \tag{4}$$

The third probability, $P_{Pipeline\_present}$, may be determined by studies of rail line and pipeline routing as presented above. Note that this example does not include possible short-duration fires that results as moving trains pass a pipe break.

As an illustrative example of use of the data, consider a single shipment of a 5 m long cask over a route of 1600 km (1000 miles) at an average speed of 32 km/hr (20 miles per hour). Assume a maximum siding stop time of 4 hours. From Equations (3) and (4),

$$P_{Cask\_location} = (5\text{ m})(1\text{ cask})/(1600\text{ km}) = 3.125 \times 10^{-6} \tag{5}$$

$$P_{Cask\_time} = (4\text{ hours})/(8766\text{ hours}) = 4.6 \times 10^{-4} \tag{6}$$

From Table 2 above, the maximum probability for presence of a pipeline adjacent to the tracks is

$$P_{Pipeline\_present} = 0.17 \tag{7}$$

These may be combined as shown in Equation (2) above

$$P_{Cask\_present} = (3.125 \times 10^{-6})(4.6 \times 10^{-4})(0.17) = 2.42 \times 10^{-10} \tag{8}$$

To obtain the overall joint annual probability that this cask will be damaged by a pipeline fire Equation (1) is used,

$$P_{Fire\_damage} = (3.5 \times 10^{-12})(2.42 \times 10^{-10}) = 8.5 \times 10^{-22} \tag{9}$$

Where the first probability, $P_{Fire\_present}$, is the sum of the probabilities tabulated in Tables 3 to 5 above.

TRAIN ACCIDENTS INVOLVING FIRES

A second category of fire accidents that could occur during rail transportation of radioactive materials is fires that occur during train derailments. To estimate these probabilities, statistics kept by the Federal Railroad Administration (FRA) have been used. These statistics are available to the public for computer download on their web site (http://safetydata.fra.dot.gov/OfficeofSafety/).

Estimation of Fire Probabilities

Data for the 10-year period between 1990 and 1999 have been used to estimate the probability that a car carrying hazardous cargo will have a fire resulting from release of contents. Table 6 shows data collected from the FRA web site.

Table 6 was constructed by first testing the field "CARSHZD" in the data base that indicates how many cars released hazardous materials (HAZMAT) during train accidents. The records for which CARSHZD was greater than zero were isolated, and then the narrative descriptions associated with the accidents were searched for the words "fire", "burn" and "explo." Where those words occurred, the

Table 6. Railroad Fire Accident Probability

Year	Number of Hazmat Releases	Number of Hazmat Fires	Total Train Miles	Total Train Kilometers	Fires per Train Mile	Fires per Train km
1990	35	2	6.08837E+08	9.79830E+08	3.28495E-09	2.04117E-09
1991	47	2	5.76835E+08	9.28328E+08	3.4672E-09	2.15441E-09
1992	27	1	5.93704E+08	9.55476E+08	1.68434E-09	1.0466E-09
1993	30	0	6.13974E+08	9.88097E+08	0	0
1994	36	2	6.55083E+08	1.05426E+09	3.05305E-09	1.89707E-09
1995	27	2	6.69823E+08	1.07798E+09	2.98586E-09	1.85533E-09
1996	34	1	6.70923E+08	1.07975E+09	1.49048E-09	9.26142E-10
1997	31	1	6.76716E+08	1.08907E+09	1.47772E-09	9.18214E-10
1998	43	0	6.82895E+08	1.09902E+09	0	0
1999	42	0	7.12453E+08	1.14658E+09	0	0
	Totals	11	6.46124E+09	1.03984E+10	1.70246E-09	1.05786E-09

narratives were read to assure that a fire had actually occurred. This approach does not include locomotive fuel fires, which, because of the comparatively limited quantity of fuel involved and distance from most train cars, should not pose a significant threat to casks. As shown in the table, about one fire per year over 9×10^8 to 1.3×10^9 train kilometers (600 to 800 million train miles) results in an average overall fire probability of 1.1×10^{-9} per train kilometer traveled. Note that the train distances traveled are for all trains regardless of whether hazardous cargoes are included in the train or not. Because of this, the probabilities do not need to be adjusted to account for the fact that some trains do not include hazardous cargoes.

Routing Considerations and Example Calculation of Overall Probability

As with the pipeline study, some routing assumptions are required before an overall estimate of the probability of a train fire accident during a cask shipment can be evaluated. Solely for purposes of illustration, assume that a single cask is included in a normally mixed freight train with all types of cargo. In such trains, there is a large probability that the cask will not be located near the cars where the fire occurs. For a typical 60 car-length freight train, assume that the cask must be within five car-lengths of the fire to be threatened directly by a fire or by propagation of fire. Thus, there are 10 chances in 60, or a probability of 0.167, that if a fire occurs, the cask will be involved. For a single 1600 km (1000 mile) length route, the probability of being involved in a train fire would be

$$P_{Cask\_in\_fire} = P_{Cask\_near\_fire} P_{Train\_fire} \mathrm{x} \text{ (route length)} \tag{10}$$

or, applying the discussion above and Table 6

$$P_{Cask\_in\_fire} = (0.167)(1.1 \times 10^{-9})(1600) = 2.9 \times 10^{-7} \tag{11}$$

For longer routes and more casks, the probability would increase proportionately.

DISCUSSION AND CONCLUSIONS

Analysis of pipeline and railroad fire probabilities has led to development of techniques of potential use to risk analysts considering radioactive materials transport. The methods of probability and statistics have been applied to develop information on the likelihood of rail cask exposure to fires.

Because of the low likelihood, but potentially severe thermal conditions caused by turbulent mixing of oxygen into the fire plume, pipeline fires fall into the category of very low probability, high consequence accidents. Such accidents are not normally included in risk assessments because they do not contribute significantly to the total risk. For comparison, the probability of a meteor striking a cask has been estimated to be on the order of 10^{-19} by Chapman [1]. Chapman estimates chance of a destructive (but not Extinction Level) impact at as much as 10^{-5} yr^{-1} for the earth as a whole. The probability of striking any particular 100 m^2 area (i.e., the vicinity of a loaded cask) is 100 m^2 divided by the earth's surface area ($5.1 \mathrm{x} 10^{-14}$ m^2) multiplied by 10^{-5} yr^{-1}, which is approximately equal to 2×10^{-18} per year. This strike probability is higher than the probability level estimated above for the joint probability of a pipe break fire impinging on a cask during rail transport.

Even the low values for a pipeline break fire probabilities provided above have some conservatism included. For example, if a pipeline ruptures near a cask, the jet of burning fluid may point in a direction away from the cask, and many fire jets will be too small or of too short a duration to cause significant damage. Furthermore, pipelines near railroad rights-of-way are usually buried. This reduces the potential exposure in rail accidents. In a National Transportation Safety Board report [2], the then Santa Fe railroad stated that 55 per cent of its 5300 km (3300 mile) pipeline network was installed along railroad right-of-way, and that in a 23 year period with 121 train derailments, no pipeline damage was experienced. If such factors are included, the pipeline fire risk is reduced even further.

The pipeline fire probabilities are based on a one-hour fire duration assumption. If a longer or shorter fire duration is assumed, the probabilities scale upward or downward proportionately, but because of the extremely low overall probability of occurrence, the effect on total risk in a typical risk analysis would likely be undetectable.

The estimate of the fraction of pipelines near railroad tracks presented above was based on limited information from the State of Texas. As the National Pipeline Mapping Service (http://www.npms.rspa.dot.gov/) completes its database, data will become available to improve these estimates through the use of Geographic Information Systems that compare nationwide pipeline and rail line maps.

For train transportation, the probability of a hazardous materials fire, assuming a freight train with a normal mix of cargoes, is high enough to be considered in transportation risk assessments. For a risk assessment, additional information such as the distribution of fire duration, the potential for car-to-car propagation of fire, and the probability that a fire will be intense enough to cause damage must also be considered.

Both tank-car spills and tank-car relief-valve fires can pose a threat to casks, but a local pool fire may not engulf the cask, and a relief-valve fire jet may not be directed toward the cask surfaces. The most commonly feared railroad accident, the Boiling Liquid Expanding Vapor Explosion or BLEVE, involving the explosive release of a liquid petroleum product such as propane is of very short duration. For this reason, a BLEVE is not likely to thermally damage a cask. Complete risk studies would take effects such as these into account.

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REFERENCES

[1] Chapman, C. R., 1998, Statement on the Threat of Impact of Near-Earth Asteroids by Dr. Clark R. Chapman, Southwest Research Institute, U.S. Congressional Hearings on Near-Earth Objects and Planetary Defense, May 21, 1998, Washington, DC.

[2] National Transportation Safety Board, 1990, *Derailment of Southern Pacific Transportation Company Freight Train on May 12, 1989 and Subsequent Rupture of CALNEV Petroleum Pipeline on May 25, 1989, San Bernardino California*, PB90-918303, NTSB/RAR-90/02, Washington, DC, p. 84.