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A REALISTIC CHARACTERIZATION OF SEVERE RAILROAD ACCIDENTS - CASE STUDY: TANK CARS

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REALISTIC CHARACTERIZATION OF SEVERE RAILROAD ACCIDENTS

CASE STUDY - TANK CARS

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I. INTRODUCTION

This paper presents the results of studies aimed at characterizing the nature of the railroad accident environment. These studies were focused on the way this environment affects proposed shipping of spent nuclear fuel and radioactive wastes. They were developed because of skepticism voiced by railroad personnel in recent years concerning the ability of nuclear packaging to safely withstand severe railroad accident conditions. These concerns were the subject of a major portion of the recent ICC hearings held concerning transport of radioactive spent fuel and wastes by rail.

It has generally been recognized by even critics that such nuclear packages are structurally better than most other containers moved by railroads. The critics objections focused on the following concerns, that:

(1) The package designers do not have a clear perception of design requirements to withstand railroad accidents.

(2) The NRC/DOT accident scenarios which function as design criteria for package design inadequately describe the severity of these accidents. In particular, the forces, fire temperatures, and fire durations specified by NRC/DOT were thought to be insufficient.

During the course of the ICC hearings, these charges were addressed and countered by the parties representing government and industry shippers.

The objective of this paper is not to state that one can accurately define the exact nature of all railroad accidents, nor to state that accident data can easily be translated into regulations and design criteria. History has shown this to be a difficult task for even those who have frequently been involved with railroad accidents. Rather, the intent is to show that upper limits for accident frequencies, physical forces, and fire effects, etc., can be established. These limits can be based on analysis of past accidents and the equipment involved. In simple language, no force is infinite no matter how long the train is and how fast it is going. Similarly, flame temperatures and fire durations are finite. Boundaries can be placed on the loadings imposed on a package. A direct comparison will be made with the programs and regulations established by the Federal Railroad Administration and the railroad industry to make tank car movement of hazardous materials safer.(1) These are compared with the regulations and design criteria used for radioactive material packages.

II. ACCIDENT FREQUENCY

A first line of reasoning is that the probability of a major nuclear shipping accident occurring is very small when viewed on a car-mile basis. The annual rail shipment volume of radioactive material is not projected to exceed over a few million car-miles per year. One difficulty in trying to convince the average person that nuclear transport is safe lies in the lack of data. There have been no major accidents in 25 years with nuclear shipments, but there have been relatively few shipments compared to railroad shipping of other hazardous materials. Recent studies have taken the opposite tack and used the accident history of the entire rail industry. However, there are also difficulties in this approach. First, this is too broad a spectrum. It involves all types of cars and ladings. The relative propensity of this equipment to cause or aggravate a major accident will vary widely. An additional problem is how to define a major accident which would have any possibility of significantly effecting a spent fuel or waste package.

In this study, an "in-between" approach was taken. A case study was made of railroad tank cars carrying hazardous material. This permitted a comprehensive study to be made since there is an adequate statistical basis (in excess of 100,000 possible tank cars, many years of experience, and billions of car-miles travelled). A large amount of government and industry attention has been devoted to the study of tank car transport. This is a direct result of the number and severity of tank-car accidents that have occurred within the last 10 years and the adverse publicity resulting. There is also a direct comparison with nuclear shipping, since tank cars are also regulated by the DOT, including the approval of package design. Also, the size and weight of these shipments are similar to spent fuel and waste cars.

The statistical data concerning tank car accidents was obtained directly from unpublished information compiled by the Federal Railroad Administration (FRA)[2] within the Department of Transportation. A number of technical studies have been published concerning proposed design criteria, accident and safety testing, etc. These, too, were reviewed in detail. The crux of the study on accident frequency was to determine how many accidents in a given year could be classified as severe. Five criterion were postulated and individually evaluated for classification purposes. These were:

(1) Damage cost - A reported damage cost in excess of $300,000.

(2) Public impact - Either any loss of life, five or more injuries reported, or evacuation of 1000 or more people.

(3) Total number of cars involved - Seven cars or more involved in an accident event.

(4) Mechanical or thermal damage to car - Five cars or more destroyed by either collision, puncture, fire, or explosion.

(5) Both mechanical and thermal damage to car - Four cars or more destroyed by both collision and fire damage.

TABLE 1

FREQUENCY OF MAJOR TANK CAR ACCIDENTS

Criterion	Annual Number of Events Maximum	Minimum	Average	Average Probability* ($x10^{-8}$/car-mile)
1. Cost	11	3	6.0	1.5
2. Public Impact	9	2	6.5	1.3
3. Number of Cars	10	2	5.5	2.6
4. Mechanical or Thermal Damage	6	1	3.5	1.3
5. Both Mechanical and Thermal Damage	6	1	2.7	1.0

*Based on total number of cars involved.

The results of this study are shown in Table 1. Examination of this data would indicate that hazardous material laden tank cars have a probability of being in a serious accident on the order of $1.0 - 3 \times 10^{-8}$ per car-mile. The range of severe train accidents is from 3 to 14 per year with a mean of about six to seven accidents. Category (5) is of greatest interest since it yields the joint probability of a car receiving both mechanical and thermal damage. This is about 1.0×10^{-8} per car-mile.

Applying this data to the transport of nuclear fuel, a typical case can be made based on the projected fuel receipt at the Barnwell Nuclear Fuel Plant (assuming all fuel received by rail).

1 car load = 4.5 MTU
Average trip distance = 1100 miles
Projected fuel receipt rate = 1500 MTU/year

Probability of a loaded nuclear cask being involved in a major accident = $(1.0 \times 10^{-8})/\text{car-mile} \times \frac{1500 \text{ MTU/yr}}{4.5 \text{ MTU/car trip}} \times \frac{1100 \text{ miles}}{\text{trip}} = .0036$ per year or once every 270 years. The range for all movement of spent fuel is probably more like once per 75-150 years.

This is in good agreement with estimates made using other statistical bases. It illustrates the unlikelihood of even being involved with a serious accident. Minor accidents are about 10-15 times more frequent, but these would have no significant effect on spent fuel cask integrity.

III. COLLISION FORCES

A major point of contention in the ICC hearings was the amount of force which could be applied to an object during an accident. Considerable confusion resulted from attempts to correlate the kinetic energy involved in a typical 70- to 80-car train accident with maximum localized forces. Clearly the salient criterion for evaluating container integrity is the force required to breach the container wall. Also of interest is the shape of the impacting object. The following relevant observations were made after examining both rail car structural data and accident reports.

(1) Trains do not behave as a column structure - examination of numerous photos indicated that the cars were scattered, stacked, and jackknifed in a number of different directions.

(2) The force required to crush or buckle the framework of a typical car is about one million pounds.[3, 4] A well designed heavy-duty car with a cushioned underframe may be able to withstand two to three million pounds, but there are comparatively few of these cars.[5]

(3) The rail car coupler itself is a major cause of punctures, particularly in tank car accidents. Typically, couplers will begin to buckle under a loading of about 1-1.5 million pounds.[6] Examination of supported lengths of steel rail, also a major cause of puncture, indicate that they, too, will buckle at or below about 1.3 million pounds.[6]

(4) Studies on the location of coupler punctures on tank cars show that the highest percentage occurred on the elliptical heads.[7] Approximately two-thirds of those occurred in the lower half of the head.

(5) The actual collision forces in an accident typically occur with the individual cars traveling at relative velocities of 15 to 20 mph. The train speed may have been considerably higher at the initiation of the accident, but as the accident progresses, the speed of the cars decrease.

(6) Much of the kinetic energy in a large train, high-speed accident is dissipated in car-to-car collisions including stacking and jack-knifing. As a result, no point on a single car would receive even a small fraction of the kinetic energy dissipated in a large train accident. Many accidents involve multiple sequential impacts with lower forces than occurs with a single severe impact.

A study performed for the Federal Railroad Administration (FRA)[8] which attempted to analytically recreate a number of devastating tank car accidents indicate a range of forces extending from about one to 3.5 million pounds[7] could have been applied to a particular tank car. The accident evaluations reviewed indicated that even in a long train, forces are higher, but not limitless. An upper limit can be estimated for hypothetical situations, of about four to five million pounds.

The FRA has proposed the following legislation requirements[1] to upgrade the capability of certain tank cars to withstand mechanical loadings and minimize the probability of car puncture:

(1) Shelf couplers - E or F type shelf couplers are required to prevent vertical disengagement of the coupler.

(2) Tank head puncture resistance system - typically a steel head shield about 0.5-inch thick to minimize the probability of puncturing the tank car shell.

(3) Performance testing - An 18-mph impact test of a tank car (brakes locked) by a 263,000-pound ram car. The ram car will be backed up by additional cars with a total weight of at least 480,000 pounds. The test car contains pressurized water. The coupler will hit the test car at the thinnest section of the tank. There is to be no loss of contents for one hour after the test.

Recent testimony has indicated that merely changing to shelf couplers and adding head shields will reduce tank car accidents by 80-85%.

IV. FIRE ACCIDENT CONDITIONS

Fire accident parameters like those involving collision forces are very complex. They include: average fire temperature, fire duration, emissivity of the fire and absorptivity of receiving body, the area of the receiving body exposed to flame, and the effective heat capacity of the receiving body. These parameters must be examined jointly since their interrelationships are complex. Isolating any individual parameter such as the temperature or duration can lead to erroneous conclusions.

There are two general types of petroleum-based fuel fires that occur in major rail accidents.

- Pool Fires - This could occur as the result of a tank car spilling its contents into a ditch along side railroad trackage. The flame temperature may vary from about 1200-2000°F locally with a bulk average of about 1400-1600°F.(8) The combustion rate is about 10 gallons per square foot of surface per hour.

- Torching - This might occur when a tank car carrying a flammable gas such as propane is, itself, in a fire. After a period of time, the safety valve opens expelling propane which ignites. The flame temperature will typically be in the range of 2100-2300°F.(1) The resulting flame is highly localized and concentrated.

Examination of the above types of fires indicate that the flame temperature is much lower than the theoretical combustion temperatures. This is due to incomplete combustion of the fuel and is evidenced by observation of a great deal of black smoke.

The following observations were developed from data from accident reports concerning fire consequences.

(1) Fires of several days duration were reported. However, duration is not necessarily representative of the amount and the intensity of the heat from the fire. Frequently, long duration fires are characterized by a number of small, scattered fires of low heat intensity or torching from a tank car valve failure or split in tank shell.

(2) The total time required to burn the contents of one entire 30,000-gallon carload of petroleum in a pool fire is about 1-1/2 hours.

(3) A hot fire that can totally envelop a large body must be large. The fuel must burn with an intense flame. Grass and wood fires, which occur due to burning of rail car components and ladings, are an insignificant source of heat.

(4) The most dramatic type of fire, the BLEVE (Boiling Liquid Expanding Vapor Explosion), is, in effect, a high-intensity fireball of short duration. The total heat input into a nuclear cask would be very small.

The above observations all focus upon the ability of a large, heavy walled, metallic container to withstand a major fire. Namely, (1) the fire must burn in one location for the specified period of time (at least one to two hours), (2) the flame intensity must be at least 1300-1500°F, and (3) must be of sufficient size to substantially envelope the body for the entire period of time. What is of importance is the capability of the fire to transfer heat to the package and the temperature rise of the package material, not how spectacular the fire seems to an observer.

Referring to the tank car case study, the FRA has proposed legislation concerning fire resistance of pressurized tank cars.[1] A thermal protection system (typically insulation) is required. The protection system limits tank car pressure during the fire by lowering the heat input into the car and assuring that the tank safety valve is adequately sized to expell sufficient vapor. A performance specification for this system protects against the following fires.

(1) Pool Fire Test - 1600 ± 100°F hydrocarbon fire for a period of 100 minutes.

(2) Torch Fire Test - 2200 ± 100°F hydrocarbon fire for a period of 30 minutes. Torch velocity of 40 ± 10 mph.

A calibration test for the flame temperature involving the temperature rise in a 4-foot by 4-foot by 5/8-inch thick steel plate is further specified.

V. COMPARISON WITH NUCLEAR PACKAGING CRITERION

Previous portions of this paper have presented data for tank cars related to accident frequencies, collision forces, and fire conditions. To a considerable degree, this data should be representative of the actual railroad environment and in particular severe accident conditions. A frequent concern during the ICC hearings was the comparison between the so-called "real" accident environment and the Nuclear Packaging hypothetical accident conditions. The only way to make a comparison is by evaluation of the conditions on a specific package. This is particularly true since the federal regulations are performance specifications or tests which are generally applicable to all modes of transportation--not just rail. The package selected for comparison was the NLI 10/24 spent fuel rail cask. This 100-ton cask is of all welded construction and is fabricated primarily from steel. Lead is used as the gamma shield. The relationship between the derived accident environment and the federal hypothetical accidents was found to be as follows:

(1) Fire - The DOT conditions recognize both a 1600°F pool fire (100 minutes) and a 2200°F localized torch fire (30 minutes). The NRC fire is 1475°F for 30 minutes. The DOT fires are test oriented with calibration by temperature rise in a steel plate. The NRC criterion is analysis oriented with stringent definition of the fire emissivity and cask absorptivity. The various fire conditions were calibrated using the TRUMP computer program to a common basis. The simulated fires were then applied analytically to the NL 10/24 cask wall for a period of one hour. Ranking in terms of severity was:

(a) 1475°F enveloping fire (most severe)
(b) 1600°F pool fire
(c) 2200°F torch fire (least severe)

The 2200°F fire was of little concern due to the localized area of the cask affected. Definition of the emissivities in the 1475°F fire made this fire most severe. These results illustrate that fire temperatures, by themselves, do not totally define a fire severity.

(2) Puncture - The major source of tank car puncture (and loss of lading) results directly from overriding couplers. The NRC criterion is a 40-inch drop of the package on a 6-inch pin. Relating the force at which the coupler buckles to an experimental test of the pin drop reveals:

	FORCE (million pounds)	LOCAL STRESS (psi)
Coupler Buckling	1.0 - 1.5	12,500 (E-type coupler face)
Pin-Drop Test	2.1 - 2.8	53,000

In this situation, the pin drop is clearly 3-4 times more severe.

(3) Major Collision - The NRC accident condition is a 30-foot drop onto an unyielding surface. The only possible comparison is the tank car head shield impact at 18 mph. There is obviously no basis for comparison since neither the impacting or target car is unyielding. The 30-foot drop test is far more severe. The crucial condition is the unyielding surface which assures that all of the impact load kinetic energy is expended in the package. For this reason, the 30-foot drop cannot be equated to a 30-mph collision. There is no object located along railroad trackage that even approximates an unyielding body. Test studies have revealed that a 30-foot drop of a cask onto an unyielding surface is more severe than a 2000-foot drop onto hard-pan soil.

VI. CONCLUSIONS

The railroad accident environment can be very severe. However, it is possible to develop worst case or limiting situations by analyses of past accidents. These conditions can be compared with federal regulations which specify hypothetical accident criteria. The NRC licensing criteria (when applied in its totality) is readily shown to be extremely severe. The major questionable area is fire duration. A duration of one to two hours (rather than 30 minutes) seems possible. However, the NRC fire accident condition is based on completely enveloping the package. From a practical standpoint, this is impossible. The heat input and subsequent temperature rise to a package, which is partially protected by the car or the ground, is much less than for the idealistic "fully enveloping" situation.

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