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Use of Risk Analysis in Enhancing the Safety of Transporting Hazardous Liquefied Gases

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ABSTRACT

Three risk analyses were performed on the land transportation of hazardous liquefied gases in Finland. The gases considered were chlorine, anhydrous ammonia, sulphur dioxide, and liquefied petroleum gas. The accident file of Finnish State Railways allowed a detailed classification of railway accidents into 14 categories. The estimated conditional probabilities were then combined with the actual traffic data to give the probability of a tank wagon being involved in a railway accident. Structural analyses of the wagons were performed to estimate the probability of leakage when an accident occurs. A review of road accidents involving heavy vehicles was performed to assess the damage probabilities of road tankers. The estimation of the accident probabilities was complemented with calculations of gas dispersion and evaluations of the population density along the transportation routes. Risk analysis was an instructive way of going through all the factors contributing to the accident risk. In this way it was possible to suggest a number of measures by which accident risk could be reduced. The following changes, based on those suggestions, have been implemented: (a) construction of the manway nozzle in transportable pressure vessels has been improved; (b) installation of head shields and buffer override restraints has been continued; and (c) tank wagons carrying hazardous liquefied gases are positioned in the middle of a train. The risk studies also provided background material for national instructions for emergency preparedness and response to accidents involving hazardous materials.

Two-thirds of Finnish land territory is covered by forest. It is therefore not surprising that the national pulp and paper industry has traditionally provided a major part of exports.

Bleached pulp is produced at 18 mills situated throughout the country. The principal bleaching agent, chlorine, is produced at only two pulp mills; liquid chlorine produced at four plants is hauled by rail to the remaining 16 mills. The annual shipment of liquid chlorine ranges from 140 000 to 175 000 tonnes.

The pulp industry has become a consumer of liquid sulphur dioxide. Sulphur dioxide is recovered at a copper smelter and part of it is liquefied and carried by rail and road to pulp mills. About 50 000 tonnes are shipped annually.

Nitrogen fertilizers are produced at four plants. These plants are the major consumers of anhydrous ammonia in Finland. Almost all anhydrous ammonia is imported by tanker ships and by rail. The domestic overland shipments amount to 150 000 to 200 000 tonnes annually, of which more than 90 percent is carried by rail.

Two Finnish oil refineries produce about 100 000 tonnes of liquefied petroleum gas (LPG), which is carried to the customers and cylinder-filling plants in rail tank wagons and road tankers.

Because of Finland's geographical position and because Finnish railways have the broad Soviet gauge, some Finnish harbors constitute an important link in the trade of petroleum products and basic chemicals between the Soviet Union and some Western

European countries. Most of these commodities are flammable liquids. In the late 1970s the Soviet Union exported anhydrous ammonia through a harbor in southwestern Finland at a rate of 200 000 tons annually. In 1985 exportation of LPG through a harbor in southeastern Finland will begin. Annual shipments are projected to reach 200 000 tonnes.

SAFETY RECORD OF HAZARDOUS MATERIALS TRANSPORTATION

The only fatal accident during hazardous materials transportation occurred in 1938 in southeastern Finland. In this accident, a passenger train and a goods train collided head-on in a dense fog at a small station. An overriding coupler hook punctured the head of a sulphur dioxide tank wagon that was coupled to the locomotive. Eight passengers were asphyxiated by the gas and two received fatal injuries in the collision. Six persons were taken to a hospital because they had symptoms of toxication.

The sleeping passengers were awakened by the crash and some of them tried to escape. The victims were those who ran into the gas cloud, which could not be seen due to the fog. Those who could control themselves stayed in the sleeping cars and were instructed to breathe through wetted towels and sheets by soldiers who happened to be traveling on the train.

In 1947, a 25-tonne chlorine storage vessel in a pulp mill in southwestern Finland ruptured 11 hr after it had been filled from rail tank wagons. The accident was caused by overfilling. The ruptured vessel was located in a building that collapsed. The five remaining vessels remained intact, but chlorine leaked for 10 days from damaged piping. In this accident, 19 workers were killed by the gas and 123 workers and local inhabitants were rescued and transported to a hospital, of which 45 were admitted.

The safety record of hazardous materials transportation in Finland has been good. Experience from these two spills, however, emphasized the necessity of preventing the recurrence of such accidents. Thus, when the domestic production of liquid chlorine began in 1954, tank wagons were equipped with head shields and buffer override restraints to prevent tank head puncture during collisions. Finnish State Railways and the producers of hazardous gases have agreed that the industry will form and equip groups that will provide technical assistance during transportation accidents. Finnish State Railways has also formed assistance groups of rolling stock maintenance workers.

STARTING POINT

The Technical Research Centre of Finland is a government-sponsored nonprofit research institute consisting of 32 laboratories. In 1975 the Research Centre performed a probabilistic risk analysis of a proposed nuclear power plant for the national energy authorities. This study was favorably received, and it was decided to explore nonnuclear applications of the method. Representatives of the authorities, chemical industry, and insurance companies were consulted, and several of them suggested chlorine transportation as a subject for risk analysis.

This study was performed in 1976, and it was sponsored by the authorities, industries producing and using chlorine, and insurance companies. The project group included an expert on reliability analysis and two experts on structural analysis. Computer codes using the finite element method were utilized in the calculation of stresses caused by internal pressure and external loads.

The following problems emerged during discussions with the railway authorities:

1. The old (1954) type of head shield is made of thick steel plate and is supported by steel bars. The new type is a curved plate with no supporting bars. How effective is the latter type in preventing tank head punctures?
2. A pneumatic type of loading valve had been employed during trial use to enhance operational safety in loading and unloading. This particular valve also has the safety feature of remaining closed if its outer part is broken off during a transportation accident. Will the new valve enhance transportation safety too?
3. The train composition rules in force required that a wagon carrying a toxic material such as chloride must not be coupled directly with a locomotive or a wagon loaded with flammable materials. Are these restrictions sufficient?
4. Given the head shield and override restraints, puncturing of a tank was regarded as possible only in violent collisions. Such collisions were expected to occur on single-track lines and at small stations at which trains meet. However, in large stations and marshalling yards, in which trains and locomotives move at reduced speeds, tank puncture was not considered possible. Is this assumption reliable?

Simultaneously the Ministry of the Interior had set up a working group to study the demands that hazardous materials make on emergency services. The working group restricted its task to materials capable of causing major accidents, that is, hazardous liquefied gases. The group presented a list of several items for further consideration:

1. The size of the gas cloud resulting from a major chlorine spill,
2. Different methods available for alerting the population during a transportation accident,
3. The effect of staying indoors,
4. Methods of stopping a leak and of reducing evaporation from a spill,
5. Methods of diluting and diverting gas clouds, and
6. The need for protective equipment.

DAMAGE AND FAILURE STUDIES

Two previous analyses of the transportation of liquid chlorine were known to the author when this study was initiated. Westbrook compared the accident risks of rail and road transportation in the United Kingdom (1). Simmons et al. have performed an analysis of rail transportation in the United States as a nonnuclear example of low-probability high-consequence accidents (2). These studies have their merits, but their approach is academic, because they were not performed to support actual safety-related decision making.

The problem in evaluating low-probability accidents is that the data base of past accidents is too small to allow any conclusion on the significance of the various potential causes of a spill. Simmons et al. used the rate of accidents for pressure tank wagons that result in the loss of most of the cargo (2). This rate, however, was a factor of 10 higher than the rate of chlorine spills. Westbrook noted the absence of pressure tank punctures in the United Kingdom and used the conditional probability of a

spill, given a "significant" accident calculated from U.S. data (1). The differences between transport conditions in the United States and in the United Kingdom were taken into account without consideration of wider application. The U.K. rate of significant accidents was used.

Lack of data on valve and tank damage to Finnish pressurized tank wagons was obvious: no damage had occurred since 1954, when the transportation of liquefied gases was resumed. Nor had any random loading valve failures occurred during the 22-year period. It was decided to use Finnish data on railway accidents, and to estimate the damage probabilities and failure rates on the basis of foreign data.

Classification of railway accidents was necessary for several reasons. Wagon velocity during an accident is an essential parameter for determining damage probability. Wagon velocities differ markedly between, for example, shunting accidents and train collisions that occur on line. The probability that a sharp or rigid object capable of damaging the tank will be present is different in different accidents. Moreover, the consequences of a spill will be on a different scale for accidents that occur in marshalling yards (which are in cities) than for accidents that occur on line.

The accident statistics of Finnish State Railways provided a good starting point for the classification of railway accidents. To classify chlorine leakages according to primary cause, three categories were used for accidents that occurred on line and two categories were used for those that occurred at stations.

- Categories of railway accidents that occur on line:
  - J Collisions
  - S Derailments
  - T Level crossing accidents
- Categories of railway accidents that occur at stations:
  - P Collisions
  - K Switching accidents
- Categories of random failures:
  - L Leakage in a moving tank wagon
  - V Leakage in a stationary tank wagon

This classification satisfies the needs of railway authorities, but was considered too coarse to be used in the estimation of damage probabilities. For instance, most level-crossing and switching accidents would be harmless to the chlorine tank and its valves.

Railway accident records and damage analyses performed in this project provided information on significant accidents and the minimum train velocities at which tank and valve damage was possible. Fourteen such accidents, called key accidents, were selected. In addition to velocity, the descriptions of the key accidents included random environmental factors causing the damage (3). For example, consider the two significant derailment accident types. Type S1 is a derailment of a chlorine tank wagon in an excavation or on a bridge. Type S2 is a derailment on a double track in which an arriving train crashes into a derailed chlorine tanker. The velocity of the derailing or colliding train was assumed to exceed 40 km h^{-1}.

The estimation of the probabilities of the key accidents required a large number of qualitative and quantitative data on the transportation system. The qualitative data were provided by Finnish State Railways, and the quantitative data were gathered from various sources by the project group. Description of the data collected for probability estimates is as follows.

1. Qualitative data
   a. Characteristics of railway sections: single or double track, section blocking, remote control, and radio link.
   b. Characteristics of level crossings: barriers and warning lights.
   c. Types of signal boxes at stations.
2. Quantitative data
   a. Departure and arrival times of trains,
   b. Number of crossing and passing trains,
   c. Total length of line in excavations and on bridges, and
   d. Road traffic densities at level crossings.

The data were written on two forms designed for this purpose. Each copy of form A contained data on a railway section and each copy of form B contained data on a train carrying chlorine wagons over a given section.

The damage modes considered in the study were: (a) impact on tank head, tank side, and valve group; (b) puncture; (c) crushing; and (d) overheating during a fire. The failure modes considered in the study were: (a) endurance or corrosion failure of the tank and (b) valve failure. When a wagon collides with an unyielding object such as a train or a rocky wall, the tank was estimated to tear off the undercarriage at velocities exceeding 18 km h^{-1}. The tank was estimated to rupture at a velocity of 40 km h^{-1}, assuming an unyielding object of collision, due to the combined action of tank deformation and splashing of tank contents.

Side impacts in railway accidents were not determined to be powerful enough to rupture the tank, except in the case in which a tank wagon rises up and falls sideways. The latter damage mechanism is rare among ordinary goods wagons, which override each other or jackknife. However, it was determined to be possible that the override restraints may contribute to the rising up of a chlorine tanker.

The loading valves are mounted on the manway cover and are protected by a dome made of steel plate 6 mm thick. Because the valve dome is a protruding part, it is likely to be the object of impacts when an overturned tanker is dragged along the ground. The dome was estimated to be able to withstand the resulting stresses unless it meets a heavy or unyielding object. In such cases, the valves may be deformed or severed. This, however, does not usually cause a major leak because of the internal excess flow valves.

The possibility of a major leak was identified for the new tank wagon in which the manway cover was connected to a nozzle to facilitate inspection of the bolts of the manway cover. It was estimated that a powerful impact on the manway flange would tear the weld of the manway nozzle, leading to a major leak.

The most vulnerable part of the tank to puncture is the head. The old head shield reinforced with steel bars was considered strong enough to eliminate head punctures. The new head shield was made of a curved steel plate 8 mm thick without stiffeners. During a collision, the latter shield would bend to meet the tank head with little energy absorption. The only effect of the shield was to make the tank head 8 mm thicker, which would increase the velocity required to puncture the tank head by 24 percent. A detached rail or switch tongue was estimated to be able to puncture the tank side at a relatively low velocity.

Tank crushing could be neglected because of the large mass required. Overheating of a chlorine tanker during a fire would make the tank shell fill with liquid and subsequently rupture (tanks carrying toxic gases do not have safety valves). A major petrol spill was considered the most significant cause of a fire. Assuming total engulfment, the chlorine tank was estimated to rupture after 6 to 7 min. The probability of this accident type occurring was considered low because petrol and chlorine were not usually hauled in the same train. Nor did trains hauling petrol and those hauling chlorine cross. Reliability data for pressure vessels and valves were used to estimate failure rates of the chlorine tank and its loading valves.

All probability estimates for leaks were performed for leak categories that had equivalent vent diameters of 3, 10, 30, and 100 mm. The range covered by the four categories was considered sufficiently large to cover all leakages that were relevant from the viewpoint of risk analysis.

CONSEQUENCE ANALYSIS

The damage and failure studies produced the probabilities of chlorine leakages in four categories for all of the railway sections and stations along the transportation routes. To complete the risk analysis, the hazard areas and the population densities were estimated. (It is not worthwhile to review the methods of consequence analysis used in the study because some of them are now outdated.)

The hazard areas were estimated for day and night, and for people outdoors and indoors. It was noticed that the average size of the hazard areas was significantly larger at night than during the day because of lower wind speeds and more stable weather categories. This is partly compensated for by the low number of people who are outdoors at night.

By using a magnetic tape of 1970 census data, which included the number of inhabitants in each 1 km^2 grid, and examining data for six municipalities, it was found that settlement was to a significant degree centered around the stations and the railway lines. Thus, the average population densities of municipalities could not be used in the estimation of population densities around potential accident sites. A simple model was developed to estimate densities for the remaining municipalities (3).

RESULTS AND CONCLUSIONS

The total amount of chlorine transported annually was 150 000 tonnes. Tank wagons with a payload of 20 and 45 tonnes were used and the average haul length was 315 km. The estimated probabilities for a liquid chlorine leak were estimated at .008 per year in train traffic and .009 in shunting operations.

The most probable causes for minor leaks (equivalent diameters of 3 and 10 mm) were:

1. Random valve failures,
2. Valve damage due to wagon overturn during shunting operations, and
3. Valve or tank damage due to an arriving train crashing into a train carrying chlorine tank wagons.

The most probable cause for major leaks (equivalent diameters of 30 and 100 mm) was tank damage, and for the new tank wagon the rupture of the manway nozzle. These were expected to occur when an arriving train crashes into a chlorine tank wagon or a train carrying chlorine tank wagons, or when trains collide head-on on a single track.

The problems that emerged during discussions with the railway authorities can now be discussed.

1. Although it increases the collision velocity required for puncture, the new type of head shield will not prevent tank head puncture in violent collisions. The head shield would protect the tank head in a low-speed collision with a flat wagon loaded with rails or similar sharp objects.
2. The new manway construction was found to be vulnerable to impacts in which the wagon is overturned. In such accidents, the manway nozzle could be ruptured. The old construction, in which the manway cover was bolted to the tank shell, was better. It was recommended that the Finnish State Railways return to the old construction or reinforce the manway nozzle with stiffeners. Compared with the problems caused by the manway nozzle, the increase in safety achieved with the new valve type was of secondary importance.
3. A study of railway accident reports indicated that the second and third wagons carrying goods were usually the most badly damaged in train collisions. If either of these was a chlorine tank wagon, a major leak could ensue. It was recommended that train composition rules be amended so that chlorine tank wagons would not be positioned among the four first or the four last wagons of a train. The rule giving a safety distance between a chlorine tank wagon and wagons loaded with flammable materials was determined to be adequate.
4. It was estimated that tank punctures were possible during shunting if the chlorine tank wagon was overturned or if a shunting engine collided with it. The resulting leaks were assessed to be small. Major leaks, however, were determined to be possible in shunting operations because of rupture of the manway nozzle.

ADDITIONAL STUDIES

The final report of the project was received favorably, and the sponsors suggested performing similar risk studies on the other hazardous liquefied gases. In 1977-1978, a comparison study on the transportation of anhydrous ammonia and sulphur dioxide was performed. A third study on the transportation of LPG was done in 1979-1980.

In these projects the damage studies for tank wagons were done with the same method as was used in the chlorine risk study. The differences in wagon construction were noted. A detailed analysis of the potential damage to road tankers was made in the LPG study. Because no damage had occurred to road tankers hauling liquefied gases, descriptions of lorry accidents were used as raw data.

The accident reports indicated the impacts the lorries involved had received. Instead of a lorry, an LPG road tanker was imagined to be involved and the accidents were classified as either nonsignificant or significant. Those accidents in which an LPG tanker was determined to have a leak were classified as significant. Road accident types, which include significant accidents, are as follows.

1. Intersection accidents
   a. Side collisions
   b. Head-on collisions
2. Level-crossing accidents
3. Accidents on road
   a. Head-on collisions
   b. Side collisions
   c. Rear-end collisions
   d. Running off the road

A sample consisting of 183 road accidents was studied and the percentage of significant accidents in each accident type was calculated. These percentages were then used as the probabilities of road accidents causing a leak to occur in an LPG tanker.

The findings of these three risk studies contributed to the following new regulations, instructions, and practices.

1. The train composition rules were amended so that a tank wagon carrying a hazardous liquefied gas must not be positioned among the first four or the last two wagons. This rule need not be followed in a case in which the tank wagon will be left at a station at which there is no shunting engine.
2. Finnish regulations on transportable pressure vessels specify that external loads must be considered in the placing and dimensioning of the manway structure.
3. Installation of override restraints and head shields has been continued.
4. The Ministry of the Interior has issued an instruction of emergency response to accidents involving hazardous liquefied gases.

CONCLUSION

Performing risk analysis of rare accidents implies that subjective evaluations and estimates must be made. Thus, the numerical values calculated are bound to be uncertain. Also, some important failure and damage modes may have been overlooked. The deficiencies, however, do not mean that the results are of poor quality or useless to practical decision making.

Risk analysis should instead be viewed as a systematic way of considering every factor affecting the risk, that is, every factor that ought to be considered when making decisions to enhance safety. An analysis requires information on different fields of science and technology. Because the analyst is not familiar with all of these fields, cooperation with various experts is both necessary and profitable. In this way, the analyst acquires an insight into the various aspects of the problem and will be able to suggest measures that will decrease the risk. By doing a quantitative analysis the analyst also acquires an understanding of the relative significance of these measures as well as those suggested by the experts contacted.

ACKNOWLEDGMENT

The author is indebted to the 11 scientists of the Technical Research Centre of Finland who participated in the research project, and particularly to Tuomas Mankamo, who developed the methodology used in the damage studies.

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