An Assessment of the Risk of Transporting Gasoline by Truck

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Project coordinator

November 1978

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1.0 SUMMARY

This report is the fourth in a series of assessments of the risk of transporting energy materials. The report presents the risk of shipping gasoline by truck. The risk assessment methodology used in this study was developed in the first report in this series.⁽¹⁾ The methodology is summarized in Section 3. The methodology is presented in the form of a risk assessment model which is constructed for ease of periodic updating of the data base so that the risk may be reevaluated as additional data become available.

The report is sectioned to correspond to specific analysis steps identified in the model. The transport system and accident environment are described in Sections 4 through 6. Release sequences are postulated in Section 7 and evaluated in Sections 8 through 10 to determine both the likelihood and possible consequences of a release. Supportive data and analyses are given in the appendices.

The risk assessment results are related to the year 1980 to allow a direct comparison with other reports in this series. For the assessment, certain assumptions about the gasoline shipping industry were made. These assumptions included:

- All gasoline is shipped to a bulk distribution terminal by pipeline and/or barge and from the distribution terminal to the retail outlet by truck.
- All shipments to the retail outlet are made in tank trucks or tank trailers designed to meet Department of Transportation specification MC-306.
- The amount of gasoline shipped corresponds to the gasoline consumption goal in the President's Energy Plan.⁽²⁾

Based on these assumptions and available data, the following industry characteristics for 1980 were calculated:

- Total gasoline shipped by truck in 1980 - 1.14×10^{11} gallons.
- Average shipment quantity - 8,400 gallons.
- Average shipment distance - 50 miles.
- Total shipping distance - 6.7×10^8 miles.

Based on these shipping assumptions and the current accident rate of 2.5×10^{-6} per mile, it is estimated that gasoline tank trucks will be involved in 1,781 accidents in 1980. It is further estimated that 110 of the accidents, or about one in 15 will result in a release of 3,000 gallons of gasoline or more from the tank truck. About one in four of the releases are expected to result in a large fire. The estimated number of fatalities from the gasoline releases in 1980 is 29. Twelve of these fatalities are estimated to be drivers of gasoline tank trucks, and the other 17 are occupants of other vehicles involved in the accident. Fatalities of other members of the public were found to occur infrequently. An additional 26 persons are expected to be fatally injured from the accident forces, regardless of the hazardous nature of the cargo. These total fatality figures (55) were compared to data from the Bureau of Motor Carrier Safety (BMCS). BMCS data would predict 43 deaths from a similar number of gasoline tank truck accidents. The calculated results are therefore in substantial agreement with available data. In addition to validating the results of the analysis, this comparison indicates the usefulness of the analysis approach used in extending the information from available data sources to calculate total shipping system risks and to predict the occurrence of less frequent, but potentially higher consequence accidents.

The risk spectrum for shipment of gasoline by truck is presented in Figure 1.1. The risk spectrum is a plot of the expected frequency (in events/yr) of events versus the number of fatalities that are predicted from those events. For example, the curve shows that for the 1980's shipping levels used in the analysis, about 25 accidents resulting in one or more fatalities from the release of gasoline in an accident are predicted to occur each year. Accidents that produce ten or more fatalities are estimated to occur at a rate of 2.2×10^{-2} per year, or one accident in about 45 years. The risk curve shows that a number of events resulting in less than two deaths/event can be expected each year from gasoline releases, but that larger consequence events occur relatively infrequently. There does not appear to be a significant possibility of very large consequence events from gasoline

FIGURE 1.1. Risk Spectrum for Gasoline Shipments by Truck in 1980

tank truck accidents. The gasoline shipping risks are compared to other risks in society in Table 1.1. The table illustrates that the risk to any individual in society from gasoline shipments is comparable to the risk from lightning or tornadoes.

Sensitivity studies were performed to determine the most important contributors to the risk. It was found that tank wall failures from puncture, impact and abrasion combine to produce over 90% of the gasoline releases. An accurate description for the puncture environment experienced by a large truck in an accident was not available. The uncertainty in the analysis would be reduced by development of such a description. The sensitivity studies also showed that the expected number of fatalities from gasoline releases in 1980 is directly proportional to the assumed number of occupants killed by fire in vehicles involved in an accident.

TABLE 1.1. Comparison of Gasoline Transportation Risks with Individual Risk from Various Accidents and Natural Disasters^(a)

Accident Type	Total Fatalities	Individual Risk per Year
All Accidents	115,821	1 in 2,000
Motor Vehicle Accident	55,511	1 in 4,000
All Industrial Accidents ^(b)	14,100	1 in 6,000 ^(c)
Falls	16,506	1 in 13,000
Drowning	7,152	1 in 29,000
Fires	6,503	1 in 32,000
Poisoning	5,335	1 in 40,000
Airplane Crashes	1,668	1 in 130,000
Railway Accidents	789	1 in 250,000
Lightning ^(d)	160	1 in 2,000,000
Tornadoes ^(e)	90	1 in 2,300,000
Gasoline Tank Truck Accidents	29	1 in 7,400,000

(a) Data are from reference 3 unless otherwise indicated.

(b) Reference 4

(c) Only workers included in population at risk

(d) Reference 5

(e) Reference 4. Average value for several years

Two possible methods for reducing the risk from gasoline releases in tank truck accidents were investigated. The first involved making the tank ten times more resistant to failure by puncture, impact and abrasion. This reduced the expected number of fatalities to nine per year. The second method involved installation of an accident-activated fire suppression system on all tank trucks. Potentially this could reduce the expected number of fatalities to less than one per year. A detailed cost-benefit analysis would be required to determine the merits of these systems.

Judgments about the acceptability of the risks from shipping gasoline by truck are beyond the scope of this analysis, but the information presented here can provide input to such decisions. The analysis has shown that the risk from gasoline shipments is less than many other commonly-accepted risks

in society. There is a clear and substantial benefit to society from the use of the gasoline that is shipped because gasoline provides about 75% of the energy consumed in the U.S. for transportation. The risks and benefits are also spread evenly throughout society, so that the population exposed to risk is essentially the same as the population receiving the benefits. It should also be noted that any analysis of this type is generally conservative; i.e., the calculated risk is usually somewhat higher than the actual risk might be if it could be measured. This results because many assumptions and simplifications must be made to make the analysis tractable. Every attempt has been made to make these assumptions as realistic as possible, but lacking information, a generally conservative assumption was made. Sensitivity studies were used to test the effect of key assumptions on the analysis results. It is felt that the results presented are the most realistic possible using existing information.

REFERENCES

1. T. I. Sweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, 1975.
2. National Energy Plan. Executive Office of the President, Energy Policy and Planning, Washington, DC, April 1977.
3. U.S. Bureau of the Census, Statistical Abstract of the United States: 1975. U.S. Department of Commerce, Washington, DC, p. 66, 1975.
4. Accident Facts 1973. National Safety Council, Chicago, IL, 1974.
5. Reactor Safety Study. WASH-1400, U.S. Nuclear Regulatory Commission, Washington, DC, p. 3, October 1975.

2.0 INTRODUCTION

To insure the health and safety of the general public, industry and government agencies are continually improving their level of understanding of the safety-related aspects of transporting energy materials.

Research programs are one method of improving the level of understanding. Such a research program is being conducted by Pacific Northwest Laboratory^(a) for the Transportation Branch of the Division of Environmental Control Technology in the Department of Energy. The objective of this continuing program is to develop a methodology for quantitatively assessing the safety of transporting energy materials and to apply it to current and future shipping systems. Risk analysis was the technique selected for this assessment. Through analysis of risk, consequences of postulated releases of energy materials during transport can be put into perspective by viewing the events relative to their expected frequency of occurrence.

Risk, as used in the context of this report, is the product of the magnitude of a possible loss and the expected frequency of occurrence of the loss. There are two measures of the risk that are of importance in a risk assessment. The first is the total risk, obtained by summing the risk associated with each particular loss. In order to perform the summation, all risks have to be expressed with respect to the same time interval (e.g., per year). Although the total risk is an important measure, it gives only the loss that would be expected on the average during the reference time interval. The range of losses which could be experienced is not discernable. For example, the risk associated with an accident that occurs once a year and results in one fatality is the same (i.e., one fatality/year) as that from an accident which occurs once in ten years but results in ten fatalities. In a plot of the expected frequency of N or more fatalities as a function of N , these two accidents would appear as discrete points. The second measure of risk is a curve called a risk spectrum, which is generated by connecting such points. The risks associated with two

(a) Operated by Battelle Memorial Institute

activities are similar only if they have the same total risk (risk magnitude) and the same risk spectrum. Both risk measures are used in this report.

The risk assessment methodology used in this report was initially applied to the shipment of plutonium⁽¹⁾ by truck and has subsequently been applied to the shipment of plutonium by rail⁽²⁾ and air,⁽³⁾ and uranium hexafluoride by truck and rail.⁽⁴⁾ A review of the methodology is presented in this report. This report presents the results of the first application of this methodology to transportation of a fossil energy material. The truck shipment of gasoline was selected as the first fossil energy material risk assessment for several reasons:

- Transportation annually accounts for 25% of the energy consumption in the U.S. About three quarters of the transportation energy is supplied by gasoline.
- Gasoline represents about one third of all hazardous materials shipments made by truck.
- Information was available or could be derived concerning the accident environment that a gasoline truck would experience.
- The risks and benefits from truck transportation of gasoline are spread evenly throughout society.
- Although much information was available concerning the truck shipment of gasoline and accidents involving these trucks, the risk to which society is exposed from these shipments was not known.

REFERENCES

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.
2. R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train. BNWL-1996, Battelle, Pacific Northwest Laboratories, Richland, WA, January 1977.
3. T. I. McSweeney, J. F. Johnson, An Assessment of the Risk of Transporting Plutonium Dioxide by Cargo Aircraft. BNWL-2030, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1977.
4. C. A. Geffen, J. F. Johnson et al. An Assessment of the Risk of Transporting Uranium Hexafluoride by Truck and Train. PNL-2211, Pacific Northwest Laboratory, Richland, WA, August 1978.

3.0 RISK ANALYSIS MODEL

Risk, as used throughout this report, is defined as the product of the likelihood of occurrence of an event and the consequences of that event. The risk model described in this section has been developed from methodologies used in prior risk assessments. A detailed description of the risk model used in this report is provided in Reference 1. The model was developed to evaluate the risk of transporting radioactive materials. By generalizing some of the component designations, it has been applied here to shipments of gasoline.

3.1 RISK MODEL DESCRIPTION

The risk assessment model provides a systematic method for handling the data required to analyze the safety of the transport environment. The components of the assessment model are shown in Figure 3.1. The following paragraphs provide a more detailed description of the components shown in this figure.

The model uses one fundamental equation:

$$R = \sum_i R_i \quad (1)$$

The total system risk R is the sum of the risks of all accidental releases as denoted by the subscript i . Only accidental releases are considered in the model. The risk of an individual release is the product of the consequences of the release and the probability of its occurrence. This equation could be expanded into a single, long, complex equation. In the current formulation of the model, each term in Equation (1) is expanded into two expressions which have more physical significance. The expanded equation for R_i is:

$$R_i = \left(A F_{R_i} \times P_{R_i} \right) \times \sum_q \left(C_{E_{i,q}} \times P_{E_q} \right) \quad (2)$$

FIGURE 3.1. Model to Calculate the Risk of Shipping Hazardous Material

The first factor, $A F_{R_i}$, is the product of the amount of material present in a shipment times the fraction of that material lost to the environment in the i^{th} release sequence. This factor can be thought of as a source for the i^{th} chain of events or failures which end with a release of radioactive material. The second factor, P_{R_i} , is the probability that the release sequence will happen during transport. The first expression, $A F_{R_i} \times P_{R_i}$, can be thought of as a probabilistic source term for each identified release sequence.

The factor $C_{E_i,q}$ in the second part of Equation 2 is the consequences of a unit release. The subscript q is added to show that the factor is a function of the specific weather conditions existing at the time of the release and the population exposed to the release. The final factor, P_{E_q} , is the probability of encountering a particular set of weather conditions within a specific population zone. The expression $\sum_q (C_{E_i,q} \times P_{E_q})$ can be thought of as the consequences of a unit release of material (unit source term) under probabilistically weighted weather conditions and population distributions.

Equation 2 is the pivotal equation in the risk model. Two preparatory steps are needed before the terms can be evaluated. These are the system description and the release sequence identification steps. Following these two steps is the release sequence evaluation step which utilizes Equations 1 and 2. The final step is to evaluate or assess the significance of the risk level determined for the transport system being evaluated. The relationship between the four steps is shown in Figure 3.1. The steps are briefly discussed in the following four subsections.

3.1.1 System Description

As shown in Figure 3.1, the system description step has seven components:

- 1) Select Industry Characteristics
- 2) Specify Material Amount, Origin and Destination
- 3) Specify Material Characteristics
- 4) Specify Transport Mode and Carrier
- 5) Specify Container and Amount of Material per Container
- 6) Calculate Number of Shipments Required
- 7) Specify Route, Restrictions, Population and Weather Zones.

Figure 3.2 shows the type of information called for by these components to describe the gasoline shipping system.

3.1.2 Release Sequence Identification

The second step in the risk assessment is identification of release sequences. This requires, first, component 8, Specify Scope of Analysis, which completes the information required to initiate work in component 9, Determine Possible Release Sequences. The relationship of these two components to the rest of the model is shown in Figure 3.1. Component 8 sets the scope of the risk assessment by selecting the factors that will be considered in the analysis. For the present analysis, primary consideration is given to the risks from failure sequences resulting from transportation accidents. The possible release sequences within the scope of the assessment are identified in component 9 by use of fault tree analysis; a method that works backwards from a release through the chains of events or failures required to breach the barriers between the material and man's environment.

3.1.3 Release Sequence Evaluation

The release sequence evaluation step considers each release sequence identified in the previous step and determines the factors in Equation 2. The assembly of this data will be described in the following subsections entitled Source Term Evaluation and Environmental Consequences Evaluation.

Source Term Evaluation. The release sequence factors in Equation 2, denoted by the subscript "R", represent the probability that material will be released and the amount of material released. The evaluation of these factors requires the input of four data bases, shown in Figure 3.1 as components 11-14. These data bases are:

- Input or Retrieve Applicable Package Closure Error Data (11)
- Input or Retrieve Applicable Mechanical Failure Data (12)
- Retrieve Applicable Transport Mode Accident Data (13)
- Retrieve Data on Environmental Characteristics of Material Shipped (14).

With the information from components 11 to 14, the model evaluates the probability and magnitude of the release (components 17 and 18 in Figure 3.1).

FIGURE 3.2. Information Required to Describe Transport System

The F_{R_i} factors of source term expression used for various release sequences and environmental conditions are discussed in Section 9.

Environmental Consequences Evaluation. The environmental terms in Equation 2 are denoted by a subscript E. The factor P_E represents the probability that a given set of weather and population density characteristics will be encountered. The factor C_{E_i} represents the consequences of a unit release from an accident when it occurs in the region characterized by the weather and population density used to determine P_E . The consequences of the release are expressed as health effects using commonly accepted methods. The evaluation of the two factors in Equation 2 requires the input from three data bases, shown in Figure 3.1 as components 14 to 16. These data bases are:

- Retrieve Data on Dispersal Characteristics of Material Shipped (14)
- Input or Retrieve Data on Route, Population and Weather Characteristics (15)
- Retrieve Data on Health Effects of Material Shipped (16).

The model uses relevant information from components 14 to 16 to evaluate the probability of experiencing a given set of weather conditions and population characteristics. These evaluations are shown as components 19 and 20 in Figure 3.1. The P_E term in Equation 2 is the probability associated with the weather and population characteristics. The expanded form of this term is given:

$$P_{E_{j,k,l}} = P_{j/k} \times P_k \times P_l \quad (3)$$

The subscripts j, k and l refer to the multiplicity of environmental conditions which could exist at the location of the accident. The variable $P_{j/k}$ is the probability of experiencing the j^{th} atmospheric stability classification when the k^{th} windspeed exists. The variable P_k is the probability of encountering the k^{th} windspeed category. The variable P_l is the probability of encountering a specified population distribution.

This data completes the description of the four terms in the risk equation. Once all of these variables are specified, the risk calculation and assessment step, the last step, can be completed.

3.1.4 Risk Calculation and Assessment

The final step in the risk assessment is to sum and evaluate the risks associated with all the applicable release sequences. As shown in Figure 3.1, this final step consists of six components numbered 21 to 26:

- Risk Calculation (21)
- Determine Risk of Hazardous Material Shipments (22)
- Identify Major Contributors to Overall Risk (23)
- Characterize Other Accepted Societal Risks (24)
- Assess Risk of Shipments Relative to Other Societal Risks (25)
- Specify Alternatives Which May Reduce Risk Level (26).

In this report, the risk of transporting gasoline by truck will be calculated and then compared with other accidental risks. Such comparisons place the risks of shipping gasoline in perspective.

REFERENCE

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.

4.0 SHIPPING SYSTEM DESCRIPTION

Gasoline is typically transported from the refinery to a distribution terminal by pipeline and/or barge. Large tank trucks are then used to ship the gasoline from the distribution terminal to the retail outlets. This is the transportation step considered in this analysis. Distribution terminals and retail outlets are located throughout the U.S. The number of terminals and retail outlets in a given area is roughly proportional to the population in that area. The distance from a distribution terminal to the retail outlets is usually less than 100 miles. The risks from gasoline transportation are therefore spread relatively evenly throughout the U.S. population and it was not necessary to look at specific shipping and receiving locations as in previous studies.

The analysis is based on the year 1980 to permit comparison with previous studies for other energy commodities. This section presents a projection of the gasoline shipping requirements in the reference year and a brief description of the tank trucks used.

4.1 GASOLINE SHIPPING REQUIREMENTS

The National Energy Plan provides for a target consumption of 1.14×10^{11} gallons of gasoline in 1980.⁽¹⁾ Interstate Commerce Commission (ICC) statistics⁽²⁾ show that the average gasoline shipment by truck contains 8400 gallons. Contacts with transportation experts from several major petroleum refining companies indicate that the average loaded shipping distance for a gasoline tank truck is 50 miles. Therefore the total number of gasoline tank truck shipments in 1980 is estimated to be 1.36×10^7 , with tank trucks being loaded 6.79×10^8 miles/year. These projections are summarized in Table 4.1.

TABLE 4.1. Assumed Gasoline Shipping Information for 1980

Projected Gasoline Sales	1.14×10^{11} gallons
Average Shipment Quantity	8,400 gallons
Average Shipment Distance	50 miles
Total Number of Shipments	1.36×10^7
Truck Miles loaded/year	6.79×10^8

4.2 GASOLINE TANK TRUCK DESCRIPTION

Gasoline is classified as a flammable liquid and its transportation is regulated under the hazardous materials transportation regulations of the U.S. Department of Transportation. These regulations are contained in Sections 100-199 of Title 49 of the U.S. Code of Federal Regulations. The regulations specify packaging, shipping and handling requirements for all hazardous materials. The regulations permit the use of several DOT specification tank trucks for gasoline transport but conversations with tank truck manufacturers and trucking companies that haul gasoline indicate that DOT specification MC-306 is in predominant use by the gasoline shipping industry.

Two basic configurations of this shipping system are in current use. Shippers in the eastern portion of the U.S. generally use the tractor/semi-trailer configuration shown in Figure 4.1. Western operators typically use the tank truck/tank trailer combination shown in Figure 4.2. The tanks in both configurations have an elliptical cross section and are constructed of aluminum alloy 5454. The tank wall thickness for the semitrailer configuration is 0.25 inches in the belly and 0.188 inches in the sides and top. The smaller tanks in the western configuration have a 0.188-inch wall thickness in the belly and 0.154 inches in the sides and top. The tanks have internal baffles for stiffening and may be divided into several compartments. For this analysis it was assumed that each tank in the western configuration is a single compartment and that the semitrailer is divided into two compartments.

FIGURE 4.1. Tractor/Semitrailer Used for Gasoline Shipments
in the Eastern U.S.

FIGURE 4.2. Tank Truck/Tank Trailer Used for Gasoline Shipments
in the Western U.S.

Each tank compartment is fitted with a manway cover and an outlet valve. The manway cover also contains a relief valve that vents to the atmosphere when the tank pressure exceeds 1 psig. Another relief valve in the cover vents at 9 psig. This analysis assumes that all compartments are loaded through the manway cover and unloaded through the outlet valve with the manway cover opened for venting. It should be noted, however that about 25% of the tank trucks currently in use are equipped for bottom loading and unloading. A more detailed description of the reference tank trucks is presented in Appendix A.

REFERENCES

1. The National Energy Plan. Executive Office of the President, Energy Policy and Planning, Washington, DC. April 1977.
2. Freight Commodity Statistics, Motor Carriers of Property, Year Ended December 31, 1972. Interstate Commerce Commission, Bureau of Accounts, Washington, DC.

5.0. TRANSPORTATION ACCIDENT ENVIRONMENT

Transportation accident related failure of a gasoline tank truck and release of the contents occur when the forces generated in an accident exceed the mechanical strength of some component of the tank. This section discusses the forces or stresses that might be generated in a truck accident environment and their likelihood of occurrence. Section 6.0 discusses the mechanical strength of a gasoline tank. The use of the information in Sections 5.0 and 6.0 to estimate the likelihood of gasoline release in a tank truck accident is demonstrated in Section 8.0.

For the purposes of this study, the stresses present in a truck accident environment have been divided into four categories: fire, impact, abrasion and puncture. Other stresses, such as crush and immersion, were judged to be unimportant contributors to the likelihood of gasoline tank failures. The four significant accident stresses are discussed individually below.

5.1 FIRE

Information on the fire environment is extracted from Reference 1. Only fires that do not involve the cargo are considered, since the intent is to establish the likelihood of tank failure. Fire can be expected to occur in 1.6% of all truck accidents.⁽²⁾ The mean fire temperature is 1850°F. Fire durations may vary from a few minutes to several hours. The expected duration of fires in truck accidents is shown in Figure 5.1.

5.2 IMPACT

The impact environment for an accident involving a large container such as a gasoline tank truck is taken from information from A. W. Dennis, Sandia Laboratories (June 23, 1976). The statistical information provided by Sandia was developed from Bureau of Motor Carrier Safety (BMCS) data. The impact accident environment information was developed from the statistical data base using a Monte Carlo computer simulation.

FIGURE 5.1. Expected Duration of Fires for Accidents Involving a Truck with Nonflammable Cargo (extracted from Reference 1)

The statistical information from A. W. Dennis is presented in Tables 5.1 through 5.4. Table 5.1 contains the basic BMCS accident distribution data. The data has been broken down into two sets, collision accidents and noncollision accidents. Collision accidents involve a primary impact with another vehicle, a train, a fixed object or a pedestrian, animal or bicycle. Noncollision accidents involve fire (before or without impact), running off the road, overturning and other accidents of this type. Noncollision accidents may include impacts with roadside ditches, banks, the roadway and other roadside features.

Table 5.2 presents the basic data in revised categories. The revised categories were established to simplify further analysis. Collisions with trucks, motor buses and streetcars were combined into a single category - collisions with trucks. Collisions with fixed objects, unreported objects and other objects were also combined into a single category. The collision rollaway and noncollision rollaway categories were combined. A new category, overturn/run off road was established to include accidents where either the primary cargo damage was due to overturning or running off the road or the collision effects on the cargo were considered to be slight. Collisions

TABLE 5.1. Distribution of Collision Accidents (BMCS Data -
1969 through 1972) (A. W. Dennis, Sandia Laboratories)

<u>Accident Classification</u>	<u>Number of Accidents</u>	<u>Fraction of Total</u>
a. Collision with:		
Pedestrian	1,520	0.0085
Truck	28,101	0.1569
Passenger Auto	87,268	0.4873
Motor Bus	787	0.0044
Other Vehicle	1,049	0.0059
Railroad Train	1,027	0.0057
Streetcar	9	0.0001
Animal/Animal Drawn Vehicle	1,344	0.0075
Bicycle	182	0.0010
Fixed Object	25,934	0.1448
Unreported Object	216	0.0012
Other Object	270	0.0015
Rollaway	2,096	<u>0.0117</u>
		0.8365
b. Noncollision:		
Overturn on Road	5,065	0.0283
Ran off Road	11,976	0.0663
Other	12,259	0.0685
Rollaway	67	<u>0.0004</u>
		0.1635
SUM	179,070	1.0000

with pedestrians, animals. etc. were included in this category since it was felt that damage to the vehicle in this type of accident would result from overturning or running off the road as a result of attempts at evasive action.

TABLE 5.2. Distribution of Collision Accident Data by Revised Categories
(A. W. Dennis, Sandia Laboratories)

<u>Accident Classification</u>	<u>Number of Accidents</u>	<u>Fraction of Total</u>
a. Collision-only:		
Truck		
Property	28,897	0.1614
Motor Bus		
Street Car		
Passenger Auto	87,268	0.4873
Railroad Train	1,027	0.0057
Object	26,420	0.1476
Fixed Object		
Unreported Object		
Other Object		
b. Collision & Noncollision:	35,458	0.1980
Overturn/Ran off Road		
Pedestrian		
Other Vehicle		
Animal/Animal Drawn Vehicle		
Bicycle		
Rollaway (collision)		
Overturn on Road		
Ran off Road		
Other		
Rollaway (Noncollision)		
SUM	179,070	1.0000

In Table 5.3, the collision-only accidents have been divided by the type of vehicle involved in the collision (another truck, car, train) and by the type of collision (head-on, end-on, etc.). The distribution of each type accident derived for use in the computer calculations is shown in the table. The information in Table 5.3 was used to develop Table 5.4. The

TABLE 5.3. Distribution of Revised Categories by Type of Vehicle - Collision Only Accidents (A. W. Dennis, Sandia Laboratories)

	<u>Fraction of Collision Only Accidents</u>	<u>Distribution Factor</u>	<u>Distribution for Analysis</u>
a. Truck	0.2012		
Head-on		0.0405	0.0081
End-on #1 ^(a) into #2 ^(b)		0.4255	0.0856
End-on #2 into #1		0.4004	0.0806
Side-on #1 into #2		0.0427	0.0086
Side-on #2 into #1		0.0910	0.0183
b. Auto	0.6076		
Head-on		0.0538	0.0327
End-on #1 into #2		0.3695	0.2245
End-on #2 into #1		0.3032	0.1842
Side-on #1 into #2		0.0742	0.0451
Side-on #2 into #1		0.1993	0.1211
c. Railroad Train	0.0072		
Struck by Train		0.7500	0.0054
Ran into Train		0.2500	0.0018
d. Object	0.1840		
Auto		0.8400	0.1546
Railroad Train		0.1600	0.0294

(a) Vehicle #1 is the truck being studied.

(b) Vehicle #2 is the other vehicle involved in the accident.

fraction of all collisions resulting in the cargo container being accelerated along its axis, decelerated along its axis or accelerated perpendicular to its axis is presented in this table.

TABLE 5.4. Collision Accident Distribution by Direction of Acceleration Vector on Cargo Container (A. W. Dennis, Sandia Laboratories)

<u>Direction of Acceleration Vector on Cargo Container</u>	<u>Distribution Factors</u>
a. The Cask is Decelerated along its Axis	
Head-on, Truck	0.0081
End-on #1 ^(a) into #2, ^(b) Truck	0.0856
Side-on #1 into #2, Truck	0.0086
Head-on, Auto	0.0327
End-on #1 into #2, Auto	0.2245
Side-on #1 into #2, Auto	0.0451
Ran into Train Object	0.0018
	<u>0.1840</u>
	0.5904
b. The Cask is Accelerated along its Axis	
End-on #2 into #1, Truck	0.0806
End-on #2 into #1, Auto	<u>0.1842</u>
	0.2648
c. The Cask is Accelerated Perpendicular to its Axis	
Side-on #2 into #1, Truck	0.0183
Side-on #2 into #1, Auto	0.1211
Struck by Train	<u>0.0054</u>
	0.1448

(a) Vehicle #1 is the truck being studied

(b) Vehicle #2 is the other vehicle involved in
the accident

The data in Tables 5.1 through 5.4 were used by Sandia Laboratories in a Monte Carlo computer code to estimate the impact environment experienced by a large truck in an accident. The results of this analysis for a truck with a gross weight of 80,000 lbs are presented in Figures 5.2 and 5.3. Figure 5.2 presents the magnitude of the velocity change versus expected frequency of occurrence in a collision accident. Figure 5.3 presents similar results in terms of the expected change in kinetic energy. The kinetic energy change has been normalized to the kinetic energy change that would be experienced in a 30-ft drop onto an unyielding surface.

FIGURE 5.2. The Expected Maximum Velocity Change Given a Truck Subjected to a Random Accident Sample (A. W. Dennis, Sandia Laboratories) (Number of Samples - 1,000; Truck Gross wt. - 80,000 lbs)

FIGURE 5.3. The Expected Maximum Kinetic Energy Change Ratio Given a Truck Subjected to a Random Accident Sample (A. W. Dennis, Sandia Laboratories) (Number of Samples - 10,000; Truck Gross wt. - 80,000 lbs)

5.3 ABRASION

Two factors determine the abrasion environment that a gasoline tank truck could experience in an accident - the type of road surface that an overturned tank might slide along and the speed at which the tank slides along the surface. The fraction of each type of road surface used in this analysis is presented in Table 5.5. These data were obtained from the State of Washington Department of Highways and are assumed to be typical of highways and streets throughout the country.

TABLE 5.5. Fraction of Roads Constructed of Various Materials

	<u>Fraction of Total Miles</u>
Road Surface	
Asphalt	0.45
Bituminous Surface Treatment ^(a)	0.43
Portland Cement	0.08
Gravel	0.01
Other	0.03

(a)Small gravel and tar

The initial speed of a gasoline truck sliding along an abrasive surface is assumed to be the pre-accident speed for all truck accidents. The data used were taken from Reference 3. These data represent an analysis of 10,838 truck accidents in the state of Texas. The fraction of all truck accidents occurring in each speed range is shown in Table 5.6.

TABLE 5.6. Truck Accidents as a Function of Pre-accident Speed

<u>Speed Range</u>	<u>Fraction of All Accidents</u>
Stop	0.058
1-10	0.321
11-20	0.157
21-30	0.156
31-40	0.113
41-50	0.116
51-60	0.072
61-70	0.005
Greater than 70	0.0005

5.4 PUNCTURE

A general description of the puncture environment that would be present in a gasoline tank truck accident is not available. Existing information,⁽²⁾ derived for small containers in an enclosed van, is not applicable to a large container such as a gasoline tank truck or trailer. The role of puncture forces in the failure of gasoline tank trucks in an accident can be inferred from data obtained from the Office of Hazardous Materials of the U.S. Department of Transportation (DOT). The Office of Hazardous Materials collects data on releases of hazardous materials during transportation. The data are collected on the incident report form shown in Figure 5.4. An incident report is required to be made by all carriers of hazardous materials in interstate commerce whenever a release occurs from the package or transport vehicle. The reported release does not have to be the result of a transportation accident.

The data obtained from DOT cover a 5-year period from 1971-1975. The reports include several types of DOT tank truck and trailer specifications. Tanks conforming to some of the specifications in the data are no longer being built for use as hazardous liquid bulk carriers, but the tank wall construction is similar to the gasoline tank trucks currently in use. The DOT provided summary data from Section F (Nature of Packaging Failure) of the incident report. This information is presented in Table 5.7. The categories "tank truck" and "tank trailer" were used when the DOT specification number was not included on the incident report. Most of these vehicles were being used for gasoline shipments at the time of the incident. Releases reported under a general category called "other conditions" (cause code 17) were not included in the table. Most of these releases occurred during loading or unloading. Loading and unloading releases were not considered in this study.

Most releases reported in cause codes 10 and 11 (defective or loose fittings, valves or closures) were not the result of an accident and did not usually result in the release of large amounts of material. Small releases such as these, that occurred during routine transport are not considered

DEPARTMENT OF TRANSPORTATION

Form Approved OMB No. 04-5613

HAZARDOUS MATERIALS INCIDENT REPORT

INSTRUCTIONS: Submit this report in duplicate to the Secretary, Hazardous Materials Regulations Board, Department of Transportation, Washington, D.C. 20590, (ATTN: Op. Div.). If space provided for any item is inadequate, complete that item under Section H, "Remarks", keying to the entry number being completed. Copies of this form, in limited quantities, may be obtained from the Secretary, Hazardous Materials Regulations Board. Additional copies in this prescribed format may be reproduced and used, if on the same size and kind of paper.

A INCIDENT		
1. TYPE OF OPERATION 1 ☐ AIR 2 ☐ HIGHWAY 3 ☐ RAIL 4 ☐ WATER 5 ☐ FREIGHT FORWARDER 6 ☐ OTHER (Identify) _____		
2. DATE AND TIME OF INCIDENT (Month - Day - Year) _____. a.m. _____. p.m.		3. LOCATION OF INCIDENT _____
B REPORTING CARRIER, COMPANY OR INDIVIDUAL		
4. FULL NAME _____		5. ADDRESS (Number, Street, City, State and Zip Code) _____
6. TYPE OF VEHICLE OR FACILITY _____		
C SHIPMENT INFORMATION		
7. NAME AND ADDRESS OF SHIPPER (Origin address) _____		8. NAME AND ADDRESS OF CONSIGNEE (Destination address) _____
9. SHIPPING PAPER IDENTIFICATION NO. _____		10. SHIPPING PAPERS ISSUED BY ☐ CARRIER ☐ SHIPPER ☐ OTHER (Identify) _____
D DEATHS, INJURIES, LOSS AND DAMAGE		
DUE TO HAZARDOUS MATERIALS INVOLVED		
11. NUMBER PERSONS INJURED _____	12. NUMBER PERSONS KILLED _____	13. ESTIMATED AMOUNT OF LOSS AND/OR PROPERTY DAMAGE INCLUDING COST OF DECONTAMINATION (Round off in dollars) \$ _____
14. ESTIMATED TOTAL QUANTITY OF HAZARDOUS MATERIALS RELEASED _____		
E HAZARDOUS MATERIALS INVOLVED		
15. CLASSIFICATION (Sec. 172.4) _____	16. SHIPPING NAME (Sec. 172.5) _____	17. TRADE NAME _____
F NATURE OF PACKAGING FAILURE		
18. (Check all applicable boxes)		
(1) DROPPED IN HANDLING	(2) EXTERNAL PUNCTURE	(3) DAMAGE BY OTHER FREIGHT
(4) WATER DAMAGE	(5) DAMAGE FROM OTHER LIQUID	(6) FREEZING
(7) EXTERNAL HEAT	(8) INTERNAL PRESSURE	(9) CORROSION OR RUST
(10) DEFECTIVE FITTINGS, VALVES, OR CLOSURES	(11) LOOSE FITTINGS, VALVES OR CLOSURES	(12) FAILURE OF INNER RECEPTACLES
(13) BOTTOM FAILURE	(14) BODY OR SIDE FAILURE	(15) WELD FAILURE
(16) CHIME FAILURE	(17) OTHER CONDITIONS (Identify) _____	19. SPACE FOR DOT USE ONLY

Form DOT F 5800.1 (10-70)

FIGURE 5.4. DOT Hazardous Materials Incident Report

G PACKAGING INFORMATION - If more than one size or type packaging is involved in loss of material show packaging information separately for each. If more space is needed, use Section H "Remarks" below keying to the item number.					
ITEM			#1	#2	#3
20	TYPE OF PACKAGING INCLUDING INNER RECEPTACLES (Steel drums, wooden box, cylinder, etc.)				
21	CAPACITY OR WEIGHT PER UNIT (55 gallons, 65 lbs., etc.)				
22	NUMBER OF PACKAGES FROM WHICH MATERIAL ESCAPED				
23	NUMBER OF PACKAGES OF SAME TYPE IN SHIPMENT				
24	DOT SPECIFICATION NUMBER(S) ON PACKAGES (21P, 17E, 3AA, etc., or none)				
25	SHOW ALL OTHER DOT PACKAGING MARKINGS (Part 178)				
26	NAME, SYMBOL, OR REGISTRATION NUMBER OF PACKAGING MANUFACTURER				
27	SHOW SERIAL NUMBER OF CYLINDERS, CARGO TANKS, TANK CARS, PORTABLE TANKS				
28	TYPE DOT LABEL(S) APPLIED				
29	IF RECONDITIONED OR REQUALIFIED, SHOW	A	REGISTRATION NO. OR SYMBOL		
		B	DATE OF LAST TEST OF INSPECTION		
30	IF SHIPMENT IS UNDER DOT OR USCG SPECIAL PERMIT, ENTER PERMIT NO.				
<p>H REMARKS - Describe essential facts of incident including but not limited to defects, damage, probable cause, stowage, action taken at the time discovered, and action taken to prevent future incidents. Include any recommendations to improve packaging, handling, or transportation of hazardous materials. Photographs and diagrams should be submitted when necessary for clarification.</p>					
31. NAME OF PERSON PREPARING REPORT (Type or print)			32. SIGNATURE		
33. TELEPHONE NO. (Include Area Code)			34. DATE REPORT PREPARED		

Reverse of Form DOT F 5800.1 (10-70)

GPO : 1970 O - 408-375

FIGURE 5.4. (Cont'd)

TABLE 5.7. Summary of DOT Hazardous Material Incident Reports for Bulk Liquid Carriers (1971-1975)

DOT Specification Number	Failure Cause Code (Section F - Incident Report)														
	<u>1</u>	<u>2</u>	<u>3</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>15</u>	
MC-300									4	3					
MC-301									1	2					
MC-302		23			1	2	1		5	1		1	1	2	
MC-303		9					2		13	8			4	2	
MC-304	1	2			1		5		31	15		1	6	4	
MC-305	1	71	1	1	1	1	6		102	82	2	2	7	8	
MC-306	4	89			3	10	13	1	102	78	2	1	13	19	
MC-307		1					2		29	16	1		2	3	
Tank Truck	30	84	1		5	6	26		96	77	4	1	8	7	
Tank Trailer	<u>11</u>	<u>79</u>	<u>1</u>	<u>—</u>	<u>5</u>	<u>6</u>	<u>29</u>	<u>2</u>	<u>135</u>	<u>75</u>	<u>3</u>	<u>2</u>	<u>3</u>	<u>4</u>	
Totals	47	358	3	1	16	25	84	3	518	357	12	8	44	49	

significant for this study. Table 5.8 presents the revised data used to estimate the fraction of tank failures in accidents that resulted from puncture forces. Failure codes 10 and 11 have been eliminated and all cause codes except puncture have been combined and categorized as "other".

TABLE 5.8. Percentage of Bulk Liquid Tank Failures Resulting from Puncture Forces

DOT Tank Specification	Failure Cause		Fraction of Failures from Puncture
	<u>Puncture</u>	<u>Other</u>	
MC-302	23	8	0.74
MC-303	9	8	0.53
MC-304	2	18	0.10
MC-305	71	30	0.71
MC-306	89	66	0.57
MC-307	1	8	0.11
Tank Truck	84	88	0.49
Tank Trailer	<u>79</u>	<u>66</u>	<u>0.54</u>
Totals	358	292	0.55

REFERENCES

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, pp. 5.4-5.5, August 1975.
2. R. K. Clarke, J. T. Foley, W. R. Hartman and D. W. Larson, Severities of Transport Accidents, Vol. III - Motor Carriers. SLA-74-0001, Sandia Laboratories, Albuquerque, NM, July 1976.
3. R. E. Scott et al., Statistical Analysis of Truck Accident Involvements. The University of Michigan Highway Research Institute, Ann Arbor, MI, December 1971.

6.0 GASOLINE TANK TRUCK FAILURE THRESHOLDS

The previous section describes the accident environment associated with highway transport of gasoline in bulk tankers. A summary of calculated response of the reference gasoline tank vehicles to this accident environment is presented below. Substantiating calculations appear in Appendix D. Response to the most significant stresses imposed in highway accidents is quantified in terms of failure thresholds. A failure threshold is the level of applied thermal or mechanical stresses that produces a release of lading (gasoline) in an accident. Thresholds are related to minimum energy or vehicle velocity required to produce the failure.

The most significant types of accident-imposed stresses are:

- impact
- puncture
- abrasion
- thermal (solar or external fire)

The response of the gasoline tanker to each type of stress associated with the accident environment is calculated independently. No attempt was made to predict the lowered level of failure when the applied stresses act simultaneously or sequentially. The effect of this simplification on the overall risk analysis was determined to be small.

The analytical approach used for prediction of response of the gasoline tanker is, in most cases, rather simplified. Comprehensive analytical treatment is not warranted because of the lack of quantitative information on the truck accident environment. A summary of failure thresholds in response to the individual accident-imposed stresses is found in the subsections below. Failure threshold calculations were performed for both reference shipping systems considered in the study. In most cases, the results did not vary significantly between the systems. Instances where differences were found are indicated in the following sections.

6.1 IMPACT

To simplify the analysis, the failure threshold for impact was calculated by representing the elliptical tank as an axially-loaded cylinder. Cases analyzed were impact against a flat surface in the direction of the longitudinal axis and impact perpendicular to the longitudinal axis against a similar surface. The minimum velocities predicted at failure for each case are shown in Table 6.1.

TABLE 6.1. Minimum Velocities Predicted at Failure

	<u>Minimum Velocity (mph)</u>
Axial impact against a flat barrier	30.6
Side impact into a flat barrier	18.7

These cases assumed that the failure threshold is reached when the volume of the tank is reduced by a volume equivalent to the head space (10% for the cases analyzed). The air and gasoline vapor above the liquid gasoline are presumed to vent out the pressure relief devices.

6.2 PUNCTURE

Puncture of the relatively thin aluminum skin of the gasoline tank can be expected whenever a fixed probe more than a few inches long contacts the skin during an accident. Because of its ductility, the aluminum skin of the tank will deform about six inches before sheer stresses finally fail the skin around the head of the probe. The minimum length puncture probe required to fail the tank walls is then six inches, although shorter probes could fail the walls in the immediate vicinity of a baffle. The minimum energy between the tank and the probe that would fail the walls was found to be 480 ft-lb. The energy required increases with probe diameter. Calculations have shown that probes with energies available in truck accidents will puncture the walls only if they are greater than 0.4 inches in diameter.

6.3 ABRASION

The failure threshold by pure abrasion was derived through experimental data related to now plow skid plates and actual measurements and observations of a tank that had failed by abrasion. The minimum velocities required to fail the skin of the tank by abrasion are shown in Table 6.2. It was determined that the likelihood of abrasive failure on loose gravel or dirt was very low.

TABLE 6.2. Minimum Velocity to Fail Tank Skin
by Abrasion

<u>Surface</u>	<u>Minimum Velocity</u>
Asphalt-Concrete	26 mph
Bituminous Surface Treatment	20 mph

6.4 THERMAL

The aluminum skin of the tank will melt in a short time if exposed to an 1850°F fire. Failure by this mechanism is usually prevented because the liquid gasoline backing the skin conducts the heat away. It was determined that exposure to an 1850°F fire for one hour would cause half the contents of the tank to be vaporized and released through the relief valve. It is assumed that some portion of the skin of a half full tank will be backed by liquid gasoline and will fail from exposure to the fire.

It was found that if all the relief valves on the tank failed to function, the tank would fail from overpressurization after a 40-minute exposure to an 1850°F fire.

7.0 RELEASE SEQUENCE IDENTIFICATION

Gasoline releases from tank truck accidents occur each year in the United States. The statistical accident information available from state and federal agencies does not provide a sufficient basis to identify the mechanisms that caused these tanks to fail in the accident. Possible ways that releases could occur (sequences of events leading to a release or "release sequences") must be identified by a reasoning process. This section describes a formalized procedure for identifying possible release sequences. The first step in the procedure is to develop fault trees using the techniques described in Section 7.1. Section 7.2 presents the fault tree developed for shipment of gasoline by truck. Analysis of the fault tree provides the release sequences. The release sequences identified from the gasoline truck transportation fault tree are presented in Section 7.3.

7.1 FAULT TREE CONSTRUCTION

The fault tree analysis technique was developed in the 1960s in the aerospace industry to identify design deficiencies before actual space flight of the equipment. Basically the procedure is to assume a failure and work backwards to identify component failures which could cause or contribute to the failure. The fault tree should be related to individual components for which failure data are available. For instance, in an electronic circuit the basic failure might occur in a resistor. In practice, fault trees seldom are developed to that degree. What occurs instead is development of fault trees in terms of basic system modules. Using the electronic example, one would carry the possible failure back through the fault tree only to the amplifier which contained the resistor. Such a fault tree is called a Top Level Fault Tree since it usually identifies only large systems which could result in a failure. Table 7.1 gives the various fault tree symbols and their meanings.

The methodology applied to transportation of gasoline involves postulating a release of gasoline during transport and then examining the series of events which must have occurred to cause the release. This form of

reasoning is thought to be much more inclusive than beginning with an initiating event and working toward a release, (i.e., constructing accident scenarios or event trees). When properly applied, the accident scenarios obtained from using the fault tree methodology should be more complete than the alternative method of trying to list all the accident scenarios without the aid of any formalized reasoning process. The tree constructed using the fault tree methodology is used as the basis for estimating the total release probability.

TABLE 7.1. Fault Tree Symbolism

Symbol	Meaning and Use
<div style="display: flex; justify-content: space-between; width: 100%;"> output inputs </div>	<p>"AND" logic gate. The simultaneous occurrence of inputs is required to cause an output.</p>
<div style="display: flex; justify-content: space-between; width: 100%;"> output inputs </div>	<p>"OR" logic gate. The occurrence of any one of the inputs will result in an output.</p>
<p>Fault event that results from the logical operation of two or more fault events. It is always the output from a logic gate.</p>
<p>Inferred fault event. Any failure except a primary failure which is not developed further due to lack of information, time or money or due to the low probability of occurrence. It can also be used where other analyses give sufficient information to indicate that further analysis would be redundant.</p>
<div style="display: flex; align-items: center;"> <div style="text-align: center; margin-right: 10px;"> <p>Output</p> </div> </div> <div style="display: flex; justify-content: space-between; width: 100%;"> Input </div>	<p>"Inhibit" gate. The condition specified in the oval is required for an input fault event to result in an output event. This condition is frequently a design limit which will not transmit a failure until the design limits have been exceeded.</p>
<p>Transfer symbol denoting that failure also impacts on other branches of fault tree. A line at the apex of the triangle represents a "transfer in." A line in the side represents a "transfer out." A number is placed in the triangle to identify transfer locations.</p>
<p>"House" defines an event that must occur, or is expected to occur, due to design and normal operating conditions.</p>

7.2 FAULT TREE FOR SHIPMENT OF GASOLINE BY TRUCK

The fault tree for shipment of gasoline by truck has been developed for routine transport on primary roads and urban^(a) streets in the U.S. The effects of sabotage or natural disasters were not included in the analysis. It is assumed for this analysis that all gasoline is shipped in tank trucks and trailers designed to meet DOT specification MC-306. A description of the tank trucks used in the analysis is contained in Appendix A.

The fault tree developed for shipment of gasoline in an MC-306 tank truck is shown in Figure 7.1. The tree was drawn using the fault tree graphics code ACORN.⁽¹⁾ A list of identified events that could contribute to a release are shown in Table 7.2 and the input labels for the gate logic rectangles are presented in Table 7.3. The fault events in the tree designated by the circle symbol were not analyzed individually because of lack of information or because they were included in other events. They are included in the fault tree only for completeness. The tree was constructed by drawing a separate branch to analyze the failure of each type of tank component - tank walls, outlet valve, relief valve and manway cover that could release gasoline in an accident. Failure of each of these components by impact, puncture, fire, crush and abrasion was examined. The contribution to failure of substandard component manufacture or human errors in operating the components was also considered, as was the effect of one accident stress on the ability of the container to withstand a subsequently-applied stress.

7.3 RELEASE SEQUENCES

The fault tree can be thought of as a compact notation for identifying and displaying large numbers of release sequences. For large trees, it is convenient to use computer programs to perform the Boolean algebra that reduces the tree to a series of release sequences or "cut sets." The computer code MFAULT⁽²⁾ was used for this analysis.

(a)The term urban as used in this report includes the suburban areas surrounding many cities.

FIGURE 7.1. Gasoline Truck Transportation Fault Tree

FIGURE 7.1. (cont'd)

FIGURE 7.1. (cont'd)

SHEET 4

FIGURE 7.1. (cont'd)

SHEET 5

FIGURE 7.1. (cont'd)

SHEET 6

FIGURE 7.1. (cont'd)

**TABLE 7.2. Listing of Basic Events for Gasoline Truck
Transportation Fault Tree**

- X 1 TRANSPORTATION ACCIDENT OCCURS
- X 2 MANWAY COVER INSTALLED IMPROPERLY
- X 3 MANWAY COVER FAULTY DUE TO NORMAL DETERIORATION
- X 4 MANWAY COVER FAULTY FROM MANUFACTURING DEFECT
- X 5 FIRE OCCURS IN ACCIDENT
- X 6 FIRE PRODUCES PRESS THAT FAILS NORMAL MANWAY COVER
- X 7 FIRE PRODUCES PRESS THAT FAILS DEFECTIVE MANWAY COVER
- X 8 IMPACT FORCES PRODUCED IN ACCIDENT
- X 11 SUNSHINE CAUSES TANK PRESSURE TO EXCEED 1 PSIG
- X 12 FIRE DURATION PRODUCES PRESSURE RISE ABOVE 1 PSIG
- X 13 SMALL RELIEF VALVE FAILS CLOSED FROM NORMAL DETERIORATION
- X 14 SMALL RELIEF VALVE FAILS CLOSED FROM ACCIDENT FORCES
- X 15 SMALL RELIEF VALVE FAILS CLOSED FROM IMPROPER INSTALLATION
- X 16 SMALL RELIEF VALVE FAILS CLOSED FROM MANUFACTURING DEFECT
- X 17 SMALL RELIEF VALVE BALL CHECK CLOSURES WHEN TANK OVERTURNS
- X 18 PUNCTURE PROBE PRODUCED IN ACCIDENT
- X 19 PUNCTURE PROBE FAILS MANWAY COVER
- X 21 MANWAY COVER EXPOSED TO FIRE
- X 22 FIRE DURATION FAILS MANWAY COVER GASKET
- X 23 IMPACT FORCES FAIL MANWAY COVER
- X 24 TANK REMAINS UPRIGHT IN ACCIDENT
- X 25 TANK OVERTURNS IN ACCIDENT
- X 26 TANK OVER HALF FULL WHEN ACCIDENT OCCURS
- X 27 IMPACT FORCES FAIL ASSEMBLY-TANK MATING SURFACE
- X 29 PRESSURE FORCES FAIL ASSEMBLY-TANK MATING SURFACE
- X 30 FIRE DURATION FAILS VALVE ASSEMBLY - TANK GASKET
- X 31 PUNCTURE PROBE FAILS ASSEMBLY-TANK MATING SURFACE
- X 33 CRUSH FORCES FAIL ASSEMBLY TANK MATING SURFACE
- X 34 CRUSH FORCES FAIL EXTERNAL VALVE
- X 35 EXTERNAL VALVE EXPERIENCES IMPACT FORCES
- X 36 IMPACT FORCES SUFFICIENT TO FAIL VALVE
- X 38 FIRE DURATION PRODUCES PRESSURE THAT FAILS EXT VALVE
- X 40 PUNCTURE PROBE FAILS EXTERNAL VALVE
- X 42 ACCIDENT FORCES RAISE INTERNAL VALVE HANDLE
- X 43 ACCIDENT FORCES BREAK OUTLET VALVE ASSEMBLY AT SHEAR SECTION
- X 44 TANK OVERTURNS AND INT VALVE DISLODGED WHEN EXT VALVE SEVERED
- X 45 INTERNAL VALVE DOES NOT RESEAT FROM LIQUID PRESSURE
- X 46 ACCIDENT FORCES FAIL INTERNAL VALVE SEAT
- X 47 INTERNAL VALVE OPENED AND NOT CLOSED MANUALLY
- X 48 INTERNAL VALVE SEAT FAULTY FROM NORMAL DETERIORATION
- X 49 INTERNAL VALVE SEAT FAULTY FROM MANUFACTURING DEFECT
- X 50 INTERNAL VALVE SEAT INSTALLED IMPROPERLY
- X 51 EXTERNAL VALVE PACKING FAULTY FROM NORMAL DETERIORATION
- X 52 EXTERNAL VALVE PACKING NOT INSTALLED OR ADJUSTED PROPERLY
- X 53 EXTERNAL VALVE EXPOSED TO FIRE
- X 54 FIRE DURATION FAILS EXTERNAL VALVE PACKING

TABLE 7.2. (cont'd)

X 55 EXTERNAL VALVE NOT CLOSED PROPERLY
X 56 EXTERNAL VALVE NOT ASSEMBLED PROPERLY
X 57 EXTERNAL VALVE SEAT FAULTY FROM NORMAL DETERIORATION
X 58 END CAP DOES NOT SEAL PROPERLY
X 59 END CAP NOT PROPERLY ATTACHED
X 60 IMPACT FORCES FAIL END CAP
X 61 CRUSH FORCES FAIL END CAP
X 62 PRESSURE FORCES FAIL END CAP
X 63 PUNCTURE PROBE FAILS END CAP
X 64 FIRE DURATION EXCEEDS 1 HOUR
X 66 IMPACT FORCES WEAKEN TANK WALLS
X 67 IMPACT FORCES SUFFICIENT TO FAIL NORMAL TANK WALLS
X 68 TANK WALLS DEFECTIVE
X 69 IMPACT FORCES SUFFICIENT TO FAIL DEFECTIVE WALLS
X 73 FIRE DURATION PRODUCES PRES THAT FAILS WEAKENED WALLS
X 74 PUNCTURE PROBE STRIKES TANK WALLS
X 75 PUNCTURE PROBE HAS SUFFICIENT ENERGY TO FAIL TANK WALLS
X 76 GAS RELEASED WHEN CRUSH FORCES FAIL TANK WALLS
X 77 TANK OVERTURNS ON ROADWAY
X 78 ABRASION FAILS WALLS IN OVERTURN ACCIDENT
X 79 TANK DOES NOT OVERTURN AND ABRASION FAILS WALLS
X 84 ABRASION WEAKENS TANK WALLS
X 85 FIRE DURATION PRODUCES PRES THAT FAILS DEFECTIVE WALLS
X 89 FIRE DURATION PRODUCES PRESS THAT FAILS NORMAL WALLS
X 93 GAS RELEASED WHEN DIRECT IMPACT FAILS RELIEF VALVES OPEN
X 94 GAS RELEASED WHEN PUNCTURE FAILS RELIEF VALVES OPEN
X 98 RELIEF VALVE OPEN FROM MANUFACTURING DEFECT
X 99 RELIEF VALVE OPEN FROM IMPROPER INSTALLATION OR MAINTENANCE
X 100 RELIEF VALVE OPEN FROM NORMAL DETERIORATION
X 102 SUNSHINE CAUSES TANK PRESSURE TO EXCEED 9 PSIG
X 103 FIRE DURATION CAUSES TANK PRESSURE TO EXCEED 9 PSIG
X 105 LARGE RELIEF VALVES FAIL CLOSED FROM NORMAL DETERIORATION
X 106 LARGE RELIEF VALVES FAIL CLOSED FROM MANUFACTURING DEFECT
X 107 LARGE RELIEF VALVES FAIL CLOSED FROM IMPROPER INSTALLATION
X 108 LARGE RELIEF VALVES FAIL CLOSED FROM ACCIDENT FORCES
X 109 MANWAY COVER DEFECTIVE
I 204 ORIENTATION AFTER ACCIDENT PERMITS RELEASE
I 260 ORIENTATION AFTER ACCIDENT PERMITS RELEASE
I 268 ORIENTATION AFTER ACCIDENT PERMITS RELEASE
I 270 ORIENTATION AFTER ACCIDENT PERMITS RELEASE
I 273 ORIENTATION AFTER ACCIDENT PERMITS RELEASE
I 302 ORIENTATION AFTER ACCIDENT PERMITS RELEASE

TABLE 7.3. Listing of Gate Logic Rectangle Labels for Gasoline Truck Transportation Fault Tree

A 1 GASOLINE RELEASED IN TRANSPORTATION ACCIDENT
 A 1 GASOLINE RELEASED IN TRANSPORTATION ACCIDENT
 A 2 GASOLINE RELEASED WHEN ACCIDENT OCCURS
 A 204 MANWAY COVER RELEASES GASOLINE IN ACCIDENT
 A 4 MANWAY COVER FAULTY OR MANWAY FAILS FROM ACCIDENT FORCES
 A 5 MANWAY COVER FAULTY WHEN ACCIDENT OCCURS
 A 6 ACCIDENT FORCES FAIL MANWAY COVER
 A 8 PRESSURE FORCES FAIL MANWAY COVER
 A 10 FIRE PRODUCES SUFFICIENT PRESSURE TO FAIL MANWAY COVER
 A 11 FIRE DURATION PRODUCES REQUIRED PRESSURE THAT FAILS MANWAY COVER
 A 16 RELIEF VALVES DO NOT OPEN WHEN PRESSURE RISES
 A 20 FIRE FAILS MANWAY COVER GASKET
 A 21 OUTLET VALVE RELEASES GASOLINE IN ACCIDENT
 A 22 ORIENTATION AND LIQUID LEVEL PERMIT RELEASE
 A 23 TANK ON SIDE AND OVER HALF FULL
 A 24 OUTLET VALVE WILL RELEASE GAS IN ACCIDENT
 A 25 VALVE ASSEMBLY-TANK MATING SURFACE WILL RELEASE GAS
 A 27 FIRE FAILS VALVE ASSEMBLY - TANK GASKET
 A 29 EXTERNAL VALVE ASSEMBLY WILL LEAK GASOLINE
 A 30 EXTERNAL VALVE WILL LEAK FROM ACCIDENT FORCES AND INTERNAL VALVE OPEN
 A 31 EXTERNAL VALVE WILL LEAK FROM ACCIDENT FORCES
 A 32 IMPACT FORCES FAIL EXTERNAL VALVE
 A 33 PRESSURE FORCES FAIL EXTERNAL VALVE
 A 35 FIRE PRODUCES SUFFICIENT PRESSURE TO FAIL EXTERNAL VALVE
 A 39 INTERNAL VALVE OPEN
 A 40 INTERNAL VALVE OPEN FROM ACCIDENT FORCES
 A 41 ACCIDENT FORCES OPEN INTERNAL VALVE
 A 42 INTERNAL VALVE OPENS WHEN WEAK LINK FAILS
 A 43 INTERNAL VALVE OPEN NOT RESULT OF ACCIDENT FORCES
 A 44 INTERNAL VALVE SEAT FAULTY
 A 45 EXTERNAL VALVE WILL LEAK AND INTERNAL VALVE OPEN FROM ACCIDENT FORCES
 A 46 EXTERNAL VALVE WILL LEAK
 A 47 EXTERNAL VALVE PACKING LEAKS
 A 48 FIRE FAILS EXTERNAL VALVE PACKING
 A 49 EXTERNAL VALVE OPEN
 A 50 EXTERNAL VALVE FAULTY
 A 51 END CAP WILL LEAK GASOLINE
 A 52 END CAP WILL LEAK NOT RESULT OF ACCIDENT AND INT. AND EXT. VALVES OPEN
 A 53 INTERNAL VALVE OPEN DUE TO ACCIDENT FORCES WHEN EXTERNAL VALVE INTACT
 A 54 END CAP FAULTY NOT RESULT OF ACCIDENT
 A 55 END CAP WILL LEAK FROM ACCIDENT FORCES AND EXT AND INT VALVES OPEN
 A 56 END CAP WILL LEAK FROM ACCIDENT FORCES
 A 57 INTERNAL VALVE OPEN
 A 58 TANK WALLS RELEASE GASOLINE IN TRANSPORTATION ACCIDENT
 A 59 GAS RELEASED WHEN FIRE FAILS TANK WALLS
 A 260 GAS RELEASED WHEN IMPACT FAILS TANK WALLS
 A 61 IMPACT FORCES FAIL TANK WALLS
 A 62 IMPACT SUFFICIENT TO FAIL WALLS
 A 64 DIRECT IMPACT FAILS DEFECTIVE WALLS

TABLE 7.3. (cont'd)

A 268 GAS RELEASED WHEN PUNCTURE PROBE FAILS TANK WALLS
A 69 PUNCTURE PROBE FAILS TANK WALLS
A 270 GAS RELEASED WHEN ABRASION FAILS TANK WALLS
A 71 ABRASION FAILS TANK WALLS
A 72 TANK OVERTURNS AND ABRASION FAILS TANK WALLS
A 273 GAS RELEASED WHEN PRESSURE FORCES FAIL TANK WALLS
A 74 PRESSURE FORCES FAIL TANK WALLS
A 75 PRESSURE FORCES SUFFICIENT TO FAIL TANK WALL PRODUCED IN ACCIDENT
A 76 PRESSURE PRODUCED WHEN WALLS WEAKENED BY ACCIDENT
A 78 FIRE CAUSES PRESSURE RISE IN TANK WHEN WALLS WEAKENED
A 83 TANK WALLS WEAKENED BY ACCIDENT
A 84 PRESSURE PRODUCED WHEN WALLS DEFECTIVE
A 89 PRESSURE RISE OPENS RELIEF VALVE WHEN TANK OVERTURNS
A 90 PRESSURE RISE IN TANK EXCEEDS 9 PSIG
A 91 FIRE CAUSES TANK PRESSURE TO EXCEED 9 PSIG
A 92 FIRE CAUSES PRESSURE RISE IN TANK WHEN WALLS NORMAL
A 97 RELIEF VALVE RELEASES GASOLINE IN TRANSPORTATION ACCIDENT
A 98 GAS RELEASED WHEN ACCIDENT FORCES FAIL RELIEF VALVE OPEN
A 101 GAS RELEASED WHEN RELIEF VALVE DOES NOT FAIL IN ACCIDENT
A 302 GAS RELEASED WHEN RELIEF VALVE FAULTY WHEN ACCIDENT OCCURS
A 103 RELIEF VALVE FAULTY WHEN ACCIDENT OCCURS
A 104 GAS RELEASED WHEN RELIEF VALVE FUNCTIONS NORMALLY
A 105 PRESSURE RISE OPENS RELIEF VALVE WHEN TANK UPRIGHT
A 106 PRESSURE RISE IN TANK EXCEEDS 1 PSIG
A 107 FIRE CAUSES TANK PRESSURE TO EXCEED 1 PSIG
A 108 SMALL RELIEF VALVE DOES NOT OPEN WHEN PRESSURE RISES
A 109 LARGE RELIEF VALVES DO NOT OPEN WHEN PRESSURE RISES
A 111 FIRE FAILS DEFECTIVE MANWAY

A partial listing of the release sequences identified from the gasoline truck transportation fault tree is presented in Table 7.4. There are a total of over seven hundred possible release sequences in the fault tree. These have been screened for presentation here to eliminate those sequences that have a probability of occurrence of less than once in 10^{12} shipments. (see Section 8). All of the release sequences were retained in the actual analysis.

TABLE 7.4. Listing of Gasoline Truck Transportation
Fault Tree Release Sequences

X 1	A 69	I268				
X 1	X 5	X 64				
X 1	X 2	I204				
X 1	X 3	I204				
X 1	X 4	I204				
X 1	X 79	I270				
X 1	X 98	I302				
X 1	X 25	X102				
X 1	X 24	X 29				
X 1	X 99	I302				
X 1	X100	I302				
X 1	X 11	X 24				
X 1	X 77	X 78	I270			
X 1	X 5	X 25	X103			
X 1	X 25	X 26	X 29			
X 1	X 8	X 67	I260			
X 1	X 5	X 12	X 24			
X 1	X 8	X 68	X 69	I260		
X 1	X 5	X 24	X 30	X 53		
X 1	X 5	X 21	X 22	I204		
X 1	X 24	X 46	X 56	X 59		
X 1	X 24	X 46	X 55	X 59		
X 1	X 5	X 25	X 26	X 30	X 53	
X 1	X 8	X 24	X 35	X 36	X 48	
X 1	X 8	X 24	X 35	X 36	X 46	
X 1	X 8	X 24	X 35	X 36	X 42	
X 1	X 5	X 17	X 89	X108	I273	
X 1	X 5	X 24	X 48	X 53	X 54	
X 1	X 5	X 24	X 46	X 53	X 54	
X 1	X 5	X 24	X 42	X 53	X 54	
X 1	X 8	X 24	X 35	X 36	X 47	
X 1	X 8	X 24	X 35	X 36	X 49	
X 1	X 8	X 24	X 35	X 36	X 50	
X 1	X 5	X 24	X 47	X 53	X 54	
X 1	X 5	X 24	X 49	X 53	X 54	
X 1	X 5	X 24	X 50	X 53	X 54	
X 1	X 8	X 25	X 26	X 35	X 36	X 48
X 1	X 8	X 25	X 26	X 35	X 36	X 46
X 1	X 8	X 25	X 26	X 35	X 36	X 42
X 1	X 5	X 25	X 26	X 48	X 53	X 54
X 1	X 5	X 25	X 26	X 46	X 53	X 54
X 1	X 8	X 25	X 26	X 35	X 36	X 47
X 1	X 8	X 25	X 26	X 35	X 36	X 49
X 1	X 8	X 25	X 26	X 35	X 36	X 50
X 1	X 5	X 25	X 26	X 47	X 53	X 54
X 1	X 5	X 25	X 26	X 49	X 53	X 54
X 1	X 5	X 25	X 26	X 50	X 53	X 54
X 1	X 8	X 24	X 35	X 36	X 43	X 44
						X 45

REFERENCES

1. J. L. Carter, ACORN a Program for Plotting Fault Trees. BNWL-2144, Battelle, Pacific Northwest Laboratories, Richland, WA, October 1977.
2. P. J. Peltó, W. L. Purcell, MFAULT: A Computer Program for Analyzing Fault Trees. BNWL-2145, Battelle, Pacific Northwest Laboratories, Richland, WA, November 1977.

8.0 RELEASE SEQUENCE EVALUATION

The previous section presented the fault tree for the shipment of gasoline by truck and listed the more important release sequences. Figure 8.1 illustrates the remaining steps in the risk evaluation and the inputs to these steps. It is necessary to assign a frequency of occurrence and a release fraction to each release sequence. This section presents the information used to evaluate these terms for each release sequence. The release fraction is input to the environmental consequence model in Section 9. The consequence of each release sequence is multiplied by its probability and this product is summed for all release sequences to determine the total risk.

FIGURE 8.1. Remaining Steps in the Risk Evaluation

8.1 BASIC EVENT PROBABILITIES

The expected frequency of each release sequence is obtained by taking the product of the probability of each event in the sequence. The estimates of the event probabilities are presented below. For most of the events, the probability is the same for both reference shipping systems used in the analysis. Where differences exist, the system that would result in the higher probability for that event was used.

Transportation Accident Occurs (X1). The accident frequency for truck transport is one accident every 400,000 miles, i.e., a rate of 2.5×10^{-6} truck accidents per mile.⁽¹⁾ For a shipping distance of 50 miles, the expected accident frequency is 1.25×10^{-4} accidents per shipment. This value is used in the analysis.

Manway Cover Installed Improperly (X2). Manway covers are removed from the tanks periodically for tank cleaning and maintenance. Previous studies⁽²⁾ have used a probability of 3×10^{-3} for human errors in performing a task embedded in a routine procedure. The manway cover is opened each time the product is loaded into or off-loaded from the tank. Most installation errors would be discovered during this process. Therefore, a probability of 3×10^{-4} was assigned to this event.

Manway Cover Faulty Due to Normal Deterioration (X3). No data are available for this event. A survey of local trucking companies engaged in gasoline transportation indicated that the manway cover was not a significant maintenance item. This event was therefore assigned a relatively low probability of 10^{-3} . An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 3 percent. This is well within the overall accuracy of the analysis.

Manway Cover Faulty from Manufacturing Defect (X4). A study of error rates in quality control inspections of electrical components gives a probability of 0.003 that a defective component will not be detected.⁽³⁾ Although not directly applicable to manufacturing defects for manway covers,

it is assumed that this value is representative of quality control in a variety of manufacturing operations. This value is in agreement with the value of human errors in routine procedures used in event X2.

Fire Occurs in Accident (X5). The probability that a fire that does not initially involve the cargo will occur in a truck accident is 0.016 (see Section 5.0).

Fire Produces Pressure That Fails Normal Manway Cover (X6). Failure of the tank by overpressurization is considered in event X89. This event is assigned a probability of zero since it is included in X89.

Fire Produces Pressure That Fails Defective Manway Cover (X7). It is assumed that a defective manway cover would fail at 1/2 the pressure rise that would fail a normal manway cover. Extrapolating the calculation in Appendix D, this would require a 25-minute fire. The probability that a fire in an accident will last 25 minutes or longer is given in Figure 5.1 as 0.1. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01 percent. This is well within the overall accuracy of the analysis.

Impact Forces Produced in Accident (X8). Based on the Bureau of Motor Carrier Safety Data presented in Section 5.0, impact forces can be expected to be present in nearly all truck accidents. A probability of 1.0 was used for this event.

(X9) and (X10). Not used.

Sunshine Causes Tank Pressure to Exceed 1 psig (X11). Curves of gasoline vapor pressure as a function of temperature are presented in Appendix B. If the gasoline in the tank is assumed to be at an average ambient temperature of about 78°F, a vapor pressure rise of 1 psi requires a temperature rise of about 6°F (see Figure B.1). Calculations in Appendix D show that the maximum expected temperature rise from solar insolation is 3.8°F per hour. Thus, about 1 hour and 35 minutes would

be required to produce a pressure rise that would open the small relief valve. The response of emergency assistance teams could be expected to alleviate this condition. The time between the ignition of a building fire and the arrival of fire-fighting forces has been used as a measure of the response time for emergency assistance personnel. In a study of 133 fires, 10 percent had a pre-burn time greater than 1 hour.⁽⁴⁾ The probability that a large truck accident will occur between the hours of 8 a.m. and 4 p.m. when insolation is significant can be extracted from BMCS data⁽⁵⁾ as 0.54. Assuming that 2/3 of all days are not overcast gives a probability for this event of 0.04. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01 percent. This is well within the overall accuracy of the analysis.

Fire Duration Produces Pressure Rise Above 1 psig (X12). A temperature rise of about 6°F is required to raise the vapor pressure of gasoline 1 psi (see event X11). Extrapolation of the calculations in Appendix D shows that a 3-minute fire is required to raise the gasoline temperature 6°F. The probability that a fire in an accident will last longer than 3 minutes is given in Figure 5.1 as 0.85.

Small Relief Valve Fails Closed From Normal Deterioration (X13). No data are available for this event. A survey of local trucking companies engaged in gasoline transportation indicated some question about the reliability of these devices. A probability of 0.05 was used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01 percent. This is well within the overall accuracy of the analysis.

Small Relief Valve Fails Closed From Accident Forces (X14). No data are available for this event. The only method envisioned for the small relief valve to fail closed from accident conditions or by direct impact

on the valve is by lodging debris on top of the valve. The valve is protected by the manway cover handle and by the protective top rails. Most accident forces would tend to open the valve. This event was assigned a probability of 0.01. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

Small Relief Valve Fails Closed From Improper Installation (X15). A probability of 3×10^{-3} was used for this event (see event X2).

Small Relief Valve Fails Closed From Manufacturing Defect (X16). A probability of 0.003 is used for this event (see event X4).

Small Relief Valve Ball Check Closes When Tank Overturns (X17). The ball check is designed to close the valve when the tank overturns. The probability of overturn in a truck accident has been estimated to be 0.2.⁽⁶⁾ A probability of 0.2 is used for this event. This value is conservative.

Puncture Probe Produced in Accident (X18). A description of the puncture environment to which a large container would be exposed in an accident is not available. Puncture accidents are lumped together in event A69. Individual puncture accidents are not analyzed (i.e., a probability of zero is used). Puncture events are included in the fault tree for completeness, so that the analysis could readily be changed if information on the puncture environment became available.

Puncture Probe Fails Manway Cover (X19). All puncture events were included in event A69. Therefore a value of zero was used for this event.

(X20). Not used.

Manway Cover Exposed to Fire (X21). Overturn is required to expose the manway to fire. It is assumed that the fire will contact the manway cover of an overturned tank 75% of the time. Since overturn is also required for a release from the manway cover, a probability of 0.75 is used for this event. The probability of overturn is included in I204.

Fire Duration Fails Manway Cover Gasket (X22). Gaskets are estimated to lose their liquid retention capability after a 20-min exposure to an 1850°F fire (see Appendix D). The probability that a fire in an accident will last 20 min or longer is taken from Figure 5.1 as 0.2.

Impact Forces Fail Manway Cover (X23). The manway cover was considered part of the tank walls for impact analysis. This event was not analyzed separately (i.e., a probability of zero was assigned).

Tank Remains Upright in Accident (X24). The probability of overturn in an accident is 0.2 (see event X17). This event is therefore assigned a probability of 0.8.

Tank Overturns in Accident (X25). A probability of 0.2 was used for this event (see event X17).

Tank Over Half Full When Accident Occurs (X26). A survey of local trucking companies engaged in gasoline transportation indicates that gasoline deliveries are made almost exclusively in truckload quantities (see Appendix A). A probability of 1.0 was used for this event.

Impact Forces Fail Assembly - Tank Mating Surface (X27). This area was considered part of the tank walls for impact analysis. A probability of zero was used for this event.

(X28). Not used.

Pressure Forces Fail Assembly - Tank Mating Surface (X29). This event requires a simultaneous failure of all three pressure relief devices and a pressure buildup in the tank from fire. The maximum probability that all three relief valves would fail simultaneously is less than 10^{-5} (see events X13 through X17 and X105 through X108). The probability that a fire will occur is 0.016. The probability of this event is, therefore, less than 10^{-6} . A value of 10^{-6} was used for the analysis.

Fire Duration Fails Valve Assembly - Tank Gasket (X30). A probability of 0.2 is used for gasket failure in a fire (see event X22).

Puncture Probe Fails Assembly - Tank Mating Surface (X31). All puncture failures were included in event A69. A probability of zero is therefore used for this event.

(X32). Not used.

Crush Forces Fail Assembly - Tank Mating Surface (X33). Crush forces are not believed to be important in accidents involving large containers. This event was not analyzed (i.e., a probability of zero is used).

Crush Forces Fail External Valve (X34). Crush events were not analyzed (see event X33).

External Valve Experiences Impact Forces (X35). The tank-trailer shipping configuration was conservatively used for this event. A side-on collision is required for the external valve to experience impact forces. The probability, given a collision, that a truck will be struck from the side by another vehicle is 0.139 (see Table 5.3). The outlet valve and manifold assembly occupies about 1/2 the length of the tank trailer. The probability that the valve and manifold assembly will be struck when side-on impact occurs is therefore taken to be 0.5. The probability used for this event is then 0.07.

Impact Forces Sufficient to Fail Valve (X36). It is assumed that all side-on impacts striking the outlet valve or manifold assembly will fail them. A probability of 1.0 is used for this event.

(X37). Not used.

Fire Duration Produces Pressure That Fails External Valve (X38). It is assumed that the external valve will fail after a pressure increase of 5 psi. Assuming that the gasoline is initially at a temperature of 78°F, Figure B.1 shows that a temperature increase of 27°F is required to raise the vapor pressure 5 psi. The calculations in Appendix D show that this requires a fire duration of at least 11 min. The probability of a fire in an accident lasting longer than 11 min is given in Figure 5.1 as 0.5.

(X39). Not used.

Puncture Probe Fails External Valve (X40). All puncture failures were included in event A69. A value of zero was therefore used for this event.

(X41). Not used.

Accident Forces Raise Internal Valve Handle (X42). The external portions of the internal valve assembly occupy less than 1% of the total length of the tank truck or trailer. The probability that a side-on impact will occur and strike the external valve handle is therefore taken to be 0.001. To raise the valve handle without breaking the valve at the shear section, requires an impact of a very specific magnitude and direction. It was conservatively estimated that 1% of the accidents in which the valve assembly is struck will result in the valve handle being raised. Therefore, a probability of 1×10^{-5} is used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

Accident Forces Break Outlet Valve Assembly at Shear Section (X43). The probability that the valve will be struck is 0.001 (event X42). It is conservatively assumed that the shear section will break for all impacts. A probability of 0.001 is used for this event.

Tank Overturns and Internal Valve Dislodged When External Valve Severed (X44). Breaking the outlet valve assembly at the shear section will sever the internal valve from the spring loaded handle that holds it closed. The internal valve will remain seated from liquid pressure in the tank but a tank rollover could dislodge the valve from its seated position. The probability of overturn is 0.2 (event X25). It is assumed that the internal valve would be dislodged in 10% of these accidents. A probability of 0.02 is, therefore, used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

Internal Valve Does Not Reseat From Liquid Pressure (X45). If the internal valve becomes dislodged the liquid pressure in the tank will tend to cause it to reseat. It is estimated that the valve would reseat 90% of the time. A probability of 0.1 is used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

Accident Forces Fail Internal Valve Seat (X46). No data are available for this event. The internal valve seat is located inside the tank and is protected from most accident forces. A probability of 10^{-3} was used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.1%. This is well within the overall accuracy of the analysis.

Internal Valve Opened and Not Closed Manually (X47). A probability of 0.003 is used for human errors of omission (see event X2). Because the internal valve is spring-loaded, it would tend to seat from the truck motion during transit. A probability of 3.0×10^{-4} is used for this event.

Internal Valve Seat Faulty From Normal Deterioration (X48). A probability of 10^{-3} was used for this event (see event X3). An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.1%. This is well within the overall accuracy of the analysis.

Internal Valve Seat Faulty From Manufacturing Defect (X49). A probability of 0.003 was used for this event (see event X4).

Internal Valve Seat Installed Improperly (X50). A probability of 0.003 was used for this event (see event X2).

External Valve Packing Faulty From Normal Deterioration (X51). A probability of 10^{-3} was used for this event (see event X3). An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

External Valve Packing Not Installed or Adjusted Properly (X52). A probability of 0.003 was used for this event (see event X2).

External Valve Exposed to Fire (X53). A probability of 0.5 was used for this event. This is believed to be conservative.

Fire Duration Fails External Valve Packing (X54). A probability of 0.2 is used for gasket failure in a fire (see event X22). This probability is also used for this event.

External Valve Not Closed Properly (X55). A probability of 0.003 was used for this event (see event X2).

External Valve Not Assembled Properly (X56). A probability of 0.003 was used for this event (see event X2).

External Valve Seat Faulty From Normal Deterioration (X57). A probability of 10^{-3} was used for this event (see event X3).

End Cap Does Not Seal Properly (X58). No data are available for this event. The end cap is a threaded pipe and cap. Damage which prevents a proper seal would also tend to make the end cap hard to install and remove and would be noticed and repaired. A probability of 10^{-3} was used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

End Cap Not Properly Attached (X59). Previous studies have used a probability of 0.01 for a human error in omitting a step at the end of a procedure.⁽²⁾ The end cap will probably be the last item put in place when gasoline is unloaded, so a probability of 0.01 is used for this event.

Impact Forces Fail End Cap (X60). This event was not analyzed. The probability of failing the end cap by impact without failing the valve assembly at the weak link is believed to be low.

Crush Forces Fail End Cap (X61). Crash events were not analyzed (see event X33).

Pressure Forces Fail End Cap (X62). This event was assigned a probability of 10^{-6} (see event X29).

Puncture Probe Fails End Cap (X63). All puncture failures were included in event A69. A probability of zero was therefore used for this event.

Fire Duration Exceeds One Hour (X64). The calculations in Appendix D show that a 1-hr fire is required to fail the tank walls by melting. The probability that a 1-hr fire will occur in an accident is given in Figure 5.1 as 0.01. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 2.0%. This is well within the overall accuracy of the analysis.

(X65). Not used.

Impact Forces Weaken Tank Walls (X66). It is assumed that a velocity change of at least 10 mph is required to significantly weaken the tank walls in an impact accident. This value is believed to be conservative. The probability of a 10 mph or greater velocity change in an impact accident is given in Figure 5.2 as 0.08.

Impact Forces Sufficient to Fail Normal Tank Walls (X67). A velocity change of 30.6 mph for the tank truck/tank trailer transport system and 23.6 mph for the tractor/semitrailer shipping system is required to fail the tank in an end-on impact. A value of 25 mph will be conservatively

assumed for the analysis. A velocity change of 18.7 mph is required when the tank is struck from the side (see Appendix D). From Table 5.4, the probability that the tank will be accelerated or decelerated along its axis is 0.855. This is taken as the probability of an end-on impact. The probability that the tank will be accelerated perpendicular to its axis is given in Table 5.4 as 0.145. This is taken as the probability of a side-on impact. The probability of a velocity change of 25 mph or greater in a collision accident is given in Figure 5.2 as 0.02 and the probability of an 18.7 mph or greater velocity change is 0.04. The total probability for this event is then 0.023.

Tank Walls Defective (X68). A value of 0.003 is used for manufacturing defects (see event X4).

Impact Forces Sufficient to Fail Defective Walls (X69). It is assumed that defective walls would fail from impact twice as frequently as normal walls. A value of 0.046 (twice that of event X67) has been used for this event. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 2.0%. This is well within the overall accuracy of the analysis.

Puncture Probe Fails Tank Walls (A69). A detailed description of the puncture environment that would be encountered by a gasoline tank truck in an accident was not available. Since the data that was available on puncture failure lacked sufficient detail to predict failure of individual components of the tank, all puncture failures are lumped together in this event. The probability that the tank will fail from puncture forces has been calculated in two ways. It is believed that these methods provide a reasonable range of values for this event. The DOT data on puncture accidents over a 5-year period are presented in Section 5.0. Table 5.8 shows a total of 358 puncture accidents over the 5-year period in tank trucks that could carry flammable liquids. It has been estimated that about 45% of the carriers involved in transportation of these commodities report to DOT.⁽⁷⁾ This implies a total of 795 tank truck puncture accidents over the 5-year period or 159 punctures/yr. BMCS data for the period 1965-1967 show that

gasoline was the commodity carried in 47% of the accidents involving tank trucks that could carry gasoline.⁽⁸⁾ This implies a total of 74 puncture accidents per year in gasoline tank trucks. For the shipping levels assumed for 1980, a total of 75 puncture accidents/yr could be expected, or a probability of 5.5×10^{-6} /shipment that the tank will fail from puncture forces. This implies a probability for this event of 0.044.

The probability of this event has also been estimated from the probability that a truck carrying a hazardous liquid or gas will be involved in an accident that results in a lading loss. This value has been estimated as 2.7×10^{-8} /mile.⁽⁹⁾ This gives a probability of 1.35×10^{-6} /gasoline shipment. If 55% of these lading losses result from puncture forces (see Table 5.8), the probability of a lading loss from puncture is 7.4×10^{-7} /shipment. This gives a probability for this event of 5.9×10^{-3} . The average of these two values 0.025 will be used for the initial stages of the analysis.

(X70), (X71), and (X72). Not used.

Fire Duration Produces Pressure That Fails Weakened Walls (X73).

Appendix D shows that a pressure rise of 30 psi is required to overpressurize normal walls. It is assumed that weakened walls will fail at 15 psi. Extrapolation of the calculations in Appendix D shows that a 25-min fire is required to produce a pressure rise of 15 psi in the tank if the gasoline is originally at 78°F. The probability of a 25-min fire in an accident is given in Figure 5.1 as 0.1. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

Puncture Probe Strikes Tank Walls (X74). All puncture failures are included in event A69. A probability of zero was therefore used for this event.

Puncture Probe Has Sufficient Energy to Fail Tank Walls (X75). All puncture failures are included in event A69. A probability of zero was therefore used for this event.

Gas Released When Crush Forces Fail Tank Walls (X76). Crush events were not analyzed (see event X33).

Tank Overturns on Roadway (X77). The probability that the tank will overturn on the roadway in an accident is given in Table 5.1 as 0.028.

Abrasion Fails Walls in Overturn Accident (X78). The fraction of various roadway surfaces used in the analysis is given in Table 5.5. For purposes of estimating abrasive failures, the road surfaces were grouped into two categories - asphalt, concrete and other surfaces (57%) and bituminous surface treatment (BST) (43%). Calculations in Appendix D indicate that a speed of 26 mph is required for abrasive failure on asphalt or concrete surfaces and 20 mph on BST surfaces. Because accident speed data are collected in 10-mph data blocks, it will be assumed that abrasive failure on concrete and asphalt surfaces will occur at a pre-accident speed of 30 mph. Table 5.6 gives the probability of a pre-accident speed of 30 mph or greater as 0.307 and the probability that the pre-accident speed will exceed 20 mph as 0.464. The probability used for this event is then 0.37.

Tank Does Not Overturn and Abrasion Fails Walls (X79). No data are available for this event. For abrasive failure against a vertical surface to occur a vertical abrasive surface must be present in an accident, the tank must slide along the surface, and the pre-accident speed must be sufficient for abrasive failure on the surface encountered. The probability that a vertical abrasive surface is present in an accident is assumed to be 10^{-3} . The probability of vehicle overturn (0.2) is used for the probability that the tank will slide along the vertical abrasive surface. It is assumed that all vertical abrasive surfaces are concrete. A speed of 26 mph is required for abrasive failure on concrete surfaces (see Appendix D). A speed of 30 mph is used here as the minimum pre-accident speed for failure on a concrete surface because accident speed data are collected in 10-mph data blocks. The probability of a pre-accident speed exceeding 30 mph is 0.31 (see Table 5.6). The probability for this event is then 6.1×10^{-5} . An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that

increasing this event probability by a factor of 10 raised the total release probability by less than 3%. This is well within the overall accuracy of the analysis.

(X81), (X82), and (X83). Not used.

Abrasion Weakens Tank Walls (X84). It is assumed that the walls will be weakened by abrasion of speeds between 10 mph and 30 mph for concrete or asphalt surfaces (53% of all roadways) and between 10 and 20 mph for BST surfaces (47% of all roadways). The probability that an accident will occur at a speed between 10 and 30 mph is 0.313. The probability that an accident will occur between 10 and 20 mph is 0.157 (see Table 5.6). The probability of overturn on the road is 0.028. This gives a probability for this event of 0.007.

Fire Duration Produces Pressure That Fails Defective Walls (X85).

Appendix D shows that a pressure rise of 30 psi is required to fail normal walls. It is assumed that defective walls would fail at half that pressure. Extrapolation of the calculations in Appendix D shows that a 25-min fire would be required to produce this pressure rise. The probability of a 25-min fire can be taken from Figure 5.1 as 0.1. An analysis was performed to determine the sensitivity of the total release probability to the probability value used for this event. It was found that increasing this event probability by a factor of 10 raised the total release probability by less than 0.01%. This is well within the overall accuracy of the analysis.

(X86), (X87), and (X88). Not used.

Fire Duration Produces Pressure That Fails Normal Walls (X89).

Appendix D shows that a 40-min fire is required to overpressurize a normal tank. The probability that a fire in an accident will last 40-min or longer is given in Figure 5.1 as 0.03.

(X90), (X91), and (X92). Not used.

Gas Released When Direct Impact Fails Relief Valves Open (X93). The manway cover and relief valves are considered part of the tank walls for impact analysis. A probability of zero is therefore used for this event.

Gas Released When Puncture Fails Relief Valves Open (X94). This event was not analyzed (see event X18).

(X95), (X96), and (X97). Not used.

Relief Valve Open From Manufacturing Defect (X98). A probability of 0.003 is used for manufacturing defects (see event X4). Since there are two relief valves that could release material in an overturn accident, a probability of 0.006 was assigned to this event.

Relief Valve Open From Improper Installation or Maintenance (X99). A probability of 0.003 is used for installation or maintenance errors (see event X2). Since there are two relief valves, that could release material in an overturn. A probability of 0.006 was used for this event.

Relief Valve Open From Normal Deterioration (X100). A probability of 0.001 is used for deterioration of tank components. Since there are two relief valves that could release material in an overturn, a probability of 0.002 was used for this event.

(X101). Not used.

Sunshine Causes Tank Pressure To Exceed 9 psig (X102).¹ (see event X11). Approximately 10 hr of exposure to direct sunlight is required to produce a tank pressure rise of 9 psi. No fire fighting response times greater than 3 hr and 10 min were reported in Reference 4. The probability of a 3-hr response time is 0.01. The probability that the response time will exceed 10 hr is conservatively estimated as 10^{-4} . Using a probability of 0.54 that the accident will occur during daylight hours and 0.66 that the weather will not be overcast gives a probability for this event of 3.6×10^{-5} .

Fire Duration Causes Tank Pressure To Exceed 9 psig (X103). Assuming that the gasoline is originally at a temperature of 78°F, Figure B.1 shows that a temperature rise of 40°F is required to produce a pressure increase of 9 psi. Appendix D shows that a fire duration of 16 min is required for a 40°F temperature rise in the tank. The probability of a 16-min fire in an accident is given in Figure 5.1 as 0.24.

Large Relief Valves Fail Closed From Normal Deterioration (X105). The probability used for a component failure from deterioration is 0.001 (see event X3). Failure of the largest relief valve requires simultaneous failure of two opposite springs. Since there could be some correlation between the failure of two large relief valve springs from deterioration a probability of 3.3×10^{-4} is used for this event. The sum of the probability that the other large relief valve will fail from all causes is 0.017. The probability that the largest relief valve will fail closed from deterioration while the other relief valve is failed closed is 5.6×10^{-6} .

Large Relief Valves Fail Closed From Manufacturing Defect (X106). A probability of 0.003 has been used for manufacturing defects (see event X4). The probability that both valves will fail from the same defect is believed to be low. The sum of the probabilities that the other relief valve will fail for any cause is 0.017. The probability that one relief valve will fail closed from a manufacturing defect while the other fails for any other reason is then 5.1×10^{-5} .

Large Relief Valves Fail Closed From Improper Installation (X107). A probability of 0.003 is used for improper installation (see event X2). The probability that the other large relief valve will fail from all causes is 0.017. The probability that one relief valve will fail closed from improper installation while the other relief valve is closed from any other failure mode is then 5.1×10^{-5} .

Large Relief Valves Fail Closed From Accident Forces (X108). A probability of 0.01 is used for failure of a relief valve by accident forces (see event X14). The probability that one relief valve will fail from accident forces while the other fails for any reason is 1.7×10^{-4} .

Manway Cover Defective (X109). No data are available for this event. The probability that the manway cover will have a defect that weakens it structurally is taken to be the same as the probability of a manufacturing defect. A probability of 0.003 is used for this event (see event X4).

Orientation After Accident Permits Release (From Manway Cover) (I204).
The tank must overturn for a significant release to occur from the manway cover. The probability of overturn in an accident is 0.2 (see event X25).

Orientation After Accident Permits Release (Impact Fails Walls) (I260).
Since the tanks are always shipped with a full load, it is assumed that gasoline will always be present at an impact site. A probability of 1.0 is used for this event.

Orientation After Accident Permits Release (Puncture Probe Fails Tank Walls) (I268). It is assumed that a release will always occur when puncture forces fail the tank. A probability of 1.0 is used for this event.

Orientation After Accident Permits Release (Abrasion Fails Tank Walls) (I270). It is assumed that a release will always occur when abrasion fails the tank walls. A probability of 1.0 is used for this event.

Orientation After Accident Permits Release (Pressure Fails Tank Walls) (I273). No data are available for this event. The failure point in an overpressurization is difficult to predict. It is conservatively assumed that all pressure failures result in a release. This event is assigned a probability of 1.0.

Orientation After Accident Permits Release (Relief Valve Faulty) (I302).
Overturn is required for a significant release from a relief valve. A probability of 0.2 is used for this event (see event X25).

8.2 RELEASE SEQUENCE PROBABILITIES

The basic event probabilities presented in Section 8.1 provide the basis for evaluating the probability of each release sequence identified in the fault tree. The probability of the release sequences presented in Table 7.4 is shown in Table 8.1. Only the release sequences with a frequency of occurrence greater than 10^{-12} per shipment are listed in the table. All release sequences were retained in the actual risk calculation. The total probability per shipment that a release will occur is 8.9×10^{-6} .

TABLE 8.1. Release Sequence Probabilities

Probability Per Shipment	Release Sequence									
3.13E-6 ^(a)	X 1	A 69	I268							
2.03E-8	X 1	X 5	X 64							
7.63E-9	X 1	X 2	I204							
2.54E-8	X 1	X 3	I204							
7.63E-8	X 1	X 4	I204							
7.76E-9	X 1	X 79	I270							
1.53E-7	X 1	X 98	I302							
9.16E-10	X 1	X 25	X102							
1.02E-10	X 1	X 24	X 29							
1.53E-7	X 1	X 99	I302							
5.09E-8	X 1	X100	I302							
4.07E-6	X 1	X 11	X 24							
1.31E-6	X 1	X 77	X 78	I270						
9.75E-8	X 1	X 5	X 25	X103						
2.54E-11	X 1	X 25	X 26	X 29						
2.72E-6	X 1	X 8	X 67	I260						
1.39E-6	X 1	X 5	X 12	X 24						
1.76E-8	X 1	X 8	X 68	X 69	I260					
1.63E-7	X 1	X 5	X 24	X 30	X 53					
6.10E-8	X 1	X 5	X 21	X 22	I204					
3.06E-12	X 1	X 24	X 46	X 56	X 59					
3.06E-12	X 1	X 24	X 46	X 55	X 59					
4.07E-8	X 1	X 5	X 25	X 26	X 30	X 53				
7.12E-9	X 1	X 8	X 24	X 35	X 36	X 48				
7.12E-9	X 1	X 8	X 24	X 35	X 36	X 46				
7.12E-11	X 1	X 8	X 24	X 35	X 36	X 42				
2.08E-12	X 1	X 5	X 17	X 89	X108	I273				
1.63E-10	X 1	X 5	X 24	X 48	X 53	X 54				
1.63E-10	X 1	X 5	X 24	X 46	X 53	X 54				
1.63E-12	X 1	X 5	X 24	X 42	X 53	X 54				
2.27E-9	X 1	X 8	X 24	X 35	X 36	X 47				
2.27E-8	X 1	X 8	X 24	X 35	X 36	X 49				
2.27E-8	X 1	X 8	X 24	X 35	X 36	X 50				
4.89E-11	X 1	X 5	X 24	X 47	X 53	X 54				
4.89E-10	X 1	X 5	X 24	X 49	X 53	X 54				
4.89E-10	X 1	X 5	X 24	X 50	X 53	X 54				
1.78E-9	X 1	X 8	X 25	X 26	X 35	X 36	X 48			
1.78E-9	X 1	X 8	X 25	X 26	X 35	X 36	X 46			
1.78E-11	X 1	X 8	X 25	X 26	X 35	X 36	X 42			
4.07E-11	X 1	X 5	X 25	X 26	X 48	X 53	X 54			
4.07E-11	X 1	X 5	X 25	X 26	X 46	X 53	X 54			
5.34E-10	X 1	X 8	X 25	X 26	X 35	X 36	X 47			
5.34E-9	X 1	X 8	X 25	X 26	X 35	X 36	X 49			
5.35E-9	X 1	X 8	X 25	X 26	X 35	X 36	X 50			
1.21E-10	X 1	X 5	X 25	X 26	X 50	X 53	X 54			
1.43E-11	X 1	X 8	X 24	X 35	X 36	X 43	X 44	X 45		

(a) Read 3.13×10^{-6}

8.3 RELEASE FRACTIONS

For the purposes of input into the environmental consequences model (Section 9), four release fractions have been selected:

- A release fraction of 1.0, corresponding to the release of all the contents of both the truck tank and trailer tank for the western shipping system or both compartments in the eastern shipping system. The nominal release size for this release fraction is 8,400 gal.
- A release fraction of 0.5, corresponding to the release of all the contents of either the truck tank or trailer tank of the western shipping system or one compartment of the eastern shipping system. The nominal release size for this release fraction is 4,200 gal.
- A release fraction of 0.35, corresponding to the release of slightly more than half the contents of one tank of the western system or one compartment of the eastern system. The nominal release size for this release fraction is 3000 gal.
- A release fraction of 0.01, for very small releases. These releases are assumed to have no consequences.

It was convenient to assign the release fractions by the portion of the tank from which the material was released, and either the accident force that caused the release or the orientation of the tank during the release. The release fractions used in the analysis are presented in Table 8.2. For conservatism, two release fractions were used for failure of the tank walls from impact. It was assumed that both tanks (or tank compartments) would fail in 50% of all failures due to impact forces. It should be noted that these release fractions are valid only for the initial stages of the accident. If the release results in a gasoline fire, all of the truck contents would eventually burn. The material initially released is used to determine the pool size for the consequence model in Section 9.

TABLE 8.2. Release Fractions for Gasoline
Tank Truck Failures

<u>Portion of Tank Failing</u>	<u>Failure Cause (Orientation)</u>	<u>Release Fraction</u>
Tank Walls	Puncture	0.5
	Pressure	0.5
	Abrasion	1.0
	Impact	0.5(50%) 1.0(50%)
	Fire	1.0
Relief Valve	Faulty (Overturn)	0.35
	Pressure (Upright)	0.01
	(Overturn)	0.35
Outlet Valve	Fire	1.0
	All Other Causes (Upright)	0.5
	(Overturn)	0.35
Manway Cover	Fire	1.0
	All Other Causes (Overturn)	0.35

REFERENCES

1. R. K. Clarke, J. T. Foley, W. F. Hartman and D. W. Larson, Severities of Transport Accidents - Vol IV - Motor Carriers. SLA-74-0001, Sandia Laboratories, Albuquerque, NM, July 1976.
2. Reactor Safety Study - An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400 (NUREG-75/014), p. III-81, U.S. Nuclear Regulatory Commission, Washington, DC, October 1975.
3. The Effect of Human Error and Static Component Failure on Engineered Safety System Reliability. HN-194, p. 1.32, Holmes and Narver, Inc., Los Angeles, CA, November 1967.
4. W. G. Labes, Fire Department Operations Analysis. IIT Research Institute, Chicago, IL, January, 1968.
5. R. E. Scott, et al., Statistical Analysis of Truck Accident Involvements. The University of Michigan Highway Research Institute, Ann Arbor, MI, December, 1971.

6. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.
7. L. M. Krasner et al., Hazardous Materials Transportation Intrusion Protection for Hazardous Cargo Tanks. DOT HS-800 513, Factory Mutual Research Corp., Norwood, MA, June 1971.
8. L. M. Krasner, Motor Vehicle Standards for Hazardous Material Transportation. DOT HS-800 240, p. 18, Factory Mutual Research Corp., Norwood, MA, Jan. 1970.
9. A Modal Economic and Safety Study of the Transportation of Hazardous Substances in Bulk. COM-74-11271, p. 151, A. D. Little, Inc., Cambridge, MA, May 1974.

FIGURE 9.1. Gasoline Transportation Accident Consequence Model

9.0 EVALUATION OF THE CONSEQUENCES OF GASOLINE RELEASES

Possible sequences of events that could result from a tank truck accident involving a gasoline spill are depicted in Figure 9.1. As shown on the figure, the consequences of a gasoline spill can be divided into three general areas--those resulting from: 1) gasoline pool fires, 2) the formation of vapor clouds, and 3) the explosion of vapors inside the tank.

9.1 CONSEQUENCES OF GASOLINE POOL FIRES

A gasoline spill will generally produce a large pool of liquid in the vicinity of the breached tank. The characteristics of gasoline pools in general are discussed in Appendix E. The pools are assumed to have an average depth of 0.5 in. Use of a shallower pool depth would increase the number of secondary fires initiated, but would have a small effect on the overall risk. The radius of a 4200-gal spill, for example, is then about 77 ft. The assumed pool shape for spills on urban streets and freeways is presented in Appendix G.

It has been estimated⁽¹⁾ that about 24% of spills from trucks carrying flammable liquids result in a fire. The consequences of a gasoline pool fire are dependent on the location of the accident. Three accident locations are considered in this study: 1) an unpopulated rural area, 2) an urban freeway and 3) a four-lane urban street. Data obtained from motor carrier accident reports submitted to the Bureau of Motor Carrier Safety in 1975 was analyzed to determine the location of accidents that resulted in a spillage of gasoline or other similar flammable liquids. This data showed the following locations for spills from accidents involving flammable liquid tank trucks:

- 68.9% - rural highways
- 22.3% - business area
- 8.8% - residential area.

Data from truck accidents in the states of Texas and Washington were used to determine the fraction of the releases in business and residential areas that occur on city streets and on urban freeways. The Texas data⁽²⁾ indicate that 32.7% of tank truck accidents occur on city streets and 18.6% on urban freeways.

Although 32.7% of all tank truck accidents occur on city streets, it is not likely that an equal percentage of releases occur on city streets. It was necessary to establish the relative severity of accidents on city streets and on rural highways or urban freeways. It was assumed that the accident environment on an urban freeway would be adequately represented by the environment on a rural highway. Accident fatalities have been used as the measure of relative severity between accidents on city streets and rural highways (and urban freeways). According to information from the Washington State Patrol,⁽³⁾ 2.08% of truck accidents on rural highways are fatal and 0.47% of truck accidents in urban areas are fatal. Therefore, the probability that a tank truck accident occurs on a city street ($p = 0.327$) and is fatal ($p = 0.0047$) is 1.54×10^{-3} , the probability that the accident occurs on a rural highway ($p = 0.487$) and is fatal ($p = 0.0208$) is 1.21×10^{-2} and the probability that the accident occurs on an urban freeway ($p = 0.186$) and is fatal ($p = 0.0208$) is 3.87×10^{-3} . The total probability of a fatal accident is then 1.55×10^{-2} . The percentage of fatalities in each area is then:

- city streets - 9.9%
- urban freeways - 24.9%
- rural highways - 65.2%

It is assumed that gasoline releases are divided between the three areas in the same proportions. Combining this information with the Bureau of Motor Carrier Safety data yields the following release locations that are used in this study:

- 68.9% - rural highways
- 6.2% - business area on city street
- 16.4% - business area on urban freeway
- 2.5% - residential area on city street
- 6.3% - residential area on urban freeway

Fatalities from gasoline pool fires may result from direct exposure to the radiant energy from the fire or from secondary fires produced on adjoining buildings. It is assumed that no secondary fires are produced from an accident on a rural highway. Although large amounts of smoke are produced

in a gasoline pool fire, it is assumed that no fatalities occur from smoke inhalation. The smoke plumes produced in the fire are very buoyant and are assumed to dilute to less than toxic levels before significant personnel exposure to the smoke occurs. (See Appendix E.)

Estimates of the number of secondary fires produced from a pool fire on a city street or an urban freeway are given in Appendix G for each of the three spill sizes used in this study. Fatalities from these fires are estimated using data compiled by the National Fire Protection Association (NFPA).^(4,5) These data are summarized in Table 9.1.

TABLE 9.1. Summary of NFPA Data on Building Fire Deaths for 1974

	<u>0-2 Deaths/Fire</u>	<u>3-10 Deaths/Fire</u>	<u>>10 Deaths/Fire^(a)</u>
Number of Fires	1,270,000	201	12
Number of Deaths	10,763	766	171
Average Deaths/Fire	0.01	3.8	14.2

(a)Combination of 1973 and 1974 data.

Using the data in Table 9.1, a probability distribution curve for deaths in building fires has been constructed. This curve is presented in Figure 9.2.

Using Figure 9.2 and the probability estimates on Tables G.3 through G.8, the probability can be estimated for various numbers of deaths from secondary fires when a gasoline spill occurs. It is first necessary to estimate the probability that a given number (n) of deaths will occur when a given number (j) of secondary fires are produced. The simplifying assumption is made that:

$$P(n \text{ deaths} | j \text{ secondary fires})^{(a)} = j \cdot P(n \text{ deaths} | 1 \text{ secondary fire})$$

This assumption slightly overestimates the term on the left. The values of $P(n \text{ deaths} | 1 \text{ secondary fire})$ are read from Figure 9.2. The results of these calculations are presented in Table 9.2.

(a)Read: "The probability of n deaths occurring given that j secondary fires have been started."

FIGURE 9.2. Probability Distribution for Fatalities in a Building Fire

TABLE 9.2. Estimated Probability of n Deaths from j Secondary Building Fires

n	P (n deaths j fires)							
	j=0	1	2	3	4	5	6	7
0	1.0	0.99	0.98	0.97	0.96	0.95	0.94	0.93
1	0.0	0.01	0.02	0.03	0.04	0.05	0.06	0.07
2	0.0	0.0035	0.007	0.01	0.014	0.018	0.021	0.025
3	0.0	3.0E-4 ^(a)	6.0E-4	9.0E-4	1.2E-3	1.5E-3	0.8E-3	2.1E-3
4	0.0	1.5E-4	3.0E-4	4.5E-4	6.0E-4	7.5E-4	9.0E-4	1.1E-3
5	0.0	1.0E-4	2.0E-4	3.0E-4	4.0E-4	5.0E-4	6.0E-4	7.0E-4
10	0.0	2.5E-5	5.0E-5	7.5E-5	1.0E-4	1.3E-4	1.5E-4	1.8E-4
15	0.0	8.0E-6	1.6E-5	2.4E-5	3.2E-5	4.0E-5	4.8E-5	5.6E-5

(a) Read 3.0×10^{-4}

The probability of n deaths given a spill is then constructed for each spill size using the following equation:

$$P(n|spill) = P(spill \text{ occurs on city street})[P(pool \text{ fire}|spill) \cdot \sum_j P(j \text{ fires} | pool \text{ fire on city street}) \cdot P(n \text{ deaths}|j \text{ fires})] + P(spill \text{ occurs on freeway}) [P(pool|fire spill) \cdot \sum_j P(j \text{ fires}|pool \text{ fire on freeway}) \cdot P(n \text{ deaths}|j \text{ fires})]$$

where

$P(n|spill)$ = the probability that n deaths occur from secondary fires given that a release occurs

$P(spill \text{ on city street})$ = the probability that the release will occur on a city street = 0.087

$P(pool \text{ fire}|spill)$ = the probability that a release will result in a pool fire = 0.24

$P(j \text{ fires}|pool \text{ fire on city street})$ = probability that j secondary fires will occur given that a pool fire has occurred on a city street (See Table G.3, G.4 and G.5)

$P(n \text{ deaths}|j \text{ fires})$ = probability that j secondary fires result in n fatalities (See Table 9.2)

$P(spill \text{ occurs on freeway})$ = probability that the release will occur on an urban freeway = 0.224

$P(j \text{ fires}|spill \text{ on freeway})$ = probability that j secondary fires will occur given that a pool fire has occurred on an urban freeway (see Table G.6, G.7 and G.8).

The results of these calculations for the three spill sizes considered are presented in Table 9.3.

TABLE 9.3. Estimated Probability of n or more Deaths from Secondary Fires Given that a Gasoline Release Has Occurred

n deaths	P(n or more deaths release) Spill Size Gallons		
	3000	4200	8400
1	6.3E-4	9.4E-4	1.8E-3
2	1.8E-4	2.7E-4	5.2E-4
3	2.7E-5	3.9E-5	7.4E-5
4	1.3E-5	1.9E-5	3.6E-5
5	6.0E-6	8.9E-6	1.7E-5
10	1.5E-6	2.2E-6	4.2E-6
15	3.6E-7	5.4E-7	1.0E-6

Deaths by direct exposure to the radiant energy from a gasoline pool fire are assumed to be limited to occupants of vehicles involved in the accident. Although other people in the vicinity of the accident could receive serious injuries, it is assumed that they could take evasive action to avoid fatal burns.

A spectrum of the number of vehicles involved in truck accidents has been estimated from data obtained from the University of Michigan Highway Safety Research Institute for heavy truck accidents in the state of Texas in 1974. The data are presented in Table 9.4.

TABLE 9.4. Distribution of Heavy Truck Accidents by Number of Vehicles Involved

Number of Vehicles Involved	Number of Accidents	Fraction of Total
1	7,234	0.232
2	23,623	0.759
3	234	0.008
4	27	0.001
5	7	0.0002
6	2	0.00006
8	1	0.00003
	31,128	

The average number of occupants per vehicle is 1.13.⁽⁶⁾ Using this figure and the data in Table 9.4, a distribution of the number of people involved in accidents can be obtained. This distribution is presented in Table 9.5 and plotted in Figure 9.3. Data from the Bureau of Motor Carriers for truck accidents in 1975 were analyzed to determine the probability that an occupant of a vehicle involved in a tank truck accident would be killed if a fire resulted. This value was determined to be 0.4.

TABLE 9.5. Estimated Number of People Involved in Heavy Truck Accidents

<u>Average Number of People</u>	<u>Fraction of Total Accidents</u>
1.13	2.3E-1
2.26	7.6E-1
3.39	8.0E-3
4.52	1.0E-3
5.65	2.0E-4
6.78	6.0E-5
9.04	3.0E-5

Using this value and the information in Figure 9.3, an estimated probability distribution for the number of vehicle occupants killed from exposure to a gasoline pool fire, given a release, has been calculated. The results of these calculations are presented in Table 9.6. It is again assumed that 24% of all releases result in fire.

9.2 CONSEQUENCES FROM THE FORMATION OF GASOLINE VAPOR CLOUDS

If a pool of gasoline does not ignite within a few minutes of the spill, evaporation of the gasoline forms a vapor cloud that will drift downwind and diffuse. Diffusion of gasoline vapor clouds is discussed in Appendix C. There is a possibility of injury from inhalation of gasoline fumes. Exposure to air containing 500 ppm gasoline for periods of 30 min can result in unconsciousness and eventual suffocation.⁽⁷⁾ The 500 ppm limit can be detected by

FIGURE 9.3. Estimated Total Number of Vehicle Occupants Involved in Heavy Truck Accidents Plotted as a Function of Accident Frequency

TABLE 9.6. Estimated Probability, Given a Release, of n or More Deaths of Vehicle Occupants from Exposure to a Gasoline Pool Fire

Number of Fatalities	P(n of more fatalities release)
1	1.9E-1
2	3.1E-2
3	9.6E-4
4	1.2E-4
5	2.6E-5
6	5.0E-6
7	6.6E-7
8	6.3E-8
9	1.3E-8

the human sense of smell. It is expected that in a 30-min period, personnel would be able to move away from the danger area. Death by exposure to gasoline vapors is therefore discounted.

The possibility exists of accumulation of flammable mixtures of gasoline downwind from the pool. During most weather conditions, the flammability hazard is confined to the immediate vicinity of the pool. Ignition of the vapor cloud under these circumstances constitutes a similar hazard to a pool fire. Under certain weather conditions, the instantaneous concentration of gasoline in portions of the vapor cloud can exceed the lower flammability limit at distances up to 280 meters from the edge of the pool (see Table C.4). The primary hazard from ignition of this cloud is the formation of a fire ball. Personnel in the path of the fire ball could be injured from direct exposure to the flames or, to a lesser extent from the radiant energy from the flame. The fire ball could also ignite secondary fires. It is expected that the fire ball would flash back to the pool, so that a pool fire would also result.

The probability of producing a large fire ball at large distances from the pool is believed to be low. Although detailed information on the consequences of formation of a fire ball in the vicinity of the pool and a flashback ignition of the pool was not available, it is believed to have consequences that are not significantly greater than those of a pool fire. For these reasons, the consequences of ignition of flammable portions of the vapor cloud have not been assessed separately from pool fires. Since the consequences of such an event would be similar to the consequences of a pool fire and the probability of occurrence is estimated to be low, it is believed that any fatalities that might result from these incidents would be accounted for in the conservatism of the gasoline pool fire consequence model. The results of the analysis show that omitting these events does not have a significant effect on the risk. It could, however, change the risk spectrum in the high consequence range.

9.3 CONSEQUENCES OF TANK TRUCK EXPLOSIONS

The damage that could be produced from a gasoline tank truck explosion has been estimated in Appendix F. Figure F.5 gives the maximum distances from the explosion site at which total destruction of buildings (30 ft), serious structural damage (75 ft) and missile damage (300 ft) can be expected. The effects of these explosions on the occupants of the buildings were not

determined. However, it was assumed that all occupants in buildings that are totally destroyed are killed, 10% of the occupants of buildings that suffer serious structural damage are killed, and 0.1% of the occupants of buildings within the range of missile damage are killed. The possibility of passersby outside the building being killed by the explosion was not included.

The urban model outlined in Appendix G has also been used to estimate deaths from explosions. The number of occupants per building used to make these estimates is given in Table 9.7. The fraction of accidents in each development type was determined by combining the accident locations presented previously with the fraction of that development type in the urban area (see Table G.2). The number of occupants per residential building is based on data from the cities of San Jose, CA, Albuquerque, NM, and Detroit, MI.⁽⁸⁾ The number of occupants in other buildings is based on a typical 150 ft² per person (information from Mr. McIntosh, Bechtel Corporation Office of Alterations and Office Space).

TABLE 9.7. Number of Occupants per Building and Accident Locations Used to Estimate Fatalities from Tank Truck Explosions in Urban Areas

<u>Development Type</u>	<u>Fraction of Accidents</u>	<u>Occupants/Building</u>
Residential A	0.12	3.5
Residential B	0.16	3.5
Industrial	0.52	11.2
Commercial	0.02	8.6
Downtown	0.01	16.0
Vacant	0.17	0.0

No data are available on the frequency of serious tank truck explosions in accidents that result in release. It has been estimated that one in a thousand releases will result in a serious explosion. This value is believed to be conservative (see discussion in Appendix F on conditions required to produce an explosion).

Some of the assumptions used previously to estimate fatalities from fires are used here to estimate the fatalities in adjacent buildings from explosions. These include:

- No fatalities from explosions in rural areas.
- 8.7% of explosions occur on urban streets, 22.4% on urban freeways and 68.9% on rural highways.

Other assumptions that have been made include:

- Explosions on city streets occur 25 ft from the curb.
- Explosions on urban freeways occur at the edge of the freeway right-of-way (see Figure G.6).

The results of the estimates of the probability distribution for fatalities from explosions is given in Table 9.8.

TABLE 9.8. Estimated Probability, Given a Release, That n or More Fatalities Will Occur in Adjacent Buildings from a Gasoline Tank Explosion

<u>Number of Fatalities</u>	<u>P(n or more fatalities release)</u>
1	4.5E-4
2	4.2E-4
3	4.0E-4
4	3.7E-4
5	3.5E-4
10	2.5E-4
15	1.6E-4
20	9.2E-5
25	4.6E-5
30	1.6E-5
35	4.6E-6
40	1.0E-6

It is assumed that all the occupants of vehicles involved in the accident would be killed in an explosion. The estimated probability distribution of deaths of vehicle occupants from an explosion, given a release, is presented in Table 9.9. The distribution of vehicle occupants given in Figure 9.3 was used to make these estimates.

TABLE 9.9. Estimated Probability Distribution
for Fatalities of Vehicle Occupants
from Explosion, Given a Release

<u>Number of Fatalities</u>	<u>Probability, Given a Release, of n or More Fatalities from an Explosion</u>
1	9.9E-4
2	7.9E-4
3	3.2E-5
4	2.4E-6
5	7.5E-7
6	2.5E-7
7	1.2E-7
8	7.0E-8
9	3.0E-8

REFERENCES

1. A Modal, Economic and Safety Analysis of the Transportation of Hazardous Substances in Bulk. COM-74-11271, A. D. Little, Inc., Cambridge, MA, p. 160, May 1974.
2. R. E. Scott et al., Statistical Analysis of Truck Accident Involvements. The University of Michigan Highway Research Institute, Ann Arbor, MI, December 1971.
3. Heavy Truck Accident Study: 1971. Washington State Patrol, Olympia, WA.
4. "Multiple-Death Fires, 1974." Fire Journal, pp. 9-11, July 1975.
5. "Fires and Fire Losses Classified, 1974." Fire Journal, pp. 43-45, September 1975.
6. Statistical Abstract of the United States: 1975. U.S. Department of Commerce Bureau of the Census, Washington, DC, 1975.
7. CHRIS-Hazardous Chemical Data. CG-446-2, U.S. Coast Guard, Department of Transportation, Washington, DC, January 1974.
8. A. N. Takata and F. Salzburg, Development and Application of a Complete Fire Spread Model. IIT Research Institute, Chicago, IL, June 1968.

10.0 THE RISK OF SHIPPING GASOLINE BY TRUCK

In this section the risk of shipping gasoline by truck is calculated using the model described in Section 3.0. The probability that a release will occur during a shipment was presented in Section 8.0 and the consequences of the release were discussed in Section 9.0. The total risk of shipping gasoline in the Year 1980 is calculated in Section 10.1 using the industry characteristics presented in Section 4.0. Major contributors to the risk and the sensitivity of the assessment to the various parameters is presented in Section 10.2.

10.1 RISK EVALUATION FOR GASOLINE SHIPMENTS

The sum of the probabilities of the release sequences presented in Section 8.2 is 8.5×10^{-6} /shipment. Based on a total of 1.37×10^7 shipments per year in 1980 (see Section 4.0), gasoline tank trucks would be expected to be involved in a total of 1,710 accidents, 110 of which would result in the release of a significant amount of gasoline. Using the release fraction information in Section 8.3 and assuming that the tanks are full when the accident occurs, 3 of these releases are expected to involve 3,000 gal of gasoline, 64 would release 4,200 gal of gasoline and 43 would result in a release of the total contents of the tank truck and trailer. Thirty-one of the releases are estimated to result in a fire.

The risk spectrum curve for all gasoline shipments in 1980 is shown in Figure 10.1. The risk spectrum is a plot of the expected frequency (in events/yr) of events versus the number of fatalities that are predicted from those events. For example, the curve shows that for the 1980's shipping levels used in the analysis, about 25 accidents resulting in 1 or more fatalities from the release of gasoline in an accident are predicted to occur each year. Accidents that produce 10 or more fatalities are estimated to occur at a rate of 2.2×10^{-2} per year, or one accident in about 45 years. The risk curve shows that a number of events resulting in one or two deaths/event can be expected each year from gasoline releases in transportation

FIGURE 10.1. Risk Spectrum for Release of Gasoline from Tank Truck Accidents in 1980

accidents. Events producing larger consequences occur relatively infrequently, however. There does not appear to be a significant potential for very large consequence events.

The risk curve was developed using the number of releases presented above and the consequence estimates presented in Section 9.0. Where necessary, the individual consequence probability distributions were extended to cover the full range (1 to 40) of number of fatalities considered in the assessment. It was not possible to determine the shape of the risk curve for events producing more than 40 fatalities. It is expected that an event such as an explosion near a crowded shopping area could produce more than 40 fatalities. Although it was not possible to determine the frequency of such an event using existing data, the probability of such an event is believed to be

very low. A review of a summary of large consequence accidents for the period 1953-1973 showed no truck accidents involving hazardous materials that produced more than 13 fatalities.⁽¹⁾ (The accident resulting in 13 deaths did not involve gasoline).

The expected number of fatalities in 1980 from the risk spectrum presented in Figure 10.1 is 29. It is estimated that 12 of these fatalities or 40% would be drivers of the gasoline tank trucks. The deaths are produced solely from the hazardous cargo carried in the tank truck. Figure 10.2 shows the effect on the risk spectrum of including the traffic deaths that can be expected from the 1,710 accidents in 1980 involving gasoline tank trucks. Twenty-six traffic fatalities would be expected in these accidents. The traffic fatality risk spectrum was developed from data for about 31,000 truck accidents in the state of Texas in 1974 (data obtained from J. C. Marsh, University of Michigan Highway Safety Research Institute, September 1976). These data are shown in Table 10.1.

FIGURE 10.2. Accident Fatalities Not Associated with Hazardous Nature of Cargo

TABLE 10.1. Traffic Fatalities in Heavy Truck Accidents

<u>n (fatalities)</u>	<u>Number of Accidents Producing n Fatalities</u>	<u>Fraction of Total Accidents</u>	<u>Probability of n or More Fatalities, Given That an Accident Has Occurred</u>
0	30,731	0.987	---
1	342	1.10×10^{-2}	1.3×10^{-2}
2	45	1.45×10^{-3}	1.8×10^{-3}
3	7	2.25×10^{-4}	3.6×10^{-4}
4	2	6.42×10^{-5}	1.4×10^{-4}
5	---	$4.2 \times 10^{-5(a)}$	7.4×10^{-5}
6	1	3.21×10^{-5}	3.2×10^{-5}

(a) Extrapolated from other data

The risk from releases of gasoline in tank truck accidents in 1980 is compared to the risk from other kinds of accidents and natural disasters in Table 10.2. The table illustrates that the individual risk from gasoline transportation is comparable to the risk from lightning or tornadoes. The data in the table are from Reference 2 for the year 1973 except as otherwise indicated.

The results of the analysis have been compared to data obtained from the Bureau of Motor Carrier Safety. Interstate motor carriers are required to make accident reports to BMCS whenever an accident results in death, injury or greater than \$2,000 property damage. The accident reports include information on the accident location and time, accident type, condition of the driver, vehicle description, cargo, result of the accident, contributing causes and driving conditions. The BMCS has recently begun a program to codify this information for computer analysis. A copy of the computer data tape for 1975 was obtained and analyzed to determine the effects of accidents involving tank trucks carrying gasoline and similar flammable liquids. The results of this analysis are presented in Table 10.3.

TABLE 10.2. Comparison of Gasoline Transportation Risks
with Individual Risk from Various Accidents
and Natural Disasters

<u>Accident Type</u>	<u>Total Fatalities</u>	<u>Individual Risk per Year</u>
All Accidents	115,821	1 in 2,000
Motor Vehicle Accident	55,511	1 in 4,000
All Industrial Accidents ^(a)	14,100	1 in 6,000 ^(b)
Falls	16,506	1 in 13,000
Drowning	7,152	1 in 29,000
Fires	6,503	1 in 32,000
Poisoning	5,335	1 in 40,000
Airplane Crashes	1,668	1 in 130,000
Railway Accidents	789	1 in 250,000
Lightning ^(c)	160	1 in 2,000,000
Tornadoes ^(d)	90	1 in 2,300,000
Gasoline Tank Truck Accidents	29	1 in 7,400,000

(a)Reference 3

(b)Only workers included in population at risk

(c)Reference 4

(d)Reference 3. Average value for several years

TABLE 10.3. Summary of Bureau of Motor Carrier Safety Data for 1975 on
Accidents Involving Tank Trucks Carrying Gasoline and Similar
Flammable Liquids

<u>Accident Consequences</u>	<u>Number of Accidents</u>	<u>Fatalities</u>	<u>Fatalities/Accident</u>
No Spill	123	1	0.01
Spill Without Fire	139	12	0.09
Spill with Fire	34	22	0.65

This data would predict that the 1710 gasoline tank truck accidents (including 79 spills without fire and 31 spills with fire) estimated to occur by this study would result in 43 total fatalities - 20 from accidents involving fire and 23 from accidents that do not result in fire. The numbers obtained in the analysis are 55 total deaths, 29 from accidents involving fire. The analysis results are thus in substantial agreement with the BMCS data.

In addition to validating the results of the analysis, this comparison also illustrates the usefulness of the approach used in the study. The available data did not permit an overall determination of the gasoline shipping risks, because not all carriers of gasoline are required to report to BMCS, and many of the reports that are made do not specify that gasoline is the flammable liquid carried. The data would also not identify accidents that occur less frequently, but could result in much higher consequences. The analysis approach used in this study was able to extend the data available to predict the risk for the entire gasoline shipping system and also to construct a risk spectrum showing how accident severity varies with accident frequency.

10.2 RISK SENSITIVITY EVALUATIONS

Before discussing the sensitivity of the risk evaluation to the value of certain system parameters, it is important to point out a fundamental sensitivity of the risk evaluation. The calculated risk is a function of the shipping assumptions. Use of a different type of truck, different shipping distances, changes in the predicted industry growth rate, etc., would result in a different risk. In general, reevaluation would be required to determine the risk under these conditions.

Risk sensitivity evaluations permit analysis of the importance of the various factors that contribute to the risk. They can be used: 1) to identify and quantify the effects of the major contributors to the risk; 2) to identify ways to decrease the uncertainty in the risk evaluation; and 3) to study the effects of possible design or regulatory changes on the risk. Most sensitivity studies are performed by repeating the risk calculation with a changed value

for the parameter of interest. In general, the dependence of the risk on a particular parameter is complex. In some cases, however, the parameter enters simply and directly into the risk calculation and the sensitivity can be determined directly.

The results of the risk sensitivity studies for the shipment of gasoline in DOT specification MC-306 tank trucks are presented in Table 10.4 and Figures 10.3 through 10.6. Table 10.4 shows the sensitivity of the expected

TABLE 10.4. Sensitivity of the Expected Number of Fatalities from Gasoline Releases to the Value of Various System Parameters

<u>Description of Sensitivity Case</u>	<u>Expected Fatalities</u>	<u>Change from Base Case</u>
Base Case (puncture probability = 0.025/accident)	29	-1
Puncture Probability = 0.044/accident	36	+24%
Puncture Probability = 0.006/accident	22	-24%
Probability of Explosion = 10^{-2} /release	36	+24%
Probability of Explosion = 10^{-4} /release	28	-3%
All Vehicle Occupants Killed in Fire	55	+90%
All Release Fractions = 1.0	29	0
Fire Suppression System on Truck	<1	-97%
Tank Ten Times Stronger	9	-70%

number of fatalities to the parameter being studied, while the figures illustrate the sensitivity of the shape of the risk spectrum curve to changes in these parameters. Most of the sensitivity studies were carried out to investigate the importance of assumptions that were made in basic event probabilities in Section 8.0 and in the consequence models in Section 9.0. These assumptions were generally necessary because data were not available for a more exact determination of the value of a parameter. In the base case,

FIGURE 10.3. Sensitivity of Risk to Probability of Failure from Puncture Forces

FIGURE 10.4. Sensitivity of Risk to Assumption of the Probability of an Explosion, Given a Release

FIGURE 10.5. Sensitivity of Risk to Number of Vehicle Occupant Fatalities in a Fire

FIGURE 10.6. Effect on Risk of Strengthening Tank or Installing Fire Suppression System

failure of the tank walls by puncture forces accounts for 39% of all releases, failure of the walls from impact forces for 39% and failure of the walls by abrasion for 14% of the releases. Fires that do not initially involve the cargo contribute to about 5% of the releases. Changes in the value of the parameters making up these release sequences may have a significant effect on the total risk. Puncture failures have been selected to illustrate this point, since the greatest uncertainty exists in the prediction of the probability of a puncture failure.

Figure 10.3 shows the sensitivity of the risk to the value of event A69. (Puncture Forces Fail Tank Walls.) The probability of this event was calculated in two independent ways (see Section 8.2). An average of these two calculations was used in the base case risk calculation. The sensitivity study shows the effect on the risk of using the high and low values calculated for this event.

It was necessary to assume a value for the probability of a gasoline tank truck explosion, given a release. A value of 10^{-3} was used in the base case. Figure 10.4 illustrates the effect on the risk spectrum of a two order of magnitude change in the explosion probability. The change affects the curve in the high consequence range, since most high consequence accidents are due to explosions. As shown in Table 10.4, however, the expected number of fatalities in 1980 is not affected significantly by the explosion probability.

The sensitivity of the risk to the release fractions used in the base case was also studied. Assuming that all release fractions = 1.0 (that is, the entire contents of both truck and trailer are released in all accidents that produce a significant release) has a negligible effect on the risk spectrum and the expected number of fatalities. Figure 10.5 and Table 10.2 also show the sensitivity of the risk to change in the value of the probability that an occupant of a vehicle involved in the accident would be killed if a fire resulted from the release. In the base case, it was assumed that each vehicle occupant involved in the accident had a 40% chance of being killed in a fire. Changing this value by assuming that all the vehicle occupants are killed in a fire produces a corresponding increase of 97% in the expected number of fatalities. This shows that deaths of vehicle occupants in a fire account for nearly all of the expected fatalities.

Two possible methods for reducing the risk from gasoline releases in tank truck accidents have been investigated. The first method involves shipping the gasoline in stronger tanks. Figure 10.6 shows the effect on the risk spectrum of making the tank 10 times more resistant to puncture, impact and abrasion forces. This has the effect of a substantial reduction in the number of releases and reduces the expected number of fatalities by about a factor of three. It has also been suggested⁽⁵⁾ that the installation of accident-actuated fire suppression systems on tank trucks might reduce the risk. Figure 10.6 also presents the results of assuming that a 100% effective fire suppression system is present in all tank truck accidents. The expected number of fatalities per year is reduced to less than one. Although a detailed cost benefit analysis would be required to determine which of these methods would be the most cost-effective, the installation of the fire suppression system would appear to merit the higher priority for further study if it is determined that the present risk is unacceptably high. Strengthening the tanks by an order of magnitude would probably require a change from aluminum to steel construction. This would have a significant impact on the cost of tank truck manufacture and would reduce the tank load because of added weight. The development of a reliable, lightweight fire suppression system at a reasonable cost appears to be feasible.⁽⁵⁾

REFERENCES

1. The Consequences and Frequency of Selected Man-Originated Accident Events. CONSAD Research Corp., Pittsburgh, PA, August 1974.
2. U.S. Bureau of the Census, Statistical Abstract of the United States: 1975. U.S. Department of Commerce, Washington, DC, p. 66, 1975.
3. Accident Facts 1973. National Safety Council, Chicago, IL, 1974.
4. Reactor Safety Study, WASH-1400, U.S. Nuclear Regulatory Commission, Washington, DC, p. 3, October 1975.
5. L. M. Krasner, et al., Hazardous Materials Transportation Intrusion Protection for Hazardous Cargo Tanks. DOT HS-800 513, Factory Mutual Research Corporation, Norwood, MA, June 1971.

APPENDIX A

GASOLINE TANK TRUCK DESCRIPTION AND OPERATING PROCEDURES

TRUCK DESCRIPTION

Gasoline is classified as a hazardous substance by the Department of Transportation and must be transported in containers meeting DOT specifications. Several DOT specification tank trucks may be used to transport gasoline, but conversations with tank truck manufacturers and trucking companies that haul gasoline indicate that DOT specification MC-306 tank trucks are the most widely used for shipping gasoline. Two basic configurations of this shipping system are in current use. Shippers in the eastern U.S. generally use a tractor/semitrailer configuration while western operators use a tank truck/tank trailer configuration.

A photograph of a typical rig used in the western U.S. is presented in Figure A.1. The truck tank has a capacity of about 4,600 gal and the trailer tank capacity is about 5,400 gal. The tanks are loaded through the dome lids in the top and unloaded by gravity through outlet valves in the back of the truck tank and in the front of the trailer tank. Tubes carrying hoses used to offload the tanks are welded to the outside of the tank. The truck tank is supported on the steel channels that form the truck frame, while, the trailer tank is the structural member of the trailer. The trailer is provided with a rear bumper capable of absorbing a "2g" deceleration of the loaded vehicle. The empty truck and trailer combination weighs about 23,000 lbs. The tanks are required to be shipped with an outage of at least 2%, (i.e., less than 98% full), but typical loads are between 8,000 and 8,500 gallons, because of state vehicle gross weight restrictions.

The tanks have an elliptical cross section with a major diameter of 96 in. and a minor diameter of 60 in. The maximum radius of curvature of the shell is about 70 in. The ends of the tanks are dished outward about 4 in. at the center. Typical tank dimensions are given in Table A.1.

FIGURE A.1. DOT Specification MC-306 Tank Truck and Trailer Used for Gasoline Shipments in the Western U.S.

TABLE A.1. Truck and Trailer Tank Dimensions for Western Shipping System

	<u>Length (in.)</u>	<u>Width (in.)</u>	<u>Height (in.)</u>	<u>Cross Section Area</u>	<u>Volume (Gallons)</u>
Truck Tank	235	96	60	4524	4600
Trailer Tank	276	96	60	4524	5400

The tanks are provided with transverse baffles to stiffen the shell and to reduce liquid movement in transit. The baffles are spaced about 60 in. apart. Multiple compartment tanks may be used, but for purposes of this analysis it is assumed that the tanks have a single compartment. This is a conservative assumption. the tanks are constructed of aluminum. A typical alloy for the shell is ASTM B-209 Alloy 5454. The minimum shell thickness allowed by DOT regulations for a tank of this type is 0.151 in. The tanks are typically constructed with a shell thickness of 0.188 in. on the bottom and side sheets and 0.154 in. on the top. The tank heads and baffles must also be at least 0.151 in. thick. They are typically manufactured from 0.188-in. thick material. The heads and baffles may be fabricated from material with 0 temper (annealed) or stronger tempers. Shell materials must have properties equivalent to H32 or H34 tempers. The tanks have a design pressure of 0 psig. They are tested at a pressure of 3 psig, primarily to ensure that welds are leak-tight.

The outlet valve assembly is shown in Figures A.2, A.3 and A.4. The valve consists of an internal valve, with its seat located inside the tank, an external gate valve and a threaded end cap. All three of these must be open before gasoline can flow out of the tank. The external portion of the valve body has a machined neck or "shear section" designed to be the area of fracture on impact. The internal valve will remain seated by liquid pressure if the external valve is fractured at the shear section. The valve assembly is attached to the tank at a flanged outlet in the bottom of one of the tank heads. The assembly is held in place with 5 clips secured to 5/8-in. studs on the tank flange. A rubber gasket, usually of a nitrile butadiene substance

FIGURE A.2. Gasoline Trailer Tank Outlet Valve for Western Shipping System

FIGURE A.3. Outlet Valve Showing Internal Valve Mechanism

FIGURE A.4. Gasoline Tank Truck Outlet Valve Assembly

such as BUNA-NR is placed between the valve and the flange. The outlet valve on the truck tank is protected by the two 10.5-in. by 3.75-in. steel channels that form the truck frame. No protection is provided for the outlet valve on the trailer tank.

Each tank is equipped with a manway cover that is used to fill the tank and that provides access to the inside of the tank for cleaning and maintenance. The manway cover is shown in Figures A.5 and A.6. The manway cover access hatch is held in place during transport by a cam-lock type safety catch. The hatch seals to an O-ring gasket in the manway cover. The gasket is typically made of a nitrile butadiene polymer such as BUNA-NR. The manway cover is attached to the tank by four spring-loaded clips on 12-in. long studs. The clips secure the manway cover to a ring welded into the tank top. A cork gasket is installed between the manway cover and the welding ring in the tank top. The manway cover is protected from damage in a rollover by two rails running the length of the tank top on either side of the manway cover. The rails are approximately parabolic in shape. They are about 5 in. high, 1-1/2 in. wide at the top and 4 in. wide at the bottom. The rails are designed to support the entire weight of a loaded tank.

The manway cover contains the pressure and vacuum relief devices for the tank (Figure A.7). The tank has a single vacuum vent with a rated flow of 2775 ft³ of air per hr at a pressure difference of 1 psig and is equipped with three pressure relief devices. The normal pressure relief device, located in the lid of the manway cover, has a venting capacity of 2960 ft³ of air per hr at 3 psig. This device begins to open at about 1 psig and is equipped with a ball-check device that closes the valve if the tank is not upright. The second pressure relief device is the manway cover lid. The spring in the center of the lid will allow the lid to lift when the tank pressure exceeds about 9 psig. The entire manway cover forms the third pressure relief valve. The four spring-loaded clips that hold the manway cover in the tank allow the entire manway cover to lift and allow gas to escape along its circumference when the tank pressure reaches 9 psig. This relief device opens at a pressure slightly higher than the lid. It lifts its maximum of about 0.75 in. when the tank pressure is 5 psig. The rated flow at 5 psig is 345,600 ft³ of air per hr.

FIGURE A.5. Tank Top Showing Manway Cover and Protective Rails

FIGURE A.6. Photograph of Manway Cover
(C-B Equipment, Inc. Lynwood, CA, 1976)

FIGURE A.7. Schematic Drawing of Manway Cover Showing Pressure and Vacuum Relief Devices

The eastern half of the United States uses a tractor tank trailer configuration. A typical 4-compartment tank trailer is shown in Figure A.8. A tank truck manufacturer indicates that these tank trailers are built 5% with 3 compartments, 80% with 4 compartments and 15% with 5 compartments. The tank trailer is constructed of aluminum with tank wall thicknesses of 0.250 in. on the belly and 0.188 in. on the walls and top, reflect the greater volume of the tank.

The typical 4-compartment tank trailer has the liquid flow from all compartments brought to a central manifold as shown in Figure A.9. The piping and gate valve have a diameter of 3 in. and are made of aluminum. Each compartment has an outlet valve that is cable actuated from a cabinet apart from the discharge area. In the case of any type of emergency, a front remote trip can be actuated that will stop the flow from all compartments. For the purposes of this study, other details of the tractor tank-trailer will be considered to be the same as the truck tank and 4-wheeler trailer combination.

OPERATING PROCEDURES

To determine typical gasoline truck operating procedures, an informal survey was conducted of common carriers in southeastern Washington engaged in

FIGURE A.8. MC-306 Semitrailer Used for Gasoline Shipments in the Eastern U.S.

FIGURE A.9. Outlet Valve Assembly for 4-Compartment Semitrailer

gasoline transportation. The results of this survey are summarized here. Gasoline tank trucks are loaded at the bulk distribution terminal to the maximum gross weight allowed by state highway regulations without overweight permits. The maximum gross weight in most states is 73,280 lbs. This gives a full load of about 8,200 gal of gasoline, leaving more than the 2% minimum tank outage required by DOT. The trucking companies indicated that overfilling of the tanks occurred very infrequently. The trucks are loaded by volume through an accurate metering device. This metering device is used to bill the retailer for the gasoline and to assess transportation changes so mistakes in filling are rare.

Deliveries are generally made to the retail outlet in truckload quantities. Less than truckload deliveries are seldom made because a surcharge is added for this service. The tanks are, therefore, full on the run from the distribution terminal to the retail outlet and empty on the return trip.

The tanks are loaded through the manway cover on top of the truck and unloaded through the outlet valve assembly by gravity feed. The manway cover is opened during offloading to provide an air vent for the tank.

The companies indicated that maintenance of the trucks was routine when they were being used for hauling gasoline. The maintenance items were those associated with the operation of any large truck rig, rather than any necessitated by the nature of the cargo.

APPENDIX B

PHYSICAL PROPERTIES OF GASOLINE

Gasoline is a light end product of the petroleum refining process. It is produced both by direct distillation and by cracking or reforming longer molecules. The chemical composition of gasoline varies with grade, but it is made up generally of hydrocarbons with from 5 to 10 carbon atoms per molecule. Most of the molecules are in the heavier range with 8 to 10 carbons per molecule. The hydrocarbons are a combination of paraffins (saturated hydrocarbons), olefins (unsaturated hydrocarbons) and aromatic and naphthenic rings. Small amounts of tetraethyl lead and other additives are also present.

The chemical makeup and physical properties of gasoline depend on the type of crude oil used as feedstock and also vary with the method used to produce the gasoline. Some physical properties of gasoline are listed in Table B.1. Ranges are given for most of the properties to reflect the variety of gasolines produced.

TABLE B.1. Physical Properties of Gasoline

Boiling Point	100°-400°F
Specific Gravity	0.71-0.75
Heat of Combustion (Complete Combustion)	-1065 Kcal/mole
Vapor Density (Air = 1.0)	3.4
Average Molecular Weight	102
Flash Temperature (100 octane)	-36°F
Self Ignition Temp. (100 octane)	853°F
(60 octane)	536°F
Flammability Limits	1.4% - 7.6%
Open Pool Burning Rate	4 mm/min
Reid Vapor Pressure (100°F)	9.5 - 13.5 psi
Evaporation Rate (80°F)	$\sim 2 \times 10^{-4}$ g/cm ² · sec

The heat of combustion presented in the table is for ideal complete combustion with carbon dioxide and water vapor as the only combustion

products. A burning pool of gasoline in open air, such as might be encountered in a transportation accident, would be expected to produce significantly less heat because of incomplete combustion.

The evaporation rate listed in the table is an approximation. The evaporation rate varies with the type of surface on which the spill occurs, the temperature, wind velocity, insolation and other factors. The value listed is what might be expected on a warm sunny day with a moderate wind. It would, therefore, tend to be a maximum value.

The Reid vapor pressure at 100°F is listed in the table. The actual vapor pressure at a given temperature can be determined from the nomograph in Figure B.1.

FIGURE B.1. Vapor Pressure of Gasoline⁽¹⁾

REFERENCE

1. J. B. Maxwell, Data Book on Hydrocarbons. Standard Oil Development Company, 1950.

APPENDIX C

ATMOSPHERIC DIFFUSION OF GASOLINE VAPORS FROM AN EVAPORATING POOL

The atmospheric diffusion of vapors from an evaporating pool of gasoline has been calculated in order to estimate the downwind areas subject to health and flammability hazards. The diffusion has been modeled by the standard Gaussian plume.⁽¹⁾

$$C = \frac{\dot{Q}}{u\pi\sigma_y\sigma_z} \exp \left[-y^2/2\sigma_y^2 - z^2/2\sigma_z^2 \right] \quad (C-1)$$

where C is the air concentration (quantity per m³), $\dot{Q}$ is the source strength (quantity per sec) and u is the windspeed (m/sec). σ_y and σ_z are the standard deviations of the plume in the crosswind (y) and vertical directions (z) and are a function of downwind distance (x) and atmospheric stability. The formulas of Briggs⁽²⁾, shown in Table C.1, were used to determine the atmospheric stability categories and the diffusion parameters. Calculations were made for each stability category using the mean windspeed for that category as determined by one year (1970) of data from the Hanford Meteorology Tower⁽³⁾. These mean winds are also shown in Table C.1. An additional calculation was also made for the extreme case of Pasquill F and a mean wind of 0.5 m/sec.

The greatest concentration of gasoline vapors will be found at the downwind edge of the pool. This maximum concentration can be calculated by assuming that the pool has an infinite extent in the crosswind direction. The concentration is given by:

$$C = \int_0^{2R} \frac{2E}{\sqrt{2\pi} u\sigma_z} e^{-z^2/2\sigma_z^2} dx \quad (C-2)$$

TABLE C.1. Formulas for the Determination of σ_z and σ_y
(x , σ_z , σ_y in meters)

<u>Stability Categories</u>					
	<u>Windspeed mph</u>	<u>0-3</u>	<u>4-7</u>	<u>8-12</u>	<u>13 & greater</u>
	Day	A	B	C	D
	Night	F	E	D	D

<u>Stability Class</u>	<u>σ_z</u>	<u>σ_y</u>	<u>u (mph)</u>
A	$0.20x$	$0.22x(1+10^{-4}x)^{-1/2}$	2.0
B	$0.12x$	$0.16x(1+10^{-4}x)^{-1/2}$	5.3
C	$0.08x(1+.0002x)^{-1/2}$	$0.11x(1+10^{-4}x)^{-1/2}$	9.7
D	$0.06x(1+.0015x)^{-1/2}$	$0.08x(1+10^{-4}x)^{-1/2}$	14.1
E	$0.03x(1+.0003x)^{-1}$	$0.06x(1+10^{-4}x)^{-1/2}$	5.5
F	$0.02x(1+.0003x)^{-1}$	$0.04x(1+10^{-4}x)^{-1/2}$	1.7

where R is the pool radius and E is the evaporation rate (quantity per m^2 per sec). Since diffusion plumes are quite narrow in the crosswind direction, this will overestimate C at the center of the downwind edge of the pool by only a few percent. Calculations were made using the physical properties of gasoline listed in Appendix B. The results of these calculations for heights above the pool 1 m and 10 cm are presented in Table C.2. Since gasoline vapor is 3.4 times heavier than air, the percentage of vapor is large enough for the gasoline to resist to some extent the vertical mixing of the atmospheric turbulence. To approximately account for this, subsequent calculations were made assuming that the vertical mixing is always similar to that present under stable atmospheric conditions (Pasquill F stability), while the lateral mixing is controlled by the existing meteorology.

Equation (1) applies to the diffusion from a point source of material. It can be used to calculate the diffusion from a horizontal area source by placing an equivalent point source $\dot{Q} = \pi R^2 E$, upwind of the pool a distance x_0 such that:

$$3\sigma_y(x_0) = R \quad (C-3)$$

TABLE C.2. Volume Fraction at Downwind Pool Edge

<u>Stability</u>	<u>Mean Wind (m/sec)</u>	<u>Volume Fraction at 1 m (percent)</u>	<u>at 10 cm (percent)</u>
A	0.9	0.42	0.91
B	2.4	0.20	0.51
C	4.3	0.12	0.37
D	6.3	0.08	0.31
E	2.5	0.15	1.2
F	0.8	0.12	5.6
F	0.5	0.17	8.4

This accounts approximately for the initial crosswind extent of the vapor cloud. Using this model, the area subject to a health hazard (0.05% and higher) and the maximum downwind distance to this concentration were calculated. The results are presented in Table C.3.

TABLE C.3. Health Hazard (0.05%)

<u>Stability</u>	<u>Mean Wind (m/sec)</u>	<u>Downwind Distance (m)</u>	<u>Area (m²)</u>
A	0.9	290	2.6×10^4
B	2.4	190	9.1×10^3
C	4.3	150	4.5×10^3
D	6.3	120	2.7×10^3
E	2.5	270	8.3×10^3
F	0.8	720	3.3×10^4
F	0.5	960	5.3×10^4

The results of the calculations presented in Table C.2 show that the maximum vapor concentrations at the edge of the pool rarely exceed the upper flammability limit (7.6%) and are usually below the lower flammability limit (1.4%). This would imply that the flammable portion of the vapor cloud is

confined to the immediate vicinity of the pool. There is another consideration, however. The diffusion parameters of Table C.1 are applicable to calculation of air concentrations which are time averages over periods on the order of 20 minutes. While this is the proper period for consideration of the health hazard, the flammability problem requires knowledge of the instantaneous concentration. Along the centerline of the diffusion plume, Slade⁽⁴⁾ and Ramsdell⁽⁵⁾ indicate that the instantaneous vapor concentration may be greater than the average concentration by a factor of 5 to 2. Using the higher value, the average volume fraction must be less than 0.28% to assure that the instantaneous fraction is below the lower flammability limit of 1.4%. Table C.4 gives the results of calculations with the model of Equations (C-1) and (C-3) for a concentration of 0.28%.

TABLE C.4. Instantaneous Flammability Hazard (0.28%)

<u>Stability</u>	<u>Mean Wind (m/sec)</u>	<u>Downwind Distance (m)</u>	<u>Area (m²)</u>
A	0.9	100	4.1×10^3
B	2.4	56	1.2×10^3
C	4.3	29	350
D	6.3	8	39
E	2.5	53	620
F	0.8	200	3.7×10^3
F	0.5	280	6.6×10^3

Using Pasquill F conditions for the vertical dispersion regardless of the meteorological situation is only an approximate attempt to account for the large specific gravity of the gasoline vapors. An even more conservative approach would be to confine the vertical mixing to some small layer next to the ground. Table C.5 shows the downwind distances and areas for the most conservative meteorological situation, Pasquill F and a mean wind of 0.5 m/sec, and for layers assumed to be 10 cm and 1 m deep. Part of the

TABLE C.5. Vertical Mixing Confined to a Shallow Layer

(Lateral Diffusion = Pasquill F, u = 0.5 m/s)				
Vapor Fraction (percent)	<u>Layer Depth - 1 m</u>		<u>Layer Depth - 10 cm</u>	
	<u>Distance (m)</u>	<u>Area (m²)</u>	<u>Distance (m)</u>	<u>Area (m²)</u>
1.4	500	1.3×10^4	8.3×10^3	1.9×10^7
0.28	3.5×10^3	4.1×10^6	1.1×10^5	1.3×10^8

instantaneous concentration fluctuations are contained in the action of the vertical eddies, which have been supplanted in the current assumption, and hence the instantaneous lower flammability limit of 1.4% is achieved when the average vapor fraction is somewhere between 0.28% and 1.4%. Table C.5 shows results for both of these values.

REFERENCES

1. F. Pasquill, Atmospheric Diffusion. Halsted Press, New York, p. 352, 1974.
2. G. A. Briggs, Diffusion Estimation for Small Emissions. ATDL Contribution 79, Air Resources Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, TN, 1973.
3. T. W. Horst, The Resuspension of Material Dispersed by Atmospheric Diffusion from a Point Source. BNWL-1964, Battelle, Pacific Northwest Laboratories, Richland, WA, 1975.
4. D. H. Slade, (ed.), Meteorology and Atomic Energy 1968. U.S. Atomic Energy Commission, Division of Technical Information, Washington, D.C., 1968.
5. J. V. Ramsdell, Jr., and W. T. Hinds, "Concentration Fluctuations and Peak-to-Mean Concentration Ratios in Plumes from a Ground-Level Continuous Point Source," Atmospheric Environment. 5:483-495, 1971.

APPENDIX D

CALCULATION OF GASOLINE TANK TRUCK FAILURE THRESHOLDS

Failure thresholds were summarized in Section 6.0. This appendix describes the analytical approach and calculations used to derive the failure thresholds. The types of stresses evolving from the accident environment identified as most significant to gasoline tanker failure are:

- impact
- puncture
- abrasion
- thermal

The response of gasoline tanker to each of these stresses is presented below. Failure threshold calculations were performed for both transport systems considered in the study. The tank truck/tank trailer system is used as the reference system to demonstrate the calculational procedures used. In cases where different results are obtained for the tractor/semitrailer system, the results of similar calculations for that system are presented.

D.1 IMPACT

Some of the typical surfaces which constitute the impact environment in a tank truck accident include: the roadway; other vehicles; large rocks or structures near the roadway (such as bridge abutments or overpass supports); roadway guardrails; highway signs; and power, lighting or telephone poles. The relatively thin and unprotected skin of the tanks inherently make the tankers vulnerable to failure by impact at moderate relative velocities.

No attempt is made to analyze the response of the tanks under impact conditions to a wide range of impact surface sizes and configurations. Rather, the failure threshold is estimated for impact against a flat surface when the relative velocity between the tank and the object is parallel to the longitudinal axis of the tank or perpendicular to it.

For the case of direct impact against a flat surface when the relative velocity is in the direction of the longitudinal axis of the tank, it is assumed that the tank is 90% full and strikes the barrier in an upright position. No allowance has been made for the energy absorbed by the truck cab. The elliptical heads project approximately four inches beyond the shell in the longitudinal direction. The impact initially flattens the elliptical head so that the shell of the tank can be approximated by a long cylinder with a radius of 42 in. and a wall thickness of 0.172 in.

Tests at Oak Ridge National Laboratory and Battelle-Columbus Laboratories^(1,2) show that thin-walled cylinders compressed between a moving plate and a fixed plate tend to compress (buckle) in a manner similar to the pleats of an accordion. The tests further indicate that the force required to buckle the tube is essentially constant over the entire distance of compression. The "accordion" effect begins at the end where the moving load is applied and continues axially down the shell to a point well past one half of the length, as shown schematically in Figure D.1.

FIGURE D.1. Buckling Mechanism of a Thin-walled Tube Under Axial Compression

It is assumed that the shell of the tank will buckle in a similar mode when impacting under inertial loading against a flat surface. Observation of gasoline tank vehicles that have been in overturn accidents indicates that the aluminum skin can undergo gross deformation similar to the "accordion" effect without failure. Failure is assumed to occur when the tank volume has been reduced by 10%. At this point, the air and gasoline vapor in the tank will have been expelled through the pressure relief devices and the tank will contain only liquid gasoline. Relief of liquid gasoline through the vents will not keep up with the continued reduction in volume due to buckling of the tank and the ensuing rapid pressure rise will rupture the tank.

The energy associated with buckling the shell of the tank is derived below, using the tank truck/tank trailer as a reference system. Results of the analysis for the tractor/semitrailer system are presented at the end of the analysis. For a thin-walled cylinder under uniform longitudinal compression.⁽³⁾

$$S' = \frac{1}{\sqrt{3}} \frac{E}{\sqrt{1 - \mu^2}} \frac{t}{r}$$

where:

S' = unit compressive stress

E = Modulus of Elasticity = 10.3×10^6 psi

μ = Poisson's Ratio = 0.33

t = thickness = 0.172 in.

r = radius = 42 in.

The unit compressive stress is found to be 25,800 psi (yield strength ~29,000 psi). Experimental results have shown that the actual stress is only about 40% of the theoretical value.⁽³⁾ A stress of 10,300 psi will, therefore, be assumed. The force in the shell is equal to the stress multiplied by the cross sectional area of the shell, or

$$F = 10,300 \pi (84) (0.172) = 468,000 \text{ lb}$$

This force (assumed to be constant) acts through approximately 24 in. to reduce the volume of the tank by 10% (neglecting the flattening of the elliptical head). The energy to produce a 10% reduction is the constant force of 468,000 lb acting through 24 in., or 0.937×10^6 ft-lb.

Equating the initial kinetic energy of the tank as the truck is moving to the energy required for 10% compression:

$$\frac{1}{2} mv^2 = 0.937 \times 10^6 \text{ ft-lb}$$

$$m = \text{mass of tank plus contents} = \frac{30,000 \text{ lb}}{32.2 \text{ ft/sec}^2}$$

$$v = \text{velocity (ft/sec)}$$

substituting

$$v = 44.85 \text{ ft/sec or } 30.6 \text{ mph}$$

A similar analysis for the semitrailer transport configuration (wall thickness = 0.188 in., weight = 60,000 lb) yields a minimum impact failure velocity of 23.6 mph.

Impact against flat surfaces perpendicular to the longitudinal axis can occur when the tank vehicle overturns and impacts the roadway or when the trailer "jackknifes" and remains upright and slides into the impacting surface. Measurements of a trailer tank that overturned and impacted a flat road surface indicate a reduction of volume of approximately 3% (see Figure D.2). The energy dissipated during the overturn can be approximated by the distance that the center of mass of the tank drops. This distance is estimated to be 3 1/2 ft. Therefore, the energy dissipated is the weight of the tank plus the contents multiplied by the drop distance (30,000 lb x 3.5 ft) or 105,000 ft-lb.

If it is assumed that an overturn involving 105,000 ft-lb of energy causes a reduction in volume of 3%, then approximately 350,000 ft-lb would be required to reduce the volume 10%. Equating the potential energy required for deformation to the kinetic energy of the tank vehicle:

FIGURE D.2. End View of Tank Truck After Overturn Accident

$$1/2 mV^2 = 350,000 \text{ ft-lb}$$

$$V = 27.4 \text{ ft/sec or } 18.7 \text{ mph.}$$

It was observed that tank vehicles frequently overturn without loss of lading if the forward velocity is low enough to prevent failure by abrasion. The equivalent velocity of the center of mass of the trailer falling through 3 1/2 ft is determined from the expression

$$V = \sqrt{2gh}$$

where:

V = final velocity (ft/sec)

g = gravitational force = 32.2 ft/sec²

h = drop height in feet

$V = 15.01 \text{ ft/sec or } 10.2 \text{ mph}$

The failure threshold of the tank overturning and subsequently skidding against a barrier would be relatively lower than a similar situation for an upright tank because the gasoline vapors and air in the headspace would not

vent. (The headspace would have rotated 90° with respect to the vents). Compression of the air might produce earlier failure by overpressurization. The reduction in velocity to produce failure was not calculated for the nonventing case. The question is somewhat academic because other factors such as abrasion during the skid would lead to earlier failure.

D.2 PUNCTURE

Puncture of the relatively thin (<1/4-in.) and unprotected skin of a gasoline tank can be expected whenever a fixed probe more than a few inches long contacts the tank during an accident. The approach used to determine the energy required to puncture the skin of the tank is to assume that all probes up to approximately one foot equivalent diameter deflect or dent the skin approximately 6 in. without failure and subsequently fail the skin material surrounding the head of the probe from sheer stresses. The puncture analysis presented below is for a tank truck/tank trailer combination vehicle. The conclusions are virtually the same for the tractor/semitrailer transport system.

The initial force associated with denting the tank skin 6 in. is determined from the expression below,⁽³⁾ developed for plates of any size or shape, any type of edge support, and a concentrated load at any point:

$$W_u = S_y (1/2 \pi t^2)$$

where

W_u = total load in pounds required to collapse plate

t = thickness of plate = 0.172 in.

S_y = yield point of the material (29,000 psi for tempered
500-series aluminum)

substituting

$$W_u = 29,000 (1/2 \pi) 0.172^2 = 1332 \text{ lb}$$

The error in using this equation can be up to 30%,⁽³⁾ so the force to collapse the plate is assumed to be 932 lb. Any probe or projectile contacting the skin of the tank must be capable of exerting a 932-lb force constantly for a distance of 6 in. before the tank skin fails from shear stresses. The energy associated with the denting is 466 ft-lb. It is further assumed that any probe impinging against the skin at an angle greater than 45° with respect to the skin (see Figure D.3 below) will ultimately puncture the tank if sufficient energy is available.

FIGURE D.3. Relative Angle of Contact Required for Puncture

The force required to shear through the tank skin is equal to the perimeter of the probe head multiplied by the thickness of the shell and the shear strength of the aluminum skin (assuming that the strength of the probe material is greater than that of the aluminum skin). For round probes, the shear force required for puncture is:

$$F = \pi D t S_s$$

where

D = probe diameter

t = skin thickness = 0.172 in.

S_s = shear strength of skin = 17,000 psi

substituting

$$F = \pi D(0.172) 17,000 = 9,186D$$

A plot of shearing force versus probe diameter is shown in Figure D.4.

The average distance that a probe must travel to effectively shear the material has been found to be approximately 1/3 of the material thickness.⁽⁴⁾

The energy required to shear through the skin of the tank can be expressed as the puncture force acting through a distance of 1/3 of the skin thickness, or,

$$E = 9,186D \frac{0.172}{3(12)} = 44D \text{ (ft-lb)}.$$

Figure D.5 shows the shearing energy as a function of probe diameter.

FIGURE D.4. Shear Force Required to Puncture Tank as a Function of Probe Diameter

FIGURE D.5. Energy to Shear Tank Skin as a Function of Probe Diameter

The total energy associated with puncture includes the initial denting of the skin and the shearing or

$$E = [466 + 44D] \text{ ft-lb}$$

Figure D.6 shows the total puncture energy as a function of probe diameter.

The minimum energy of 466 ft-lb can be equated to the kinetic energy of the moving tank during transport to determine the minimum velocity for puncture:

$$\frac{1}{2} mv^2 = 466 \text{ ft-lb}$$

$$m = \text{mass of tank} = \frac{30,000 \text{ lb}}{32.2 \text{ ft/sec}^2}$$

FIGURE D.6. Total Energy for Puncture as a Function of Probe Diameter

v = velocity (ft/sec)

substituting

$v = 1$ ft/sec, or less than 1 mph

Thus, any probe can potentially puncture the tank if its length exceeds 6 in. and the diameter is sufficient to prevent buckling during the process of denting the tank.

The minimum probe diameter can be determined assuming a 6-in. minimum length and circular cross-section. The equation for buckling of a rigidly fixed column is:⁽⁵⁾

$$P_{crit} = C \frac{EI}{L^2}$$

where

$$\begin{aligned}P_{crit} &= \text{buckling force (minimum)} \\&= 932 \text{ lb} \\C &= \text{a constant based on configuration} \\&= 2.47 \\E &= \text{Modulus of Elasticity} = 10.3 \times 10^6 \text{ psi} \\I &= \text{Moment of Inertia} = \frac{\pi d^4}{64} \text{ (in.}^4\text{)} \\L &= \text{Length} = 6 \text{ in.}\end{aligned}$$

substituting

$$d = 0.40 \text{ in.}$$

D.3 ABRASION

The predicted failure threshold by pure abrasion of the skin of a gasoline tank was derived from the results of analytical and experimental studies of abrasion rates of snow plow skids on roadways and observations of a tank that had overturned and failed by abrasion. The analysis assumes that the gasoline tanker overturns onto a flat surface. The elliptical tank cross section is typically flattened as shown in Figure D.2. The skin of the tank and baffles are deformed as shown in Figure D.7 and D.8. Primary wear areas in the skin occur at the ends of the tank and at the baffles as indicated in Figure D.7. The primary wear areas support most of the weight of the tank and its contents during skid along the roadway.

Observations of the primary wear areas on a tanker that had overturned indicated that primary wear occurs over an area of approximately 165 in.² in a tank with four baffles (22.5 in.² at each baffle and 37.5 in.² at each end).

The sequential mode of failure by abrasion is assumed to be as follows: 1) the overturned tank is pressurized due to flattening of the shell upon contact with the roadway, and 2) the skin is abraded away during skidding to a thickness where the pressure causes the stress in the skin to rise above the yield stress.

FIGURE D.7. Deformed Configuration of a Tank Overturning with Forward Velocity Showing Primary Wear Areas

Measurement of a tank that had overturned in a highway accident (Figure D.2) showed a reduction in tank volume of approximately 3%. Assuming 10% of the tank volume is head space and the gasoline is incompressible, the 3% reduction in overall tank volume would reduce the head space volume by 30%. The increased pressure due to the volume reduction is assumed to remain constant as long as the tank is skidding because the pressure relief devices along the top of the tank have rotated 90° and are covered with liquid gasoline. Using the relationship $P_1V_1 = P_2V_2$, where P and V are the headspace pressure and volume, the pressure rise is found to be 6.3 psi due to flat-tening of the tank. This is well below the manhole cover relief valve setting of 9 psi.

FIGURE D.8. Side View of Tank Truck After Overturn Accident (Note: Failed Sections Around Baffles Have Been Repaired)

The cross section of the tank is elliptical (96-in. major axis diameter, 60-in. minor axis diameter) and the tank heads are ellipsoidal. Measurement of a tank indicated that the radius at the center of the ellipsoidal head is equal to the diameter of the major axis of the cross section along the longitudinal axis (96 inches). The shell and head are thus designed to fail at the same pressure. The stress in the shell is calculated using the relationship:⁽³⁾

$$\sigma = P \frac{r}{t}$$

where:

σ = stress, psi

P = pressure, psi

r = radius, inches

t = shell thickness (0.172 in.)

The longitudinal cross section is assumed to be a circle with a diameter equivalent to the major diameter of the ellipse. The stress in the head is calculated using the relationship:⁽³⁾

$$\sigma = P \frac{r}{2t}$$

The point of highest stress is assumed to be in the center of the head. The formula is based on the assumption that the head can be treated as a sphere with a radius equivalent to the radius at the center point (96 in.).

The thickness at which the yield stress (29,000 psi) in the heads or shell is reached due to the pressure of 6.3 psi caused by overturn is found to be 0.0104 in., using either of the above equations. It is estimated that many factors such as stress risers due to the baffles, local heating and uneven loading will increase this failure thickness by a factor of four. Thus, when the shell or head thickness is reduced to 0.042 in. by abrasion, gross failure results. A total of $0.172 - 0.042 = 0.130$ in. must be abraded away to produce failure. Removal of the skin material by abrasion is based

on data derived from the wear rates of snow plow skid plates. The volume of material abraded from snow plow skid plates fabricated of steel is estimated to be 232.5 in.³ of steel on a 60-in.² contact plate (1/2-in. thick by 10-ft long) used on a dry or lightly snow-covered highway. (Information from G. Thompson, State of Washington Department of Highways, Pasco, WA, June 1976.)

Estimates of wear are based on the parameters shown in Table D.1.

TABLE D.1. Snow Plow Skid Plate Wear Data

Plow Weight (lb)	Miles Traveled Before Removal of 232.5 in. of Steel (3-7/8 in. Thickness)	
	Asphalt-Concrete	Bituminous Surface Treatment ^(a)
2,000	150	100
1,000	300	200

(a) 1/4- to 1.2-in. rock

Converting to a wear rate:

Surface	Wear Rate (inches of wear per foot of travel per pound of contact pressure)
Asphalt-Concrete	1.468×10^{-7}
Bituminous Surface Treatment	2.202×10^{-7}

Experiments are currently underway at Battelle-Columbus Laboratories to develop methods to predict the wear rate of snow plow skids. On a wear-rate fixture, it was determined that mild steel wears at a rate of 1×10^{-7} in. per foot per psi of contact pressure. Aluminum was found to wear at a corresponding rate of 15×10^{-6} . The test fixture presses the materials against an 80-grit belt moving at approximately 50 mph (information from W. Glaeser, Battelle-Columbus Laboratories, June 1976). Relatively soft aluminum alloys (3003) and harder alloys (6061-T6) were found to wear at essentially

the same rate. The Battelle-Columbus experimental wear rate data can be correlated to observed snow plow steel skid plate wear rates by using the ratio of wear rates:

$$\frac{\text{experimental aluminum wear rate}}{\text{experimental steel wear rate}} = \frac{15 \times 10^{-6}}{1 \times 10^{-7}} = 150$$

Applying this rate, the predicted wear rate for aluminum used for snow plow skids on road surfaces is:

<u>Surface</u>	<u>Wear Rate Range (in./ft-psi)</u>
Asphalt-concrete (A-C)	2.202×10^{-5}
Bituminous Surface Treatment (BST)	3.303×10^{-5}

The contact pressure on the primary wear areas of a tank with four baffles can be determined by dividing the total normal force (weight of tank plus lading) by the area derived earlier for the primary wear areas (165 in.²). A loaded tank weighs approximately 30,000 lb. The contact pressure is, therefore, 30,000 lb/165 in.², or 181.8 psi.

To determine skid distance to remove the previously determined 0.134 in. skin thickness, the skin thickness is divided by the appropriate wear rate multiplied by the contact pressure (181.8 psi). The following skid distances result:

<u>Surface</u>	<u>Skid Distance Range (ft)</u>
Asphalt-concrete	35.4
Bituminous Surface Treatment	21.6

The initial velocity, V_0 that will produce a given skid distance (assuming constant deceleration) is determined by the following relationship:⁽⁴⁾

$$V_0 = \sqrt{V_f^2 - 2aS}$$

where

$$V_f = \text{final velocity} = 0$$
$$a = \text{deceleration} = \frac{F}{M}$$

where

$$F = \text{retarding force} = fW$$

$$f = \text{coefficient of friction} = 0.45$$

$$W = \text{loading and tank weight} = 30,000 \text{ lb}$$

$$F = (0.45)(30,000)$$

$$= 13,500 \text{ lb}$$

$$M = \text{Mass} = w/g$$

$$= \frac{30,000 \text{ lb}}{32.2 \text{ ft/sec}^2} = 932 \text{ slugs}$$

$$= 932.84 \text{ lb sec}^2/\text{ft}$$

$$a = \frac{13,500 \text{ lb}}{932.84 \text{ lb sec}^2/\text{ft}} = -14.5 \text{ ft/sec}^2$$

Substituting into the above relationships yields:

$$V_o = 5.4\sqrt{5}$$

Substituting the previously determined skid distance to wear through a 0.134-in. thick skin, the initial velocities are as follows:

<u>Surface</u>	<u>Initial Velocity Range to Wear Through 0.134 Skin Thickness</u>
Asphalt-concrete	32 mph
BST	25 mph

Nonuniform deformation (buckling) of the skin in the primary wear area plus the hydrostatic pressure of the loading and transient forces not accounted for will tend to aggravate wear and reduce the skid distance ranges by an estimated 20%.

Corresponding initial velocities become:

<u>Surface</u>	<u>Initial Velocity Range to Wear Through 0.108 in. Skin Thickness</u>
Asphalt-concrete	26 mph
Bituminous Surface Treatment	20 mph

Velocity ranges for failure by abrasion on softer dirt and loose gravel surfaces normally encountered on the shoulders of roadways were determined to be greater than the maximum speeds encountered in truck accidents. Abrasive failure velocities for the tractor/semitrailer transport system are essentially the same. The thicker tank skin tends to increase the velocity, while the greater tank weight decreases the initial velocity required for failure. These two effects are approximately equal in magnitude.

D.4 THERMAL

Gasoline tanks can and do burn violently, but the violent burning is normally restricted to cases where the source of fuel initially comes from the tank itself after failure by other modes such as puncture. An intact gasoline tanker would normally be expected to survive an extended external fire (calculated below) if the tank starts in a near full condition and the pressure relief devices are functioning.

The primary means of thermal failure identified is the case where the gasoline level is lowered within the tank, permitting the high temperature external heat source to impinge directly on portions of the tank not backed up by liquid gasoline. The situation is similar to that of an aluminum pan on a stove overheating. The aluminum pan is prevented from overheating as long as the bottom has a water covering. Once the water has vaporized, the pan rapidly overheats.

The calculations presented below are for the truck tank/tank trailer transport system. Similar results are obtained for the tractor/semitrailer system. The calculations are based on the assumption that failure occurs when 1/2 of the tank contents have vaporized. The following additional assumptions are made:

1. Latent heat of vaporization of gasoline is 133-145 Btu/lb⁽⁶⁾ at one atmosphere.
2. The tank contains 4,500 gal (28,000 lbs) of gasoline.
3. The thermal input from an external hydrocarbon fire is 17,000 Btu/hr-ft².⁽⁷⁾
4. The surface area of the tank exposed to the fire is about 120 ft².

The thermal input is:

$$120 \text{ ft}^2 (17,000 \frac{\text{Btu}}{\text{hr-ft}^2}) = 204 \times 10^6 \text{ Btu/hr}$$

One half of the 28,000 lb of gasoline must vaporize and be released out the vent before failure. Multiplying the weight of gasoline vaporized by the latent heat of vaporization:

$$14,000 \text{ lb} (139 \frac{\text{Btu}}{\text{lb}}) = 1.96 \times 10^6 \text{ Btu}$$

The time to failure can be found by dividing the total thermal input required by the rate of thermal input:

$$\frac{1.96 \times 10^6 \text{ Btu}}{2.04 \times 10^6 \text{ Btu/hr}} = 0.96 \text{ hr}$$

Exposure of a greater tank surface area would, of course, result in a shorter time to failure. In most cases, it would be expected that less surface area would be exposed to the fire. The melting point of aluminum is approximately 1220°F. Very rapid failure of the tank (within a few minutes) would be expected if a source of external heat above ~1500°F were to impinge directly against a portion of the tank not backed up with gasoline.

An unlikely, but conceivable, mode of failure due to thermal input would occur if all three pressure relief devices failed simultaneously. The burst

pressure can be approximated by considering the tank as a cylindrical shell with a diameter of 96 in. and wall thickness of 0.172 in. The burst pressure can be found from the expression:⁽³⁾

$$P_u = 2S_u \frac{b-a}{b+a}$$

where

P_u = burst pressure

S_u = ultimate strength $\approx$ 38,000 psi

b = outer radius = 48 in.

a = inner radius = 47.83 in.

substituting

$$P_u = 136.4 \text{ psi}$$

The ellipsoidal heads on the tank do not behave as a sphere, and the tank baffles tend to concentrate stress in the shell. The burst pressure has been reduced by an estimated factor of 3 to account for this fact. The tank would then be assumed to burst at 45 psi. A further lowering of the assumed burst pressure to 30 psi is included to account for reduced material strength due to elevated temperature.

To find time to failure, the thermal input calculated earlier is used (2.04×10^6 Btu/hr). The tank will fail when the vapor pressure reaches 30 psi. The temperature that produces a vapor pressure rise of 30 psi is estimated from Figure B.1 as 178°F.

Gasoline has a specific heat of approximately 0.5 Btu/lb°F. The thermal input to raise the temperature of the 28,000 lbs of gasoline to 178°F is

$$(28,000 \text{ lb})(0.5 \frac{\text{Btu}}{\text{lb}^\circ\text{F}}) = 14,000 \text{ Btu}/^\circ\text{F}$$

If the gasoline is assumed to start at a temperature of 78°F, the heat energy required to reach 178°F will be 1.395×10^6 Btu.

Dividing the total heat required by the heat flux

$$\frac{1.395 \times 10^6 \text{ Btu}}{2.04 \times 10^6 \text{ Btu/hr}} = 0.68 \text{ hr to burst}$$

Thermal failure of the gasket material on the tank manway cover or outlet valve in a fire is also a potential release mechanism. The gasket materials used on the tank are either cork or elastomer ("O"-ring types). A study of thermal degradation of cork gaskets in a fire indicates that the material maintains its sealing properties for a relatively long period of time.⁽⁸⁾ The failure mechanism is slow, but progressive charring when the cork is exposed to surfaces heated to about 800°C. Based on the information in Reference 8, it is estimated that cork and "O"-ring gaskets will lose their liquid retention properties after a 20-min exposure to an 1850°F heat source.

Releases from the tank can also occur when the tank overturns and solar insolation causes a pressure rise that opens the relief valves. The maximum solar input to the tank area 12-ft wide by 20-ft long is absorbing this solar energy, the thermal input to the tank is about 52,800 Btu/hr.

Using the relationship

$$q = C_p \Delta T$$

where

q = thermal input = 52,800 Btu/hr

C_p = specific heat of gasoline = 0.5 Btu/lb

ΔT = temperature rise in °F/hr

$$\Delta T = \frac{q}{C_p} = 105,600 \text{ °F lb/hr} \div 28,000 \text{ lb gasoline/tank}$$

$$\Delta T = 3.77 \text{ °F/hr.}$$

REFERENCES

1. J. H. Evans, "Experimental Study of the Stress-Strain Properties of Cask Materials Under Specified Impact Conditions" in Proceedings of the Fourth International Symposium on Packaging and Transportation of Radioactive Materials. CONF-740901, Miami Beach, FL, pp. 232-243, September 1974.
2. E. C. Lusk and R. F. Burian, "Impact Protection for Radioactive Material Shipping Containers" in Proceedings of the Fourth International Symposium on Packaging and Transportation of Radioactive Materials. CONF-740901, Miami Beach, FL, pp. 438-448, September 1974.
3. R. J. Roark, Formulas for Stress and Strain. McGraw-Hill, New York, NY, 1965.
4. E. Oberg, F. Jones and H. Horton, Machinery's Handbook, 20th Edition. Industrial Press, Inc., New York, NY, 1975.
5. S. H. Crandall and N. C. Dahl, ed, An Introduction to the Mechanics of Solids. McGraw-Hill, New York, 1959.
6. T. Baumeister and L. S. Marks, ed, Standard Handbook for Mechanical Engineers 7th Edition. McGraw-Hill, New York, NY, 1967.
7. F. E. Adcock, ATMX-600 Railcars for Radioactive Waste Shipments. RFP-1411, The Dow Chemical Company, Rocky Flats Division, Golden, CO, p. 31, January 1979.
8. F. E. Dixon, "A New Thermal Shield for (Type B) Transportation Packages." Reprinted from Engineering Review, September 1967.

APPENDIX E

CHARACTERISTICS OF GASOLINE FIRES

Fire is the most important mechanism which produces property damage or personal injuries following a release of gasoline from a tank truck accident. Property damage is not assessed in this report. Injuries and deaths may be produced by direct exposure to the radiant energy from the gasoline fire, by secondary fires started in buildings near the spill site or by inhalation of smoke from either of these fires. These mechanisms have been modeled using techniques available in the literature.

For purposes of the fire model, the spilled gasoline is assumed to collect in a pool 1/2-in. in depth. This is an average value for land surfaces.⁽¹⁾ Pool depths on asphalt or concrete would probably be less than this value, while depths in soil would be greater. For an assumed spill volume of 3000 gal, this produces a pool with a radius of about 55 ft.

It has been estimated from available accident statistics that 24% of spills from tank trucks carrying flammable liquids result in fires.⁽²⁾ The properties of gasoline fires are not well known. The energy radiated from the fire is the most important characteristic for predicting injuries and deaths or the possibility of igniting secondary fires. The radiant heat flux is dependent on the size of the pool, the substrate on which the spill occurred, the height above the pool, the distance from the pool and the direction of windspeed. A conservative estimate of the safe separation distance as a function of pool size and flame angle is shown in Figure E.1. Flame angle can be predicted from windspeed using Figure E.2. Molecular weight divided by boiling temperature (M/T_b) for gasoline is about 0.25. The safe separation distance is based on a radiant flux of 10,000 Btu/hr/ft² (0.75 cal/cm²/sec). As shown in Figure E.3, exposure to this heat flux for longer than about 25 sec. will cause third degree burns on uncovered skin. This figure assumes no attempts by the exposed individual to avoid the intense heat. If an individual simply turns to ward off the effects of the heat, the effective irradiance could be reduced by a factor of $1/\pi$.⁽³⁾ The time required to produce severe burns is increased substantially under these conditions.

FIGURE E.1. Safe Separation Distance from a Hydrocarbon Fire (Ref. 1)

FIGURE E.2. Flame Angle as a Function of Windspeed and M/T_b (pool radius = 30-150 ft)(Ref. 1)

FIGURE E.3. Radiant Exposures to Cause Various Flesh Burns (Ref. 3)

At a windspeed of 10 knots, Figure E.1 predicts a safe separation distance of about 55 ft from the downward edge of a burning pool of gasoline 110 ft in diameter. This value may be conservative because Figure E.1 was derived assuming a clean flame. In actuality, heavy hydrocarbons like gasoline result in very smokey fires. The presence of smoke in the fire reduces the emissivity of the flame, resulting in smaller radiant heat fluxes. Actual measurements of heat fluxes from gasoline fires are not available, but measurements have been made for JP5 fires.⁽⁴⁾ JP5 is a heavy hydrocarbon with combustion properties similar to those of gasoline. The results of a representative set of measurements are presented in Figure E.4. The radiant heat fluxes were measured 10 ft from the crosswind edge of a flaming 10-ft diameter pool of JP5 on a water substrate. The heat flux measured 5 ft above the ground was about 3600 Btu/hr/ft². This can be compared with the no wind case in Figure E.1, which can be extrapolated to give a safe separation distance (10,000 Btu/hr/ft²) of about 2 ft for a 10 ft. diameter pool. Figure E.5

FIGURE E.4. Radiation from 10-ft Diameter JP5 Fires versus Radiometer Level Above Ground (Ref. 4)

FIGURE E.5. Radiant Flux as a Function of Distance from JP5 Fire (Ref. 4)

shows that the radiant heat flux varies by about a factor of two in going from 2 ft to 10 ft from the edge of the fire. There is this reasonable agreement between the JP5 experiments and the calculations represented in Figure E.1. The results presented in Figure E.1 are believed to be conservative and will be used as the gasoline fire model.

The variation of the radiant heat flux from a gasoline fire with distance for various windspeeds may be estimated by assuming that the heat flux varies in the same way as the JP5 heat flux plotted in Figure E.5. The curve labeled "view factor" in Figure E.5 has been used as representative of the experimental measurements on JP5 fires. It is assumed that the ratio of the JP5 heat flux of the safe separation distance to the heat flux at a particular distance is the same as the ratio of the gasoline heat flux at the safe separation distance ($0.75 \text{ cal/cm}^2 \text{ sec}$) to the heat flux at the distance of interest, i.e.,

$$\phi_{\text{JP5}}(\text{SSD})/\phi_{\text{JP5}}(x) = \phi_{\text{GAS}}(\text{SSD})/\phi_{\text{GAS}}(x) \quad (1)$$

The values for JP5 are taken from Figure E.5 and the value of the heat flux from the gasoline fire at that distance is calculated. The results for a fire on a 55-ft radius pool are plotted in Figure E.6.

Figure E.7 shows the irradiance as a function of time required to ignite various materials. Whitewood can be used to represent the flammable exteriors of buildings.⁽³⁾ The "safe separation distance" heat flux of $0.75 \text{ cal/cm}^2 \text{ sec}$ can be seen to be capable of igniting secondary fires after an exposure time of about 1 min.

As stated previously, gasoline pool fires produce large amounts of smoke since the atmosphere directly above the pool becomes oxygen deficient. If inhaled, the sooty smoke could induce coughing and sneezing and possibly produce respiratory damage. Inhalation of large concentrations of the smoke for a sufficient length of time can be fatal. Smoke inhalation is not believed to be a significant health hazard in gasoline fires, because the smoke plumes are strongly buoyant. It is assumed that the smoke will be carried high into the air and be diluted by the atmosphere to below toxic concentrations before they descend to ground level.

FIGURE E.6. Variation of Radiant Heat Flux with Downwind Distance from a 55-ft Radius Gasoline Pool Fire

FIGURE E.7. Radiant Exposures to Ignite Various Materials (Ref. 3)

REFERENCES

1. A Modal Economic and Safety Analysis of the Transportation of Hazardous Substances in Bulk. COM-74-11271, A. D. Little, Inc., Cambridge, MA, p. 226, May 1974.
2. Ibid, p. 160.
3. A. N. Takata, Review of Fire Hazard Distances. IIT Research Institute, Chicago, IL, April 1970.
4. E. L. Capner and R. S. Alger, "Characterization and Suppression of Aircraft Fuel Fires." WSCI 72-26 presented at Western States Section/The Combustion Institute 1972 Fall Meeting, Monterey, CA, October 1972.

APPENDIX F

ESTIMATE OF DAMAGE FROM GASOLINE TANK TRUCK EXPLOSIONS

The volatility of gasoline leads to the possibility of an explosion following an accident involving a gasoline tank truck. These explosions are basically of two types--deflagrations in vapor clouds and detonations inside the tank.

Appendix C shows that explosive concentrations of gasoline vapor in air can be encountered as the vapor cloud drifts away from a gasoline spill. Ignition of this mixture produces a deflagration. A deflagration is characterized by a subsonic flame front velocity and small pressure changes (typically a maximum of 1.5 psi.)⁽¹⁾ Although these pressures can cause window breakage and exterior building damage, the possibility of producing deaths from such blast waves is believed small.

The type of explosion that is of major interest from a damage standpoint is the detonation of an explosive mixture inside the tank. A detonation is characterized by a flame front with supersonic velocity. The detonation of gasoline vapors in a confined area can produce blast waves that have a significant potential for causing damage.

Brasie and Simpson⁽²⁾ have developed a method for estimating the damage resulting from a chemical explosion. The first step in their procedure is to estimate the weight of TNT that will produce a blast equivalent to the chemical explosion as a function of the standard heat of combustion of the confined vapor and the amount of vapor in the confined area. Damage produced at various distances is then determined from the equivalent TNT weight of the explosion.

The TNT equivalent yield of a hydrocarbon explosion can be estimated from the following expression:

$$W = \frac{\alpha \cdot \Delta H_c \cdot m}{2,000 \text{ Btu/lb TNT}} \quad (\text{F-1})$$

where W is the mass in pounds of TNT with a yield equivalent to the hydrocarbon explosion, ΔH_c is the standard heat of combustion in Btu/unit mass and m is the mass of vapor in the confined area. α is an empirical factor developed from experimental observations. It accounts for the inefficiencies in explosions, since ΔH_c is the yield for complete combustion.

No experimental data are available for gasoline explosions, so that α cannot be evaluated directly. As an alternate approach, an effective heat of combustion was calculated to replace ($\alpha \cdot \Delta H_c$) in Equation F-1. These calculations are based on experimental measurements by Stecher⁽³⁾ of the gasoline explosion pressure over the entire range of flammable mixtures of air and gasoline. Stecher's data are plotted in Figure F.1.

Several assumptions were made in calculating the equivalent heats of combustion. The explosion pressures are assumed to be the final static pressure after combustion in a closed, constant volume container. The reaction is assumed to be adiabatic (the change in the total energy of the system is zero) and no work is done on the surroundings. This implies that the change in internal energy (ΔU) of the system is also zero.

The burning process is assumed to proceed in two steps--a combustion step at constant temperature and a pressurization step. The process is depicted in Figure F.2. If the process proceeds as shown in Figure F.2, we have:

$$\Delta U = \Delta U_c + \Delta U_p = 0 \quad (\text{F-2})$$

The relationship of ΔU to enthalpy (ΔH) is given by:

$$\Delta U = \Delta H - V\Delta P - P\Delta V \quad (\text{F-3})$$

or since $\Delta V = 0$ (constant volume container):

$$\Delta U = \Delta H - \Delta (VP) \quad (\text{F-4})$$

FIGURE F.1. Explosion Pressures over the Explosive Range of Gasoline (Ref. 3)

FIGURE F.2. Assumed Burning Process for Calculation of Equivalent Heat of Combustion of Gasoline

The enthalpy change in each step of the combustion process can be calculated separately, so that:

$$\Delta U_c = \Delta H_c - \Delta (VP)_c \quad (F-5)$$

$$\Delta U_p = \Delta H_p - \Delta (VP)_p \quad (F-6)$$

If the gas in the enclosed volume is assumed to be ideal, so that $\Delta(VP) = R \Delta(nT)$, then for the combustion step $\Delta(VP)_c = R T \Delta n$ and for the pressurization step $\Delta(VP)_p = R n \Delta T$. Applying these relationships and adding Equations F-5 and F-6 together gives:

$$\Delta U = \Delta U_c + \Delta U_p = 0 = \Delta H_c + \Delta H_p - R \Delta(nT) \quad (F-7)$$

Equation F-7 is solved for ΔH_c in the following way:

- For the gasoline-air mixture of interest, calculate the total number of moles initially present (n_1), assuming that 1 g-mole of gasoline is present.
- Calculate the number of moles present after combustion (n_2) by assuming that the combustion products are N_2 , CO_2 , H_2O and excess O_2 or unburned gasoline.
- Read the final pressure (P_2) from Figure F.1.
- Calculate T_2 from the ideal gas law at constant volume

$$T_2 = \frac{n_1}{n_2} \cdot \frac{P_2}{P_1} \cdot T_1 \quad (F-8)$$

- Estimate ΔH_p from the relationship

$$\Delta H_p = \Delta T \sum_i n_i C_p^*(i) \quad (F-9)$$

where the summation is over all the combustion products (N_2 , CO_2 , H_2O and O_2) and $C_p^*(i)$ is the mean specific heat of each substance. A sample calculation of ΔH_c is given in Attachment A.

Figure F.3 contains a plot of the effective heats of combustion for various gasoline-air mixtures. Equation F-1 can then be used to calculate the equivalent TNT yield. The mass of gasoline in the tank is calculated for the particular gasoline-air mixture assuming that the volume of the tank is 4,500 gal and that the ambient temperature before the explosion is 77°F.

FIGURE F.3. Effective Heats of Combustion of Gasoline

When the equivalent TNT yield has been found, the damage limits can be estimated from Figure F.4. The scaled range for serious damage given in Figure F.4 is $27 \text{ ft/lb}^{1/3}$. The serious damage limit for the explosion of interest is determined by multiplying the scaled range by the cube root of the TNT equivalent yield. A plot of the probable total destruction, serious structural damage and missile damage limits for various gasoline and air mixtures is given in Figure F.5. A sample calculation of the TNT equivalent yield and damage limits is given in Attachment B.

FIGURE F.4. Explosion Damage Limits versus Scaled Range⁽¹⁾

FIGURE F.5. Probable Total Destruction, Serious Structural Damage and Missile Damage Limits for Gasoline and Air Mixtures

The conditions required to produce an explosive concentration of vapors in the gasoline tank should also be considered. At 70°F, the vapor pressure of gasoline is about 7.5 psi (see Appendix B). If the vapor is in equilibrium with the liquid in the tank, the vapor will be about 51% gasoline by volume. Even for a temperature of 20°F, the air-gasoline mixture is 19% gasoline by volume. If complete mixing is assumed, an explosion in a gasoline tank that is partially filled with liquid is impossible. Because the gasoline vapors are 3.4 times heavier than air, it is possible that concentration gradients could be present in the vapor space, so that some portions of the vapor could be within the flammable limits. However, an ignition source must still contact the flammable region for an explosion to occur, and the explosive yield would be much smaller than those predicted above for an explosive mixture that completely fills the tank. The most likely configuration to produce a serious explosion would be an empty tank that is somehow open to the atmosphere. For an explosion to occur, an ignition source would be required when the mixture in the tank was diluted to within flammable limits.

ATTACHMENT A

SAMPLE CALCULATION OF EFFECTIVE HEAT OF COMBUSTION OF GASOLINE

This sample calculation will be carried out for a mixture that is 1.5% gasoline by volume. The explosion pressure for this mixture is taken from Figure F.1 as 65 psig. Assuming the mixture contains 1 g-mole of gasoline the number of g-moles of air $n_1 = \frac{1}{0.015} = 66.7$ g-moles. Using an average chemical formula for gasoline of $C_{7.3}H_{14.6}$, and assuming complete combustion to N_2 , CO_2 and H_2O in excess oxygen, the number of moles of combustion products $n_2 = 51.9 N_2 + 7.3 CO_2 + 7.3 H_2O + 2.84 O_2 = 69.3$ g-moles. Assuming ideal gas behavior, the final temperature of the combustion products:

$$T_2 = \frac{n_1}{n_2} \cdot \frac{P_2}{P_1} \cdot T_1 = \frac{(66.7 \text{ g-moles})}{(69.3 \text{ g-moles})} \cdot \frac{(79.7 \text{ psia})}{(14.7 \text{ psia})} \cdot (298^\circ K)$$

$$T_2 = 1553^\circ K = 2336^\circ F$$

Next calculate ΔH_p from $\Delta H_p = \Delta T \sum_i n_i C_p^*(i)$ using the following mean values for specific heats. (4)

$$C_p^*(CO_2) = 12.3 \text{ kcal/g-mole } ^\circ K$$

$$C_p^*(H_2O) = 9.6 \text{ kcal/g-mole } ^\circ K$$

$$C_p^*(N_2) = 7.7 \text{ kcal/g-mole } ^\circ K$$

$$C_p^*(O_2) = 8.1 \text{ kcal/g-mole } ^\circ K$$

$$\text{Then, } \Delta H_p = (1553^\circ K - 298^\circ K) \left[\underset{N_2}{51.9(7.7)} + \underset{CO_2}{(7.3)(12.3)} + \underset{H_2O}{7.3(9.6)} + \underset{O_2}{(2.8)(8.1)} \right]$$

$$\Delta H_p = 731 \text{ kcal}$$

and

$$\Delta H_c = R\Delta(nT) - \Delta H_p$$

$$\Delta H_c = 1.99 \times 10^{-3} \text{ kcal/g-mole } ^\circ\text{K} [69.3(1553) - 66.7(298)] - 731$$

$$\Delta H_c = -557 \text{ kcal/g-mole gasoline}$$

ATTACHMENT B

SAMPLE CALCULATION OF TNT EQUIVALENT

This calculation is performed for an air-gasoline mixture that is 2.25% gasoline by volume. Assume that the tank volume is 4,500 gal, the ambient temperature is 77°F and that the gasoline air mixture behaves as a perfect gas. The number of moles of gasoline in the tank is calculated from the ideal gas law:

$$n = \frac{PV}{RT} = \frac{(14.7 \text{ psia}) (2.25\% \text{ gasoline}) (4,500 \text{ gal}) (0.13 \text{ ft}^3/\text{gal})}{(10.73 \frac{\text{ft}^3 \text{ psia}}{\text{lb-mole } ^\circ\text{R}}) (537^\circ\text{R})}$$

$$n = 0.034 \text{ lb-moles gasoline}$$

The mass of gasoline in the tank

$$m = (0.034) \text{ lb-moles} \times 102 \text{ lb/lb-mole}$$

$$m = 3.5 \text{ lb gasoline}$$

To find the equivalent yield, read ΔH_c from Figure F.3.

$$\Delta H_c = -696 \frac{\text{kcal}}{\text{g-mole}} = -12,300 \text{ Btu/lb gasoline}$$

The equivalent yield is then

$$W = \frac{(\Delta H_c) (m)}{2000} = \frac{(-12,300 \text{ Btu/lb}) (3.52 \text{ lb})}{2000 \text{ Btu/lb TNT}}$$

$$W = 21.6 \text{ lb TNT}$$

To find the limit of serious structural damage, read the scaled range from Figure F.4 (27 ft) and multiply by $W^{1/3}$. The limit of serious structural damage is then

$$L = (21.6)^{1/3} (27) = 75 \text{ ft.}$$

REFERENCES

1. W. Geiger, "Generation and Propagation of Pressure Waves Due to Unconfined Chemical Explosions and Their Impact on Nuclear Power Plant Structures." Nuclear Engineering and Design 27:189-198, 1974.
2. W. C. Brasie and D. W. Simpson, "Guidelines for Estimating Damage Explosion." Loss Prevention 2, 1968.
3. G. E. Stecher, Fire Prevention and Protection Fundamentals. Chilton Co., 1953.
4. J. M. Smith and H. C. Van Ness, Introduction to Chemical Engineering Thermodynamics. McGraw-Hill, 1959.

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APPENDIX G

ESTIMATE OF SECONDARY FIRES INITIATED BY GASOLINE POOL FIRES

This appendix describes the method used to estimate the number of secondary building fires that would be produced if a tank truck accident initiated a gasoline pool fire on a city street or freeway. For the purposes of this analysis, three spill sizes are considered--3,000 gal., 4,200 gal. and 8,400 gal. The analysis is based on an assumed "typical" urban area developed from the work of Takata and Salzberg.⁽¹⁾ The model includes suburban areas surrounding a typical city. Very densely populated areas such as might be found in the business districts of very large cities are excluded from the analysis. (It is assumed that the large tank trucks used to carry gasoline would avoid traveling in these areas whenever possible.)

The analysis is based on the pool fire model described in Appendix E. However, on a city street the gasoline pool would not be expected to assume a circular shape. City streets are usually sloped from the center toward the curbs to facilitate runoff. This will generally confine the pool to one side of the street. The curbs will also limit the spread of the pool. The pool shape assumed for this analysis is shown in Figure G.1(a). The pool G.1(a) is assumed to be confined to an area 40-ft wide (about one half the width of a typical four lane street) and as long as the diameter predicted by the pool model. The safe separation distance from the fire is estimated using the pool model (see Figure E.1). The flame angle and safe separation distance for the three pool sizes as a function of distance is presented in Table G.1. The safe separation distance for several windspeeds and directions is illustrated in Figure G.1(b and c).

It is theoretically possible that flammable concentrations of gasoline vapors could accumulate in sewer systems following a spill on a city street. It is believed that such events would make a minimal contribution to the overall risk, so they were not analyzed in detail.

a) POOL SHAPE

FIGURE G.1. Assumed Gasoline Pool Shapes and Safe Separation Distance for Various Windspeeds for a Gasoline Pool Fire on a City Street

TABLE G.1. Flame Angle and Safe Separation Distance
as a Function of Windspeed for Gasoline
Pool Fires

Windspeed		Flame Angle ^(a) day	Safe Separation Distance (ft) ^(b)		
m/sec	mph		3,000 gal. spill	4,200 gal. spill	8,400 gal. spill
1	2.24	3	32	41	80
3.5	7.83	11	45	60	100
7	15.66	30	68	90	160
10	22.37	43	79	100	175
18	40.26	60	90	110	190

(a) From Figure E.2

(b) From Figure E.1

A model urban area was developed to determine the probability of initiating secondary building fires from gasoline pool fires of the three assumed spill sizes. Previous attempts⁽¹⁾ to model urban areas have classified the land development into as many as 23 types of residential areas, several types of industrial areas, schools, commercial areas and downtown districts. For the purposes of this study, these have been condensed into six types of areas. The basic characteristics of the land development types and the percentage of each in the model urban area are listed in Table G.2.

Each type of land development is depicted graphically in Figures G.2 through G.5. A city block is assumed to be 380 ft long and 210 ft wide with a 15-ft wide alley running lengthwise through the center of the block. Building sizes and lot sizes are averages based on figures for Detroit, Michigan; Albuquerque, New Mexico, and San Jose, California. The gasoline pool fire is assumed to occur on a four lane street that is 60 ft wide. All other streets are 40 ft wide. The buildings in the residential areas are assumed to be 25 ft from the curb because of zoning restrictions. Commercial buildings are assumed to sit in the center of the lot. Industrial buildings are assumed to be separated from the street by a 6-ft wide sidewalk and downtown buildings by a 10-ft wide sidewalk.

TABLE G.2. Model Urban Area Land Development

<u>Development Type</u>	<u>Building Size (ft)</u>	<u>Lot Size (ft)</u>	<u>Percentage of Total Land Area</u>
Residential A	38 x 22 W	63.3 W x 97.5 D	31.2
Residential B ^(a)	62 L x 24 W	95 W x 97.5 D	43.4
Industrial	56 L x 30 W	76 W x 97.5 D	18.4
Commercial	36 L x 36 W	76 W x 97.5 D	0.6
Downtown	50 L x 50 W	51 W x 97.5 D	0.4
Vacant & Schools	--	--	6.0

^(a) 42 ft x 24 ft house with attached garage 20 ft x 24 ft.

The following simplifying assumptions have been made to estimate the secondary fires from a gasoline spill on a city street:

- The spill can occur with equal probability at any position along a four lane street.
- All buildings have flammability characteristics of wooden structures.
- The wind is equally likely to blow from any direction.
- The probability of various windspeeds is that given in Table G.3.
- The probability of an accident occurring on a city street is independent of the type of land development in which the accident occurs.

TABLE G.3. Probability of Various Windspeeds⁽²⁾

<u>Windspeed (m/sec)</u>	<u>Probability</u>
0 - 1	0.255
1 - 3.5	0.508
3.5 - 7	0.161
7 - 10	0.052
10 - 18	0.024

FIGURE G.2. Residential Area Models Used to Estimate Secondary Fires from Gasoline Spills

FIGURE G.3. Industrial Area Model Used to Estimate Secondary Fires from Gasoline Spills

COMMERCIAL

FIGURE G.4. Commercial Area Model Used to Estimate Secondary Fires from Gasoline Spills

DOWNTOWN

FIGURE G.5. Downtown Area Model Used to Estimate Secondary Fires from Gasoline Spills

Using the urban model, gasoline pool shape and the other assumptions discussed above, the probability of initiating secondary fires from a gasoline spill on a city street has been estimated for each land development type for the three spill sizes. The results are presented in Tables G.4 through G.6.

TABLE G.4. Probability of Secondary Building Fires from a Gasoline Pool Fire on a City Street - 3000-gal Spill

Development Type	Probability of Number of Fires Indicated						
	0	1	2	3	4	5	6
Residential A	--	--	0.400	0.585	0.010	0.005	--
Residential B	--	0.247	0.625	0.125	0.003	0.005	--
Industrial	--	--	0.327	0.665	0.003	0.004	0.001
Commercial	--	--	0.120	0.530	0.350	--	--
Downtown	--	--	0.160	0.310	0.530	--	--
Vacant & Schools	1.0	--	--	--	--	--	--

TABLE G.5. Probability of Secondary Building Fires from a Gasoline Pool Fire on a City Street - 4200-gal Spill

Development Type	Probability of Number of Fires Indicated							
	0	1	2	3	4	5	6	7
Residential A	--	--	0.155	0.505	0.310	0.015	0.015	0.005
Residential B	--	--	0.640	0.320	0.020	0.010	--	--
Industrial	--	--	0.080	0.605	0.280	0.015	0.015	0.004
Commercial	--	--	0.330	0.540	0.130	--	--	--
Downtown	--	--	--	0.050	0.520	0.430	--	--
Vacant & Schools	1.0	--	--	--	--	--	--	--

TABLE G.6. Probability of Secondary Building Fires from a Gasoline Pool Fire on a City Street - 8400-gal Spill

Development Type	Probability of Number of Fires Indicated							
	0	1	2	3	4	5	6	7
Residential A	--	--	--	--	--	--	1.0	--
Residential B	--	--	--	--	1.0	--	--	--
Industrial	--	--	--	--	--	1.0	--	--
Commercial	--	--	--	--	--	1.0	--	--
Downtown	--	--	--	--	--	--	--	1.0
Vacant & Schools	1.0	--	--	--	--	--	--	--

To estimate the probability of initiating secondary fires from a gasoline tank truck fire on an urban freeway, a model freeway was developed. The model freeway is shown in Figure G.6. The freeway is assumed to have six lanes with a total fenced right of way of 200 ft. Each lane is assumed to be 12 ft wide and the shoulders are 10 ft wide. A 10-ft median separates the two traffic flows. A two lane street is assumed to run along the fence with the mixture of the development types discussed previously located along the street.

The model gasoline pool used to estimate the secondary fires from a gasoline spill on an urban freeway is shown in Figure G.7. The freeway is assumed to be graded toward the outside shoulders for runoff, so that the spill forms a pool from the center lane to the edge of the right of way (about 75 ft). The pool length is taken to be the diameter predicted by the pool model in Appendix E. The assumptions on wind direction and speed and building flammability characteristics outlined previously for a spill on a city street are made here also. The values of safe separation distance given in Table G.1 were again used. The results are presented in Tables G.7 through G.9.

FIGURE G.6. Model Urban Freeway Used to Estimate Secondary Building Fires Initiated by a Gasoline Pool Fire

FIGURE G.7. Assumed Gasoline Pool Shape for a Spill on an Urban Freeway

TABLE G.7. Probability of Secondary Building Fires Initiated by a Gasoline Pool Fire on an Urban Freeway - 3000-gal Spill

<u>Development Type</u>	<u>Probability of Number of Fires Indicated</u>			
	<u>0</u>	<u>1</u>	<u>2</u>	<u>3</u>
Residential A	0.997	0.002	0.001	--
Residential B	0.997	0.002	0.001	--
Industrial	0.990	0.002	0.008	--
Commercial	0.997	0.002	0.001	--
Downtown	0.990	0.001	0.003	0.006
Vacant & Schools	1.0	--	--	--

TABLE G.8. Probability of Secondary Building Fires Initiated by a Gasoline Pool Fire on an Urban Freeway - 4200-gal Spill

Development Type	Probability of Number of Fires Indicated				
	0	1	2	3	4
Residential A	0.876	0.008	0.051	0.072	--
Residential B	0.870	0.022	0.100	0.008	--
Industrial	0.868	0.009	0.079	0.043	--
Commercial	0.870	0.017	0.074	0.039	--
Downtown	0.867	0.002	0.031	0.053	0.047
Vacant & Schools	1.0	--	--	--	--

TABLE G.9. Probability of Secondary Building Fires Initiated by a Gasoline Pool Fire on an Urban Freeway - 8400-gal Spill

Development Type	Probability of Number of Fires Indicated							
	0	1	2	3	4	5	6	7
Residential A	0.74	--	0.031	0.072	0.085	0.065	0.007	--
Residential B	0.074	--	0.092	0.123	0.044	--	--	--
Industrial	--	--	0.702	0.195	0.092	0.01	--	--
Commercial	0.074	--	0.048	0.123	0.079	0.01	--	--
Downtown	--	0.136	0.156	0.448	0.055	0.137	0.058	0.01
Vacant & Schools	1.0	--	--	--	--	--	--	--

REFERENCES

1. A. N. Takata and F. Slazburg, Development and Application of a Complete Fire Spread Model Volumes I and IV. IIT Research Institute, Chicago, IL, June 1968.
2. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. p. 10-12, BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.

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