AN ASSESSMENT OF THE RISK OF TRANSPORTING
PROPANE BY TRUCK AND TRAIN

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INTRODUCTION

Rural areas that are not served by natural gas lines depend on the shipment
of propane for use as a fuel. Most of the long distance transportation of
propane is by pipeline. However, local distribution and final delivery of
propane usually requires shipment by tank truck or rail tank car. Environ-
mental control systems are required to prevent release of propane during
transport. Environmental control equipment for propane transportation
systems includes containment barriers and relief valves designed to prevent
significant releases of material during normal transport. Some protection
from release during transportation accidents is also provided by rail tank
car head shields and tank insulation.

An important part of an effective environmental control engineering program
for propane transportation systems is the quantification of the level of
protection afforded by the control systems currently in use or those that
might be developed in the future. Risk assessment techniques are a method of
measuring the effectiveness of the environmental control systems by quantify-
ing the safety of the transportation system.

Risk assessment attempts to place the consequences of accidental release of
hazardous materials into perspective by considering the probability that
the release will occur. A commonly-used measure for the risk to society
from operating a particular system is the product of the consequences of
a release and its estimated frequency of occurrence, summed over all
possible releases from the system. If the release consequences are expressed
in terms of fatalities, the system risk can be compared to the risks from
other systems or to other risks in society such as accidents or natural
disasters. Additional perspective on the risk from a particular system can
be gained by developing a risk spectrum. A risk spectrum is a plot of the
expected frequency of a given level of consequences (or greater) versus
consequence level. It is a valuable tool for comparing the risk from dif-
ferent systems or activities. Risk spectrum information is also needed for
judgments about the acceptability of the risk from a particular system.
Occasionally society may attach different values to high consequence events
than to a series of lower consequence events that produce the same overall
risk. In order for the risk from two systems to be considered equivalent,
both the total risk number and the risk spectrum must be similar.

This paper presents an assessment of the risks of transporting propane by truck and train. The study, carried out as a part of Pacific Northwest Laboratory's (PNL) Transportation Safety Studies Project, was conducted for DOE's Division of Environmental Control Technology. The remainder of this paper reviews the risk assessment methodology that has been developed by PNL and presents the results of its application to propane transportation systems.

TRANSPORTATION RISK ASSESSMENT METHODOLOGY

The risk assessment methodology used in the Transportation Safety Studies Program evolved from a number of risk analysis models originally developed for use in the nuclear industry. Initially, risk assessment techniques were suggested as a method of evaluating sites for nuclear power facilities.[1] Application of early methods was limited to analyses of fixed facilities. Fixed facilities have a well-defined population distribution and the population in the immediate vicinity of the plant (the exclusion area) is controlled by the facility operator. The population distribution in the vicinity of a transportation accident, however, is highly variable. Transportation accidents may occur in rural areas (with very low population densities) in suburban areas or in urban areas (with relatively high population densities). Since transportation accidents can occur at virtually any location along the shipping route, a variety of geographic and meterological conditions can also be encountered. The variability in the population distribution, geography and meteorology for transportation accidents adds a degree of complexity not found in risk assessments of fixed sites.

Four basic steps are followed in the PNL transportation risk assessment methodology to develop the information required to perform the risk analysis. These four basic steps are:

- A detailed description of the transportation system, including projected industry characteristics, size and number of shipments, material characteristics, container types, transport modes, routes traveled, and weather and population zones.

- The identification of possible material release sequences, using fault tree analysis.

- The evaluation of the probabilities and consequences of releases, using container failure data and mathematical models for dispersion and health effects.

- The calculation and assessment of risk, defined as the product of the probability of a release of material to the environment and the consequences of that release.

SYSTEM DESCRIPTION

The results of the risk assessment of transporting propane by truck and train are related to the year 1985 to allow a comparison with other reports in this series. To apply the risk assessment methodology described above to the propane transportation system, it was necessary to make some assumptions about the propane shipping industry. These assumptions included the following:

- Shipping systems and basic distribution patterns are the same as in the mid-1970's. Most propane is shipped in two or more stages, as shown in Figure 1, from refineries or processing plants to an intermediate terminal and then onto the consumer.

- The total amount of propane shipped in 1985 corresponds to the projected U.S. requirements for 1985, scaled up to account for second stage movements.

- About two-thirds of the total propane movements are by tank trucks, while roughly three percent of total movements are by rail tank car. The remainder of the propane shipments are made primarily by pipelines. All second stage deliveries are assumed to be made by trucks.[2,3]

- All tank truck shipments are assumed to be made in tank trucks or trailers designed to meet Department of Transportation (DOT) specification MC-331.

- All rail tank car shipments are assumed to be made in an insulated rail tank car with headshields, designed to meet the new DOT specification 112J340W.

The shipping system description developed from these assumptions is summarized in Table 1.

TABLE 1. Simplified Propane Shipping System Model

Propane Tank Type	Transport Mode	Amount/ Container (m³)	Material Shipped/Year (million m³)	Number of Shipments/ Year	Average Shipment Distance (km)	Accident/ km
MC - 331 Tank Truck	Truck	43.0	40	980,000	210	1.55×10^{-6}
MC - 331 Bobtail	Truck	10.6	20	1,980,000	80	1.55×10^{-6}
DOT - 112J340W Rail Tank Car	Rail	127.2	3	25,000	400	6.21×10^{-6}

DOMESTIC PROPANE

REFINERY OR GAS PROCESSING PLANT

IMPORTED PROPANE

PIPELINE

TANK TRUCK

ALL TRANSPORT MODES

RAIL TANKCAR

PIPELINE

RAIL TANKCAR

DISTRIBUTION OR UNDERGROUND STORAGE

TANK TRUCK

BARGE, TANKER

RAIL TANKCAR

BARGE, TANKER

CONSUMER

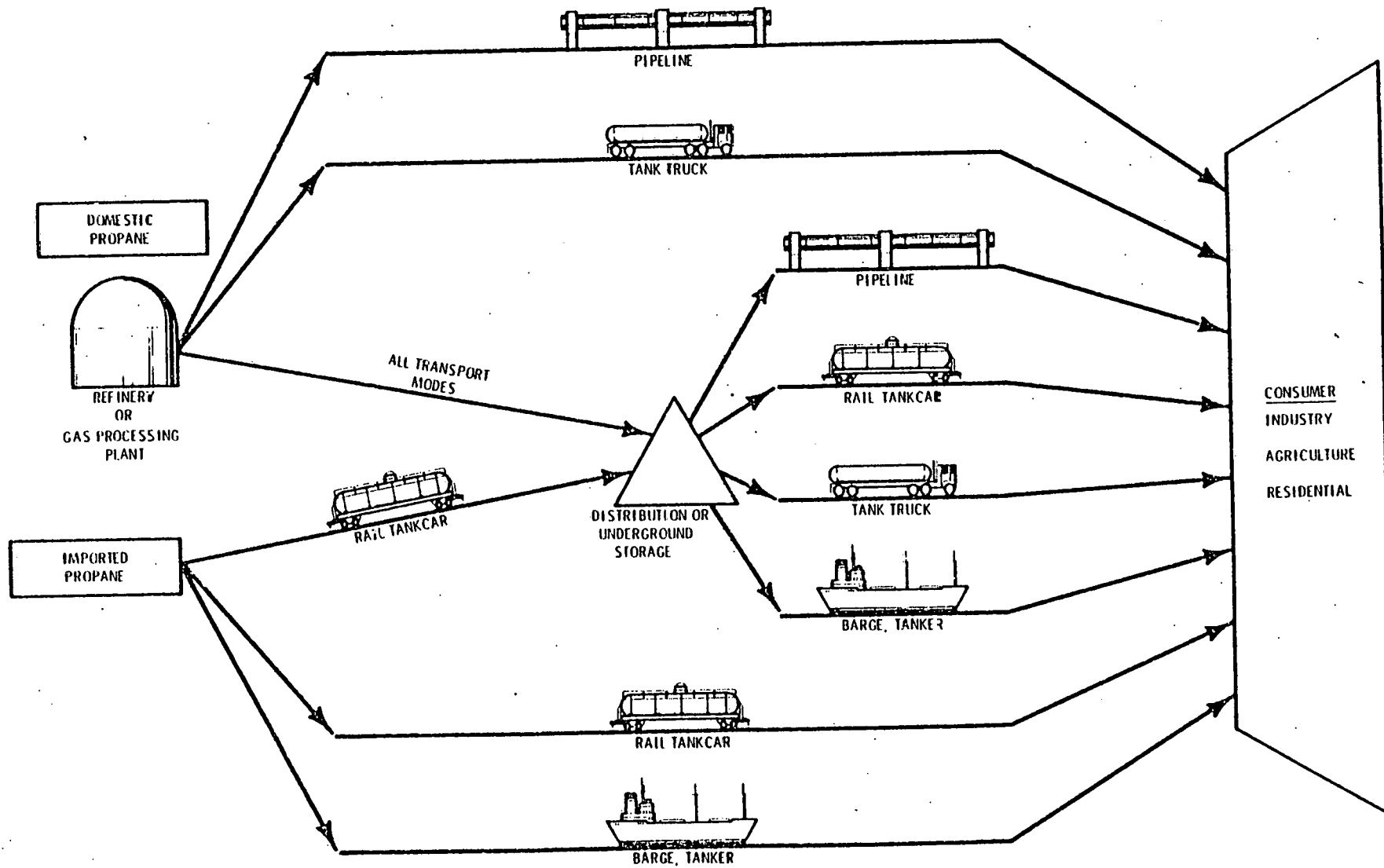INDUSTRY

AGRICULTURE

RESIDENTIAL

FIGURE 1.   General Patterns of LPG Transport and Distribution

RELEASE SEQUENCE IDENTIFICATION

To determine the probability of a container failing during normal transport or during a transportation accident, possible release sequences must be postulated. Propane releases occur every year from tank trucks or rail tank cars. However, the statistical information available from state and federal agencies does not provide a sufficient basis to identify the mechanisms by which these tanks fail. Thus, possible release sequences are identified by a deductive reasoning process that works backward from a release through the possible chain of events that could produce the release. Fault tree analysis was used to perform these reasoning processes. Releases during normal transport and releases caused by forces produced in transportation accidents were considered in identifying the release sequences. Releases during loading or unloading operations were not investigated in this study.

RELEASE SEQUENCE EVALUATION

Identified release sequences were evaluated to determine the probability of occurrence and the resulting environmental consequences. To calculate the probability of a tank truck or rail tank car failing during normal transport or during a transportation accident, it was necessary to estimate tank failure thresholds, and examine the forces generated in an accident environment.

Both the truck and train accident environments were evaluated using, information developed by Sandia Laboratories.[4] For this study, the stresses present in truck and train accidents were divided into four categories: fire, impact, puncture and crush. Other stresses, such as abrasion and immersion were assumed to contribute insignificantly to the likelihood of propane tank failures and were not included. Support data on propane releases was obtained from the Office of Hazardous Materials in the Department of Transportation.

Propane tank failure threshold estimates were obtained using mathematical analysis and engineering estimates. Only thresholds relating to the accident environment and posing a threat to the propane tank (fire, impact, puncture and crush) were evaluated. Conservative assumptions were required in some instances to carry out the analysis. Sensitivity studies were performed to determine the effect of these estimates on the overall risk.

The final step in the evaluation of release sequences is the determination of release fractions. For the purposes of this risk analysis, the lists of release sequences were divided into six categories and release characteristics were assigned to each. The six release rate categories are described in the following paragraphs:

- The first release category represents a continuous slow leak from an equivalent 2.5-cm diameter opening. These release sequences do not generally occur as a result of transportation accidents. This release is postulated to occur either as a result of a defective weld or corrosion in the tank itself or from a release through a defective internal valve that travels on through defective or missing external hardware.

- The second release category represents a continuous outflow from an opened or damaged valve. These release sequences occurred as a result of mechanical forces (impact or puncture). Accidents with fire present are not included here. The rate of release of propane is assumed to be the equivalent of that emanating from the area of a 7.6-cm diameter opening.

- A third release category is the outflow of propane from activated safety relief valves in an accident where fire is present. This release is modeled as a continuous leak.

- The fourth release category is that of a small, continuous leak of propane in an accident situation with a fire present. The propane is released, as in release category #2, from a 2.5-cm diameter opening. The elevated temperature results in a larger release rate.

- A fifth release category is a release of propane from a major mechanical failure (impact or puncture) of the propane tank. These represent major accident sequences where a fire is not initially present, although the released propane may later be ignited. It is assumed that the total contents to the tank are released almost immediately.

- The last category of release corresponds to an explosive rupture of the propane tank, caused by an overpressurization of the tank or a weakening of the tank walls by fire. These represent major accident sequences were a fire (not caused by the propane cargo) is the cause of tank failure. It is assumed that the total contents of the tank are released almost immediately.

To express the risk from propane releases in a form suitable for comparison to other societal risks, conversion factors were developed to allow modification of the consequence portion of the risk number (in this case to fatalities). Areas which were evaluated include: health effects, meteorology, demography and quantity of the release dispersed.

The potential sequences of events following a release are depicted in Figure 2. The major health effects of the release scenarios considered in this report are direct flame exposure, explosion effects (overpressure and fragmentation), radiant heat flux and secondary fires. Consequences to the public are measured in terms of expected fatalities. The number of fatalities for each major health effect is estimated by determining a size and shape for each effect and applying this information to a uniform population density. An exclusion zone on either side of the transportation pathway is assumed to exist for all releases, since the general public does not reside immediately adjacent to major transportation pathways.
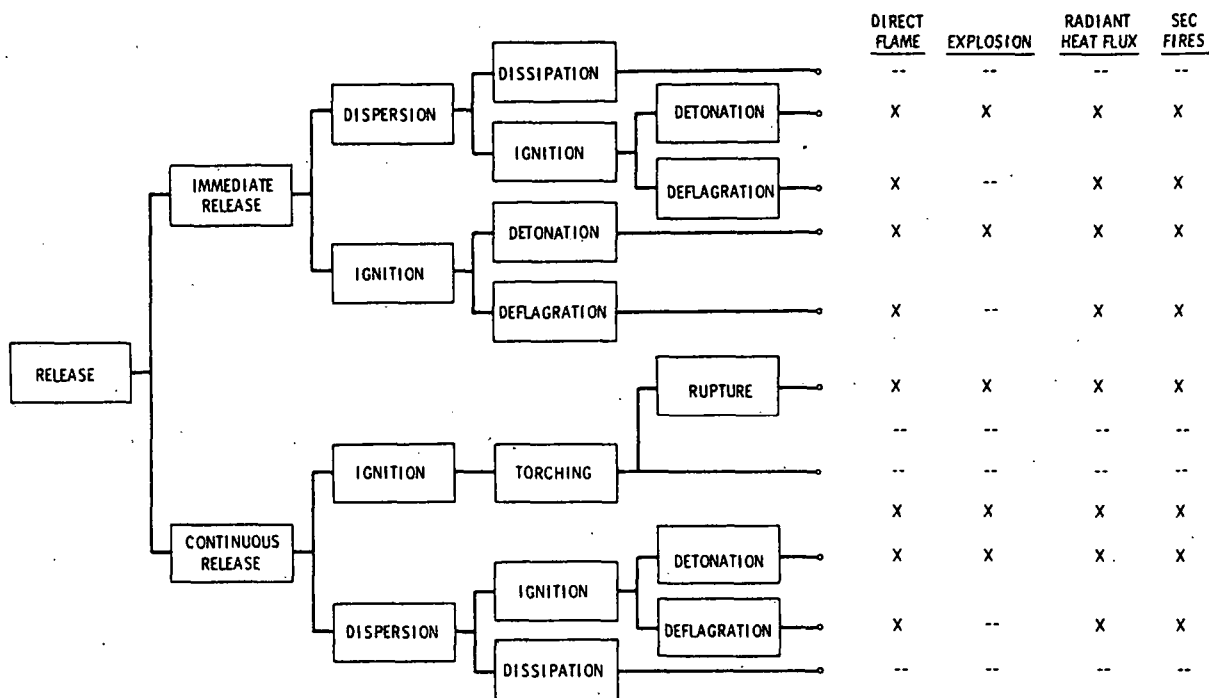
FIGURE 2. Event Tree

Event tree structure:

RELEASE
- IMMEDIATE RELEASE
  - DISPERSION
    - DISSIPATION
    - IGNITION
      - DETONATION
      - DEFLAGRATION
  - IGNITION
    - DETONATION
    - DEFLAGRATION
- CONTINUOUS RELEASE
  - IGNITION
    - RUPTURE
    - TORCHING
  - DISPERSION
    - IGNITION
      - DETONATION
      - DEFLAGRATION
    - DISSIPATION

	DIRECT FLAME	EXPLOSION	RADIANT HEAT FLUX	SEC FIRES
DISSIPATION	--	--	--	--
DETONATION	X	X	X	X
DEFLAGRATION	X	--	X	X
DETONATION	X	X	X	X
DEFLAGRATION	X	--	X	X
RUPTURE	X	X	X	X
	--	--	--	--
TORCHING	--	--	--	--
	X	X	X	X
DETONATION	X	X	X.	X
DEFLAGRATION	X	--	X	X
DISSIPATION	--	--	--	--

Meteorological information was obtained by averaging actual data from 26 sites throughout the country. Population distribution information was obtained by dividing the U.S. into the nine Census Bureau regions. The population densities were grouped into three classes within each region: urban, "other urban" and rural areas. Population data was extrapolated to 1985. The distance traveled by propane tank trucks and rail tank cars in each region was then estimated.

Atmospheric dispersion and vaporization models were used to determine the extent of a propane vapor cloud from a release prior to ignition.

Accepted dispersion models were used to determine the cloud areas of potentially flammable concentrations. No evacuation was assumed in calculating fatalities, since most release sequences were completed within about 30 minutes, which is insufficient time for a formal evacuation program.

RISK EVALUATION OF PROPANE SHIPMENTS

Because of the complicated nature of the shipping system model, the risk analysis was divided into three parts, each part corresponding to one of the three propane tank types. The risk involved with shipping propane was determined separately for the bobtail truck, the tank truck and the rail tank car, and is shown in Table 2. These risks were then summed to determine the overall transportation system risk.

TABLE 2. Summary of Propane Shipping Risks

Shipping Container	Transport Mode	Accidents (events/year)	Release of Propane (events/year)	Significant Release of Propane (events/year)	Events per Year Resulting in ≥ 1 Death
MC - 331 Tank Truck	Truck	320	40	9	1.6
MC - 331 Bobtail	Truck	250	70	5	0.6
DOT - 112J340W Rail Tank Car	Rail	60	40	0.4	0.1

Risk spectrum curves for the three propane tank types are shown in Figure 3, along with the risk spectrum for the entire shipping system for the reference year. These risk curves portray total risk to the public from all release types. The shipment of propane in tank trucks contributes the greatest portion to the total system risk. The contribution of a particular tank type or mode to the total system rish, however, is dependent on the number of shipments per year made in that tank. Figure 4 shows the propane shipment risk spectrum in perspective with other risks, including those from previous risk assessment studies in this series.[7] The total public risk from propane shipment accidents is compared to the risk from other kinds of accidents and natural disasters in Table 3.

The results of this study indicate that the risk to the public of shipping propane is higher than the risks involved with shipping nuclear materials, but is generally lower than the risk spectrum presented for man-caused and natural disaster events.

Further perspective on the total risk to the public from transporting propane may be gained by examining some of the benefits provided by this energy material. Propane and other liquefied petroleum gases are a significant source of fuel in the United States, supplying about 3 percent of total U.S. energy demand in 1976. Propane may be directly substituted for natural gas, and is a clean-burning fuel.[8]
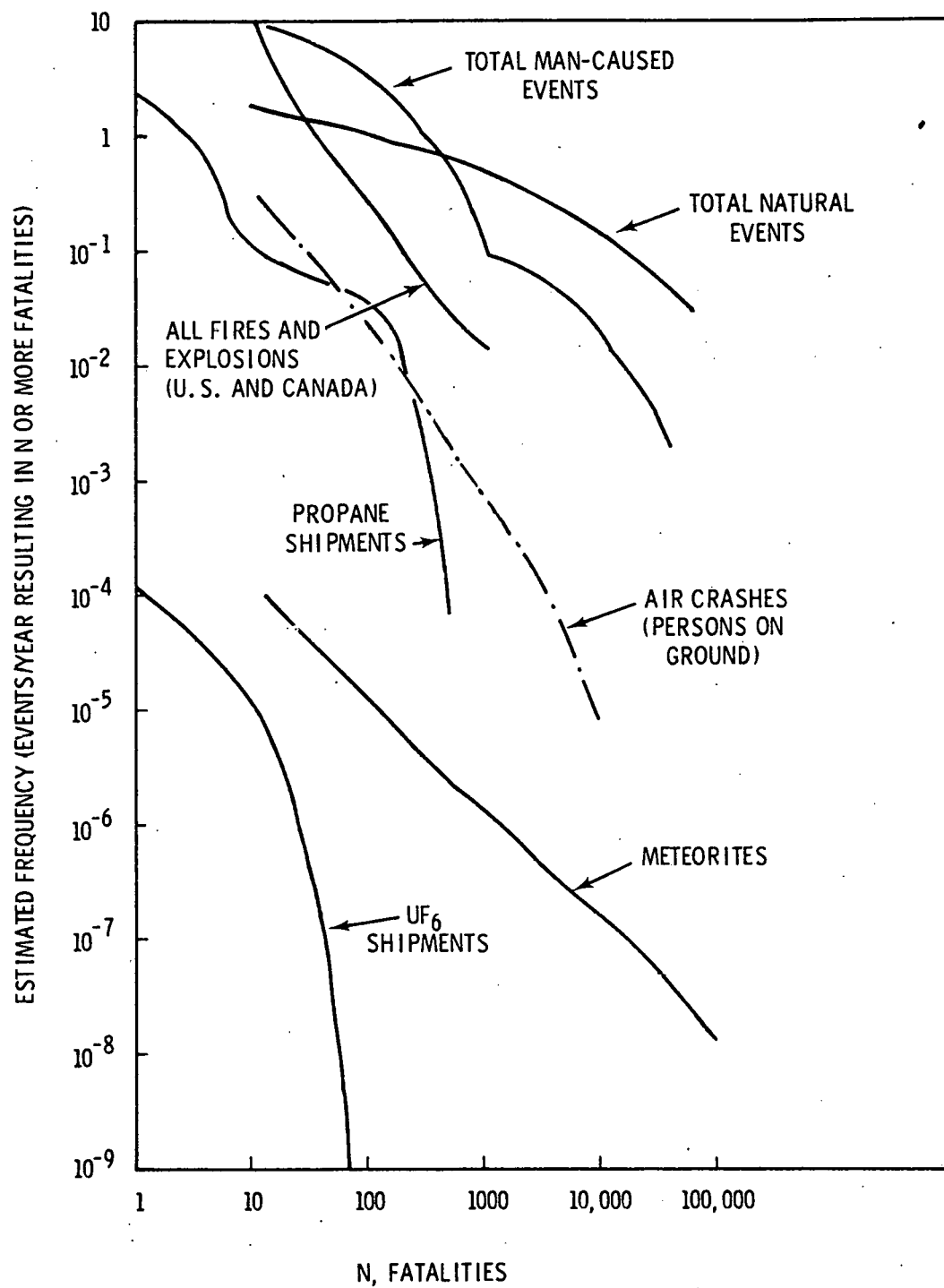
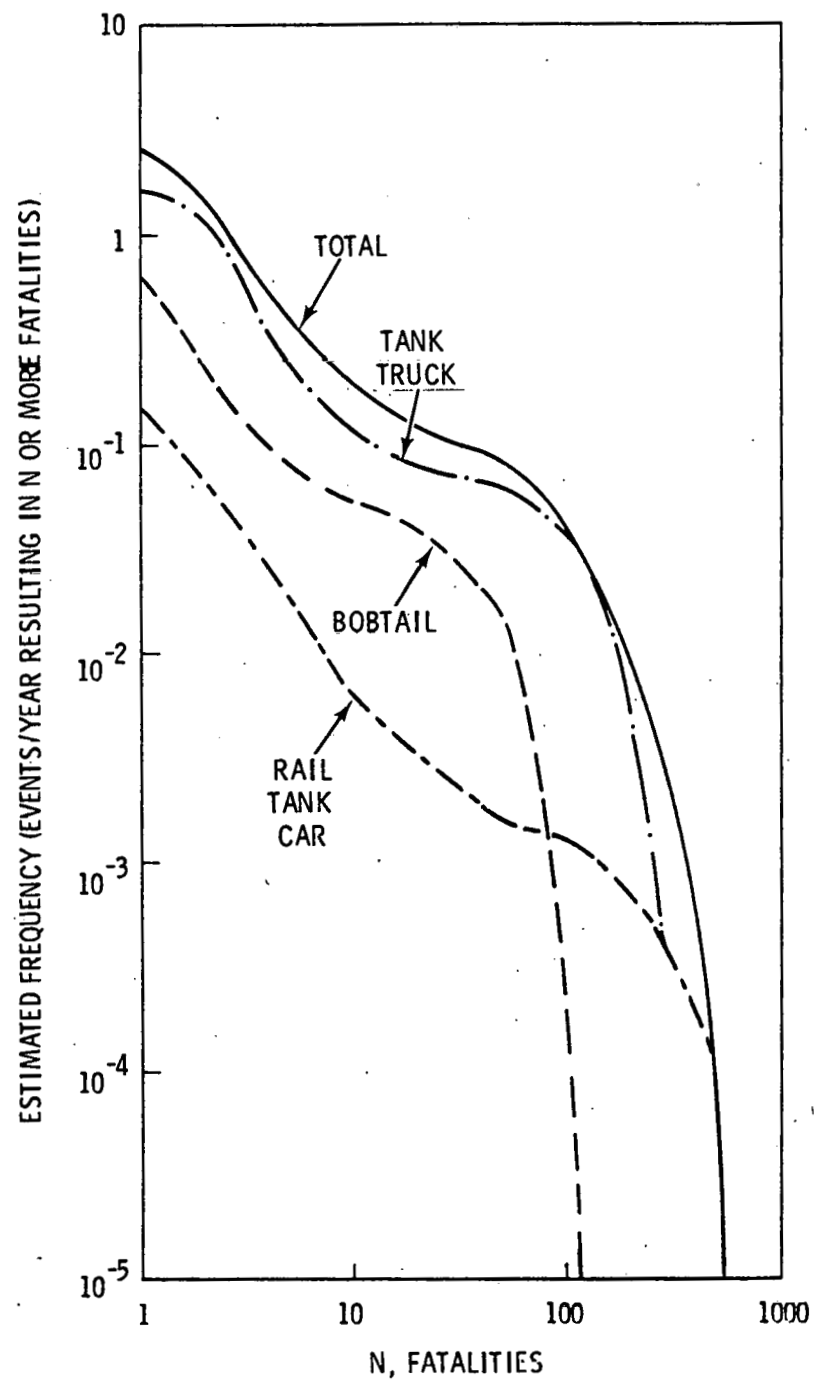FIGURE 4. Risk Spectrum for Propane. Shipments in 1985 Compared to other Risks

FIGURE 3. Risk Spectra for Propane
Shipments in 1985

TABLE 3. Average Total and Individual Risk from
Various Accidents and Natural Disasters

Event	Total Risk (Fatalities/year)	Individual Risk (b)
All accidents	103,030 (a)	1 in 2,000
Motor vehicle accidents	46,700 (a)	1 in 5,000
Air crashes	1,552 (a)	1 in 140,000
Dam failures	35 (c)	1 in 6,300,000
Gasoline	28 (d)	1 in 7,900,000
Propane shipments	15	1 in 15,000,000
Air crashes (persons on ground)	6 (e)	1 in 33,000,000 (f)
Meteorites	1.0×10^{-3} (g)	1 in 2×10^{11}

(a) Based on 1975 statistics.

(b) Based on total U.S. population (220,000,000).

(c) Average for dam failures 1889-1972 (ref. 5).

(d) From Reference 6.

(e) Average for years 1960-1973 (ref. 5).

(f) Based on population at risk.

(g) From Reference 5.

Propane is also a staple on farms, where it is used for crop drying, flame weeding, tobacco curing, stock tank heating, and frost protection. It also powers trucks, pumps, standby generators, and other farm equipment. Commercial establishments, such as hotels, motels, and restaurants, use propane much like the homeowner. Industry relies on it for soldering, heat-treating, annealing, volcanizing, and many other uses. As an engine fuel, its minimal emmissions allows propane to be used indoors. This same feature makes it a desirable fuel in congested areas.

The LPG industry serves about thirteen million customers, including homes, farms, individuals, businesses, and government groups. LP-gas is essentially a rural fuel, and roughly 1-1/2 million farms depend on the fuel for a variety of uses. Industry market calculations show approximately 60 million people dependent on LP-gas for one use or another.[2]

MAJOR CONTRIBUTORS TO OVERALL RISK

During the analysis of the three propane tank types, the release sequences were grouped into six categories, corresponding to the six release rates described earlier. The hazards from transporting propane stem from the flammable nature of the cargo and resulting effects. In evaluating the conseouences of each release category, four effects of the released propane were addressed: explosion (over-pressure effects); direct flame exposure; radiant heat effects, including damage from secondary fires; and missile damage.

For both truck and rail transport, it was found that the release sequences that involved dispersion of the propane had the greatest potential for producing fatalities.

These release sequences primarily include failure of the tank itself by impact or puncture mechansims. The failure of the tank in an impact or puncture accident situation was assumed to result in a release of the entire tank contents to the atmosphere, forming a large vapor cloud. The flammable area of the resultant cloud was large enough to affect many of the general public, and this resulted in the most severe consequences when ignited. It was found that in an accident where the propane is immediately ignited, or a fire is involved in the accident, consequences were more localized, and less likely to result in fatalities to the general public. However, these explosion and immediate fire sequences could result in fatalities to the population immediately surrounding the ruptured tank truck. This population would include truck drivers, emergency response teams (most commonly fire-fighters), and people in other vehicles involved in the accident.

In addition to fatalities to the general public, about six deaths per year from propane truck accidents may be expected in 1985 to account for drivers and other people in the immediate vicinity of the accident. Transport of propane by rail tank car is expected to account for about one or two deaths per year (firefighters) in addition to members of the general public.

The actual fatality-causing mechanisms experienced varied with population distributions, largely because of shielding effects. In urban areas, direct flame contact and explosion effects caused the majority of deaths. Radiant heat effects played a minor role in causing public fatalities. In "other urban" and rural areas, explosion effects and radiant heat caused most of the fatalities. Direct flame contact was not a major danger in these areas.

RISK SENSITIVITY STUDIES

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 different shipping routes, different containers, changes in the predicted industry growth rate, etc., would result in a different risk. In general, reevaluation of the risk would be required for these changed conditions.

For this risk assessment, the area presenting the greatest uncertainty is the consequence model. To test the effects of some of the assumed parameters on the risk of shipping propane, several sensitivity studies were carried out. Secondary fires were shown to be an insignificant source of fatalities. Risk values did not change substantially when the presence of secondary fires was totally deleted from the model. There was also some doubt regarding the value to be used for the TNT equivalent yield for a propane vapor cloud. A maximum value of TNT equivalency, one, was employed in this sensitivity study to generate some confidence limits for the analysis. Because of the magnitude of explosion consequences depends on the TNT equivalency value assumed, risk did increase substantially over the base case, which applied a yield of 10% to the TNT equivalency.

Another parameter in the consequence model that was subjected to a sensitivity test was the fraction of fatalities resulting from exposure to direct flame. In the base case, it was assumed that only 10 percent of the population exposed to direct flame would die. The others would survive, being able to shield themselves from the flames by hiding in buildings or running away. To ascertain the importance of this parameter to the final risk number, two sensitivity studies were performed. The first set the value of this parameter at zero, where none of those exposed to the area of direct flame would die. Although risk did decrease slightly, the change was not significant. The second study set this parameter at 100 percent; that is, all those within the flammable region would die. In this case, the total risk number was increased by about thirty percent over the base case.

Another area presenting uncertainty is the amount of package defects present for any propane shipment. Leaks through values and piping systems represented a large source of propane release. Eliminating these releases (that is, assuming that no package defects exist) eliminates all released of propane during normal transportation. This essentially reduces the risk of transporting propane to releases occuring during transportation accidents only. However, because normal releases do not have severe consequences, adjustments to this parameter did not substantially affect the total system risk.

It was assumed in this analysis that all propane tanks when exposed to a fire fail from metal overheating when the tank is half full. To test the effects of this assumption on risk, a sensitivity analysis was performed assuming the tanks failed at 3/4 full and 1/4 full. The results of these studies showed the total risk to be insensitive to this assumption, although the risk from that particular release sequence was altered. This is primarily because the release sequence involving failure of a tank by fire was of a very low probability and had localized consequences. This release sequence thus did not contribute substantially to public risk.

Total risk values proved to be relatively insensitive to the presence of head shields on rail tank cars. Although head shields did reduce the normal incidence of puncture accidents by about fourty percent, they had little effect on impact accidents. Since the release sequence involving a mechanical failure of the tank included both impact and puncture accident sequences the overall effect of the head shields on risk values was fairly small. Risk was reduced only two percent by the addition of head shields to rail tank cars.

The effect of insulation on the propane tanks was more noticeable. A tank truck with insulation and a rail tank car without insulation were analyzed in sensitivity studies. The addition of insulation to the tank truck decreased the rise of the release sequence of tank failure by fire by almost seventy percent. However, there was no change in the other release sequences. Similarly, the analysis of an uninsulated rail tank car resulted in an increased tank fire failure risk of over fifteen times the base case. Again, however, the risk from other release sequences was not changed. The lack of insulation increased the total risk of shipping propane by rail by only six percent. This is explained by the fact that initial failure of the tank by fire accounts for less than 1% of the system risk in rail transport. Almost 80% of the risk stems from failure of the tank by impact on puncture.

Several states are attempting to institute regulations that outlaw the transport of hazardous materials within a heavily populated region. To gain an understanding of how such a regulation might impact the risk of shipping propane, a sensitivity study on the amount of travel within an urban region was performed. Since it is believed unrealistic to totally outlaw hazardous material shipments through cities, an approximate figure of 20% of the base case travel through urban areas was assumed. This assumption resulted in a substantial public risk reduction. Consequences of dispersed releases were drastically reduced, primarily because of the decrease in available population for experience of the effects of released propane. The results of this analysis and other sensitivity studies are shown in Table 4.

TABLE 4. Total Public Risk Sensitivity Cases for Propane Shipments

Description of Sensitivity Case	Estimated Annual Frequency of Occurrence of One or More Fatalities Relative to Base Case	Total Public Risk Level Relative to Base Case
Base Case - Total System	1.00 (2.35)	1.00 (15.04)
Base Case - Bobtail	1.00 (0.62)	1.00 (2.92)
Base Case - Tank Truck	1.00 (1.59)	1.00 (11.43)
Base Case - Rail Tank Car	1.00 (0.14)	1.00 (0.69)
No Secondary Fires	1.00	1.00
TNT Yield - 1.0 (a)	2.81	4.81
Direct Flame - % kill - 0.0 (b)	0.93	0.97
Direct Flame - % kill - 1.0 (b)	1.36	1.28
No Package Defects (b)	0.97	0.99
Ten Times Package Defects (b)	1.04	1.09
Tank Fails at 3/4 Full	1.00	1.00
No Head Shields (c)	1.02	1.02
Insulated Tank Trucks (b)	0.99	0.99
Uninsulated Rail Cars (c)	1.07	1.06
20% Travel in Urban Regions	0.83	0.59

(a) Based on bobtail base case alone.

(b) Based on tank truck base case alone.

(c) Based on rail tank car base case alone.

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