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Hazardous Material Transportation Risks in the Puget Sound Region

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PREFACE

The risk analysis discussed in this report was performed in conjunction with the Hazardous Materials Study for the Central Puget Sound Region, made possible by a cooperative agreement between the U.S. Department of Transportation and the Puget Sound Council of Governments.

The authors wish to acknowledge the contributions of Theodore Glickman of the Transportation Systems Center, who conceived and monitored this effort, and David Teeter, Project Director for the Council.

TABLE 1.1. Total Risk for the Transport of Selected Hazardous Materials in the Central Puget Sound Region

Commodity	Total Risk (deaths/year) Truck	Rail	Total
Chlorine	--	3.6×10^{-2}	3.6×10^{-2}
LPG	3.1×10^{-2}	2.1×10^{-4}	3.1×10^{-2}
Methanol	--	7.6×10^{-6}	7.6×10^{-6}
Sodium Hydroxide	1.4×10^{-5}	7.3×10^{-10}	1.4×10^{-5}
Motor Anti-knock Compound	--	4.2×10^{-5}	4.2×10^{-5}
Total	3.1×10^{-2}	3.6×10^{-2}	6.7×10^{-2}

of 6.7×10^{-2} can be interpreted as an average of one death in the CPSR public due to the transport of these materials every 15 years.

An estimate of total risk for the transport of all hazardous materials by truck and train in the CPSR was made by ratioing results for the five commodities by their relative shipping volumes within their relative shipping volumes within their respective DOT shipping classification. Categories not specifically represented in the study were considered by adding their shipping volumes to the commodity with similar consequence mechanisms. For example, combustible liquids were assumed to be similar to flammable liquids. Results of this analysis indicate a total risk of 9.1×10^{-2} deaths per year, or one death every 11 years in the CPSR. This result, when compared to the five commodity risk result, indicates that the commodities considered in this study are major risk contributors in the transport of HM by truck and rail in the CPSR.

Approximately 700,000 persons live within 3 km of the transportation route considered in this study. Based on this number, the average annual probability of an individual being killed due to the hazardous nature of these shipments is about 1 in 10 million. This value is very low compared to average individual risks for other activities in the U.S. in Table 1.2. If the total U.S. values for chlorine and propane shipments in 1985 are summed, the individual risk is 1 in 9 million. This indicates that risks in the CPSR due to the transport of

This study provides a benchmark for risk studies of other regions in the areas of determining public safety levels, identifying primary contributors to risks and providing insights on general approaches to risk control. If additional regional studies of hazardous material transportation risks are undertaken, it is recommended that additional models be developed to determine risks to emergency response personnel and further refine uncertainty estimates for risk levels. The information provided by the additional models could be used in evaluating specific alternatives in emergency response planning, accident scene personnel training and hazardous material facility operations.

2.0 INTRODUCTION

A study of hazardous material (HM) transportation in the Central Puget Sound Region (CPSR) of Washington State (King, Kitsap, Pierce and Snohomish Counties) is being conducted by the Puget Sound Council of Governments (PSCOG) under a Cooperative Agreement with the U.S. Department of Transportation (DOT). The purpose of the PSCOG study is to develop effective and workable hazardous materials prevention and response systems for the CPSR, based upon the collaboration and cooperation of various levels of government, public agencies and the private sector. The study has four essential tasks:

1. Identify the types and amounts of hazardous cargo transported through the region by ship, rail, motor carrier, air, and pipeline
2. Evaluate the roles, responsibilities, and capabilities of agencies with hazardous materials prevention or response mandates
3. Survey federal and state programs elsewhere to determine their applicability to the Central Puget Sound Region
4. Develop options for a regional prevention and response plan based on the preceding analysis, and incorporate public responsibilities and resources requirements.

To develop options for the regional prevention and response plan, it is desirable to understand all potential impacts due to HM transportation. Accidental releases of material have occurred in the past in the CPSR, but these events have been rare. Historic information alone is not adequate to evaluate all potential public safety impacts or to evaluate changes in safety levels due to an improved response plan. Thus, a need for quantitative predictive public safety information was identified.

Battelle, Pacific Northwest Laboratories (BNW) has developed many quantitative safety assessment tools for the transportation of HM. These mathematical analysis techniques have been applied to nationwide shipments of propane (Geffen et al. 1980), chlorine (Andrews et al. 1980), gasoline (Rhoads et al. 1978) and nuclear materials.

relative safety levels can be used to rank alternative actions. Uncertainty analysis is also used in this step to determine the statistical significance of differences between alternatives.

In this study, public safety levels are quantified, and primary contributors to potential hazards identified for the transport of hazardous materials in the CPSR. Identification and evaluation of specific safety improvement actions could be used to support the implementation of results from the PSCOG regional planning study. This study provides a technical basis for additional studies to develop and evaluate specific emergency response procedures.

3.0 BATTELLE-NORTHWEST SAFETY ASSESSMENT METHODOLOGY

Two major public safety factors being considered in Puget Sound Council of Government's Study of hazardous material transportation are release sizes and frequencies and potential accident consequences. When public safety is quantified in terms of both release frequency and consequences, changes to the HM system can be evaluated on a consistent basis. Risk assessment techniques are well suited to this type of analysis and were selected for use in this study. Through the use of risk assessment, consequences of postulated releases of hazardous materials during transport can be put into perspective by viewing the events relative to their frequency of occurrence.

Risk, as used in the context of this report, is concerned with both the magnitude of a possible loss and the frequency of occurrence of the loss. There are two measures of risk that are of importance in a risk assessment. The first is the total risk, obtained by summing the product of magnitude and frequency for all potential losses associated with hazardous material releases from the system. In order to perform the summation, all losses 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 estimated 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 points of frequency versus magnitude. The risks associated with two activities are similar only if they have the same total risk and the same risk spectrum. Both risk measures are used in this report.

The risk assessment methodology described in this section was developed by Battelle, Pacific Northwest Laboratories and applied to the shipment of plutonium (McSweeney, Hall et al. 1975; Hall et al. 1977; McSweeney and Johnson 1976).

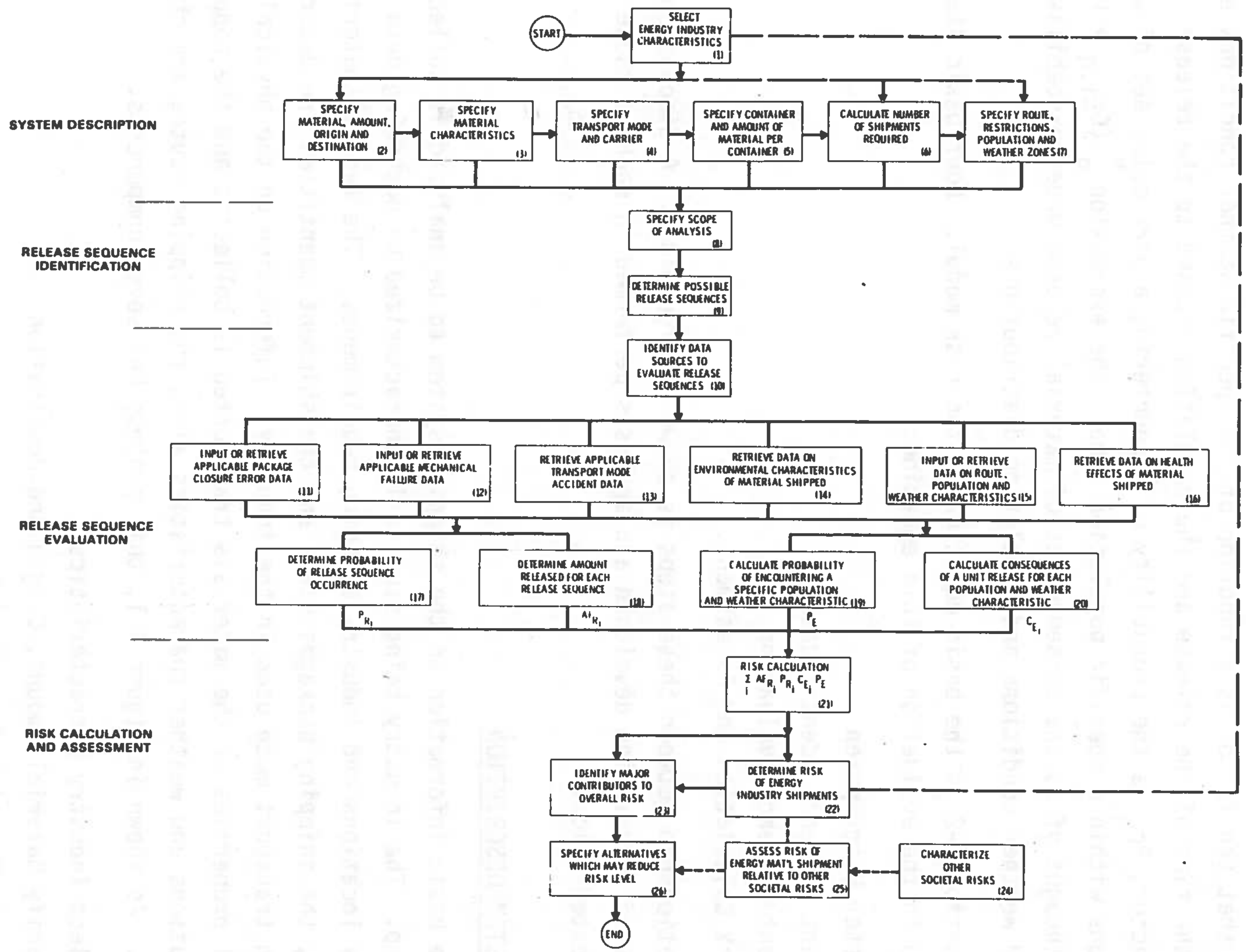

FIGURE 3.1. Model to Calculate the Risk of Shipping Hazardous Material

HM transportation and environmental conditions data used in this report are summarized in Sections 4 and 5.

3.2 RELEASE SEQUENCE IDENTIFICATION

Activities during this step identify possible sequences of events that can result in consequences to transportation workers or the general public during transportation of the hazardous materials being studied. The limits of the analysis are defined before these activities begin by specifying the kinds of events that will be considered during the event sequence identification step. For example, in this step one specifies whether loading and unloading accidents will be considered or if acts of sabotage are within the scope of the analysis.

Several methods are available for identifying event sequences. These methods are summarized briefly below. The method selected for application to a particular system depends on the complexity of the system, how comprehensive the analysis must be, and the availability of data to evaluate the event probabilities. A combination of these methods may also be employed.

- Historical Data/Experience. Sequences of events leading to a system failure are identified from historical data on accidents that have occurred with the shipping system being studied or similar systems.
- Direct Postulation. Event sequences are identified based on the judgment of an experienced analyst who examines the shipping system and postulates the failure modes directly.
- Deductive Reasoning. This is the "how can this happen" approach. Event sequences are identified by assuming that the undesired event has occurred and working backward to identify the sequences of events that must occur to cause this system failure. Fault tree analysis is a formalized way of performing these deductive reasoning processes.
- Inductive Reasoning. This is the "what happens if" approach. Event sequences are identified by starting with a system component failure and identifying the sequence of succeeding events that lead to a system failure. Event tree analysis is a formalized method for performing those reasoning processes.

and population conditions at the time of failure. The consequences of the failure may be determined by mathematical modeling, from historical accident data and/or from information on tests that have been conducted with the material being shipped. In general, consequences must be evaluated for each type of failure that can occur for each combination of weather condition and population distribution that can be encountered along the route. The probability of encountering the various population distributions and weather conditions along the route must also be determined.

The model uses relevant historical information to evaluate the probability of experiencing a given set of weather conditions and population characteristics. The P_E term in Equation 3-2 is the probability associated with the weather and population characteristics. The expanded form of this term is given:

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

The subscripts j, k, and l refer to the multiplicity of environmental conditions that 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} wind speed exists. The variable P_k is the probability of encountering the k^{th} wind speed category. The variable P_l is the probability of encountering a specified population distribution.

3.4 RISK CALCULATION AND ASSESSMENT

The information developed in the previous steps is used to calculate the risk for the shipping system being studied. Both the total risk and a risk spectrum are calculated. The results are then analyzed to determine the primary contributors to the risk and to specify and evaluate alternatives that could reduce the system risk, if the current risk is judged by society to be unacceptable. Since the information to perform the risk assessment has been developed in discrete data blocks, sensitivity studies can also be carried out to test the effect on the system risk of assumptions and approximations that were made to develop key pieces of information. This may identify areas where further analysis is required or delineate the limitations of the assessment.

4.0 HAZARDOUS MATERIAL TRANSPORTATION IN THE CENTRAL PUGET SOUND REGION

The PSCOG (1980) selected 95 commodities that are shipped in the CPSR to obtain shipping volumes and characteristics for all transportation modes. These materials were selected based on the following criteria:

1. Materials that will be transported and/or stored in bulk or large quantities within the four-county region. The hazardous materials are classified by Department of Transportation proper shipping names and classes (examples: Corrosives, Flammable Liquids).
2. Materials that, if not contained, may cause unacceptable risks to human life within a specified area adjacent to the spill and will, consequently require evacuation.
3. Materials that, if spilled, could cause unusual risks to emergency response personnel responding on-scene.
4. Materials that, if involved in a fire, will pose unusual risks to fire-fighting and law enforcement personnel.
5. Materials requiring unusual storage and/or transportation conditions to assure safe containment.
6. Materials requiring unusual treatment, packaging, or vehicles during transportation to assure safe containment.

Table 4.1 is a complete listing of the PSCOG HM transportation commodities.

Results of extensive field work with HM shippers, carriers and receivers by the PSCOG indicated that rail, truck and marine transport modes are the most important in the CPSR. A comprehensive risk assessment of each commodity and mode would identify potential safety problems specific to each. However, resources to conduct such a study would exceed those provided for this project. Thus, it was decided to limit the scope of this risk assessment to five commodities shipped primarily in bulk: chlorine, LPG, methanol, motor fuel anti-knock compound and sodium hydroxide.

TABLE 4.1. (contd)

DOT CLASS	PROPER SHIPPING NAME	U.N. NUMBER
COMBUSTIBLE LIQUID	FUEL OIL	1993
	KEROSENE	1223
	PETROLEUM DISTILLATE	1268
FLAMMABLE SOLIDS	CALCIUM CARBIDE	1402
	LITHIUM METAL	1415
	MAGNESIUM METAL	2793
	NITROCELLULOSE (Wet with not less than 20% water)	1555
	PHOSPHORUS, AMORPHOUS RED	1338
	PHOSPHORUS, WHITE OR YELLOW (dry or wet)	1381
	POTASSIUM METAL	2257
	RUBBER SCRAP OR BUFFINGS	1345
	SODIUM METAL (or metallic)	1428
OXIDIZERS	BARIUM NITRATE	1446
	CALCIUM NITRATE	1454
	POTASSIUM NITRATE	1486
	SODIUM NITRATE	1498
	BARIUM CHLORATE	1445
	CALCIUM CHLORATE	1452
	SODIUM CHLORATE	1495
	CALCIUM PERMANGANATE	1456
	POTASSIUM PERMANGANATE	1490
	ZINC PERMANGANATE	1515
	CALCIUM PEROXIDE	1457
	CHROMIC ACID MIXTURE (dry or solid)	1463
ORGANIC PEROXIDE	BENZOYL PEROXIDE	2085
	ORGANIC PEROXIDE LIQUID OR SOLUTION, NOS	2756
	ORGANIC PEROXIDE SOLID,NOS	N/A
	PARAMENTHANE HYDROPEROXIDE	2125
	SUCCINIC ACID PEROXIDE	2135
POISON A	CYANOGEN	1026
	HYDROCYANIC ACID/HYDROGEN CYANIDE	1051
	NITROGEN PEROXIDE LIQUID	1067
	NITROGEN TETROXIDE LIQUID	1067
	PHOSGENE	1076
	POISON LIQUID OR GAS, NOS	9035

TABLE 4.2. Commodities Selected for Risk Assessment in Central Puget Sound Region (1979)

DOT Class	Rail Tons/Yr	Truck Tons/Yr	Representative Material	Class Fraction of Total (%)	Commodity Fraction of Class (%)	Commodity Fraction of Total (%)
Explosives	3,430	--	--	--	--	--
Non-flammable	112,247	45,996	Chlorine	8.4	60	5.0
Flammable Gas	100,758	13,415	LPG	6.0	97	5.8
Flammable Liquids	50,341	710,586	Methanol	40.0	5	2.0
Combustible Liquids	863	470,397	--	--	--	--
Flammable Solids	421	--	--	--	--	--
Oxidizers	0	7,395	--	--	--	--
Poison B	13,108	--	Motor Fuel Anti-knock Compound	0.7	32	0.22
Radioactive Material	660	--	--	--	--	--
Corrosives	203,557	157,414	Sodium Hydroxide	19.1	75	14
Total	485,400	1,405,200	--	74.	--	27

4.1 RAIL TRANSPORT OF SELECTED HAZARDOUS MATERIAL IN THE CENTRAL PUGET SOUND REGION

All five of the commodities selected from the PSCOG data for risk assessment are transported by rail. Based on flow information summarized from the PSCOG report (1980) by the Transportation Systems Center (Glickman and Woodman 1980), it was decided to divide the Central Puget Sound Region into eleven subregions that tend to be homogeneous with regard to HM flow. TSC accounted for the various levels of shipping activity in the CPSR rail system by defining a network of 15 links. These links are shown in Figure 4.1. There are no rail links in subregion 7. Highway links in this subregion are discussed in Section 4.2. Subregions 5A and 10A were defined to consider intracity shipments in Seattle and Tacoma respectively.

Table 4.3 is a listing of annual HM shipments in the CPSR by commodity and rail transport link. Based on annual shipment volumes, these commodities can be ranked: LPG, methanol, chlorine, sodium hydroxide and motor fuel anti-knock compound.

TABLE 4.3. Annual Rail Shipments of Selected Hazardous Materials in the Central Puget Sound Region (1979)

Rail Segment	Commodity: Methanol	LPG	Sodium Hydroxide	Motor Fuel Anti-knock Compound	Chlorine
1	709	2,124	0	137	588
2	147	0	329	22	79
3	856	2,120	329	131	645
4	856	2,091	178	132	644
5A	0	0	0	0	0
B	858	1,990	256	132	732
6A	858	1,983	256	132	734
B	718	1,870	256	132	936
8A	0	366	0	0	2
B	0	118	0	0	209
9A	718	1,819	256	132	936
B	1	13	5	0	25
10A	0	0	137	0	0
B	656	1,665	2,051	130	1,206
11	0	9	0	0	72

Table 4.4 is a description of transportation systems assumed to be used for the rail transportation of the selected commodities in the CPSR. While actual tank car fleets may vary in capacity, the capacities used in the risk analysis are the upper limit of existing cars and are therefore a conservative representation of potential HM hazards. All tank cars are built to U.S. Department of Transportation specifications and have capacities from 150,000 lbs to 205,000 lbs.

4.2 TRUCK TRANSPORT OF SELECTED HAZARDOUS MATERIALS IN THE CENTRAL PUGET SOUND REGION

Only two of the five commodities selected for risk assessment from the PSCOG data are transported in appreciable volumes by truck in the CPSR: LPG and sodium hydroxide. To be consistent with the rail transport analysis described in Section 4.1, the highway system in the Central Puget Sound Region was also divided into

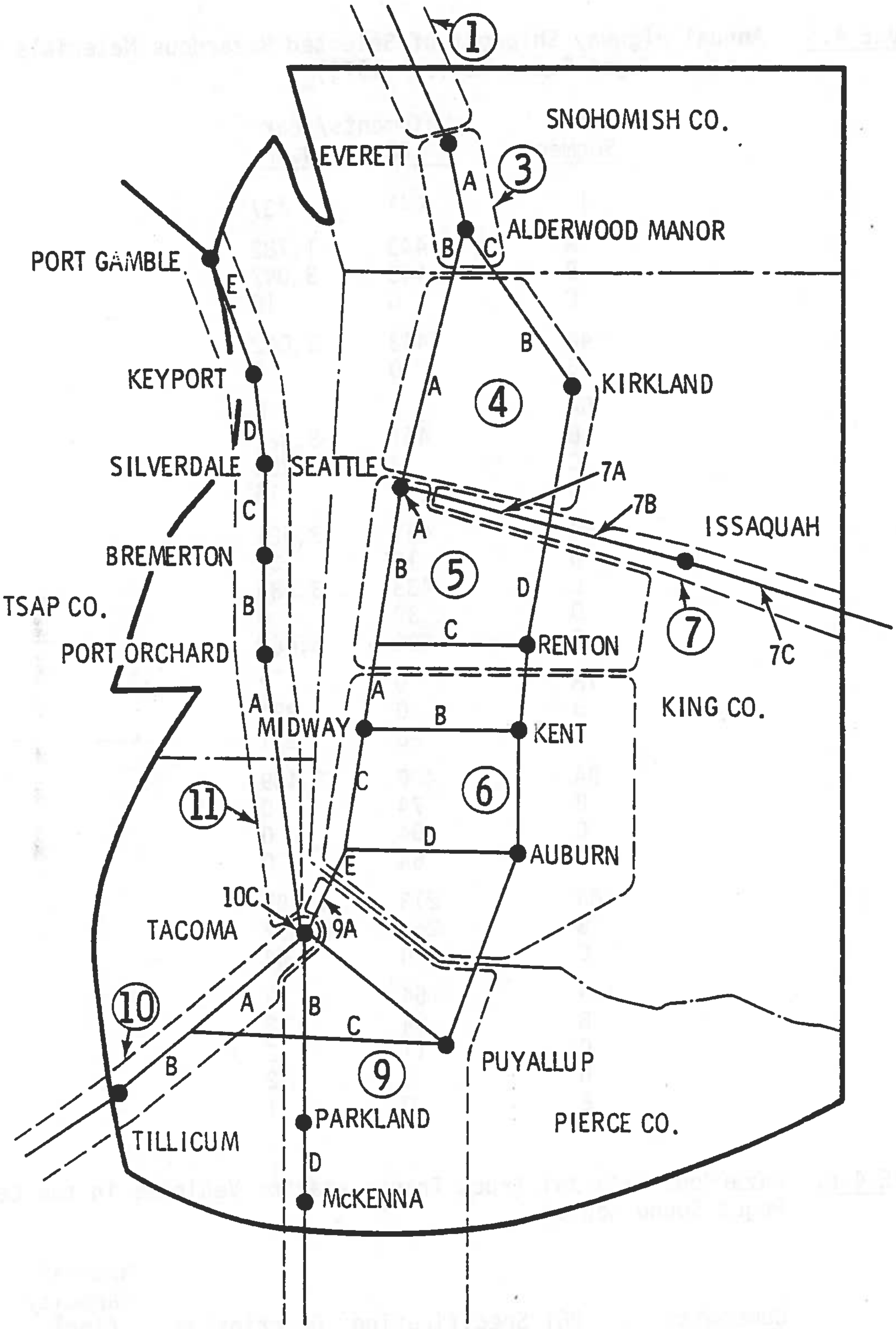

FIGURE 4.2. Central Puget Sound Region Highway System

5.0 CENTRAL PUGET SOUND REGION TRANSPORTATION ENVIRONMENT

The transportation environment in the CPSR is described in this study using available information on transportation accident rates, atmospheric conditions and population along transportation corridors. This section describes the allowed values of each parameter and the methodology used to generate their corresponding probabilities. All information in this section was used in Step 3 of the Battelle-Northwest risk assessment methodology: release sequence evaluation.

5.1 TRANSPORTATION ACCIDENT RATES

To predict the frequency of hazardous material releases in transportation accidents, information on accident frequencies, severities and the response of the shipping system to accident forces must be known. This section describes accident frequencies used for truck and rail transportation in the CPSR. No specific accident severity data was available for the CPSR. For this reason, information used in this study was developed from U.S. accident experience (Dennis 1978). Response of the transportation systems to accident forces is discussed in Section 6 of this report.

5.1.1 Rail Transportation Accident Rates

Historic accident experience in the CPSR was not adequate to generate rail accident rates for the transportation links. Thus it was assumed for this study that national accident rates are representative of the CPSR. Using information on accident rates and national statistics on the frequency of loaded rail cars, TSC indicated that a rate of 0.28×10^{-6} accidents per loaded car-mile (1.7×10^{-7} accidents/car-km) is representative of rail systems in the CPSR. This value was used for all rail transport links in this analysis.

Table 5.1 is a listing of all rail transport links defined in Section 4. Multiplying segment lengths in column 1 by the rail accident rate of 1.7×10^{-7} accidents per loaded car-km yields the accident rate per loaded car trip on each segment.

TABLE 5.2. Truck Transport Subregion Accident Rates[a]

Subregion	Subregion Length (km)	Accident Rate/ 10^6 Vehicle -km	Accidents/ Truck Trip
1	33	0.62	2.0×10^{-5}
3A	24	0.62	1.5×10^{-5}
B	9	0.62	5.6×10^{-6}
C	9	0.62	5.6×10^{-6}
4A	18	1.3	2.3×10^{-5}
B	21	0.62	1.3×10^{-5}
5A	6	1.9	1.1×10^{-5}
B	15	0.84	1.3×10^{-5}
C	6	0.62	3.7×10^{-6}
D	3	1.3	3.9×10^{-6}
6A	9	0.62	5.6×10^{-6}
B	6	1.9	1.1×10^{-5}
C	9	0.62	5.6×10^{-6}
D	6	0.62	3.7×10^{-6}
E	3	0.62	1.9×10^{-6}
7A	9	1.9	1.7×10^{-5}
B	12	1.5	1.8×10^{-5}
C	48	0.62	3.0×10^{-5}
9A	9	0.62	5.6×10^{-6}
B	9	4.3	3.9×10^{-5}
C	15	0.87	1.3×10^{-5}
D	24	4.3	1.0×10^{-4}
10A	12	1.2	1.4×10^{-5}
B	21	0.62	1.3×10^{-5}
C	3	1.9	5.7×10^{-6}
11A	39	3.6	1.4×10^{-5}
B	12	1.9	2.3×10^{-5}
C	12	0.62	7.4×10^{-5}
D	9	0.62	5.6×10^{-6}
E	18	1.9	3.4×10^{-5}

(a) Rate = (accident rate) x (subregion length)

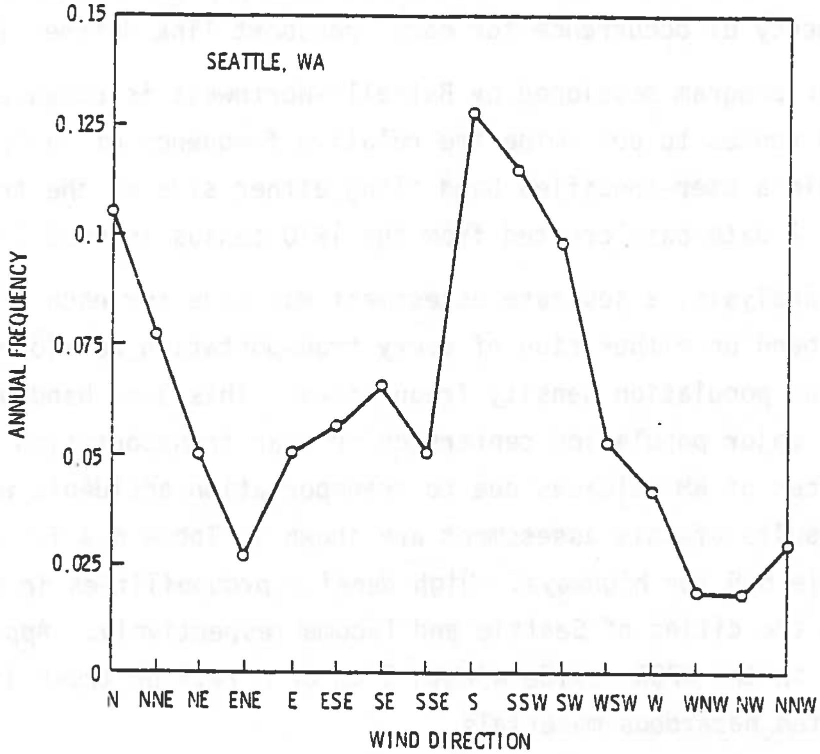

FIGURE 5.1. Relative Frequency of Wind Direction in Seattle

a frequency plot of wind direction in Seattle. Traveling to the east or west of population centers, if practical, rather than to the north or south could reduce the risk of some commodities up to 75%. A detailed assessment of this parameter for local conditions would be required to determine actual risk reductions. Data was not available to include wind direction in the risk model for this study.

5.3 POPULATION ALONG TRANSPORTATION CORRIDORS IN THE CENTRAL PUGET SOUND REGION

When areas of lethal effects have been calculated for releases of specific hazardous materials, they are assumed to be released in regions of constant population density. The product of area and population density represents a measure of potential consequences of a hazardous material release. When this potential number of fatalities is combined with weather probabilities and the

TABLE 5.5. Highway Population Densities

Highway Shipments Segment		Probability of Encountering Populations (persons/km^2)							
Number	Length (km)	0	1	10	100	500	1000	1500	2000
1	33	0.34	0.	0.22	0.44	--	--	--	--
3A	24	0.	0.	0.	0.42	0.57	--	--	--
B	9	0.	0.	0.	0.	0.50	0.	0.50	
C	9	0.	0.	0.	0.	1.0	--	--	--
4A	18	0.	0.	0.	0.	0.	0.	0.20	0.80
B	21	0.17	0.	0.	0.	0.68	0.17	--	--
5A	6	0.	0.	0.	0.	1.0	--	--	--
B	15	0.40	0.	0.	0.	0.20	0.40	--	--
C	6	0.	0.	0.	1.0	0.	0.	--	--
D	3	1.0	--	--	--	--	--	--	--
6A	9	0.	0.	0.	0.	1.0	0.	--	--
B	6	0.	0.	0.	1.0	--	--	--	--
C	9	0.	0.	0.33	0.67	--	--	--	--
D	6	0.	0.	0.	1.0	--	--	--	--
E	3	0.	0.	0.	1.0	--	--	--	--
7A	9	0.	0.	0.	0.50	0.50	--	--	--
B	12	0.	0.	1.0	--	--	--	--	--
C	48	0.93	0.	0.	0.07	--	--	--	--
9A	9	0.	0.	0.	1.0	--	--	--	--
B	9	0.	0.	0.	0.50	0.50	--	--	--
C	15	0.	0.	0.50	0.50	--	--	--	--
D	24	0.85	0.	0.	0.15	--	--	--	--
10A	12	0.	0.	0.	0.	0.33	0.67	--	--
B	21	0.66	0.	0.17	0.17	--	--	--	--
C	3	--	--	--	--	--	1.0	--	--
11A	39	0.33	0.	0.25	0.17	0.17	0.08	--	--
B	12	0.33	0.	0.33	0.33	--	--	--	--
C	12	0.25	0.	0.	0.75	--	--	--	--
D	9	0.50	0.	0.	0.50	--	--	--	--
E	18	0.20	0.	0.80	--	--	--	--	--

6.0 HAZARDOUS MATERIAL TRANSPORTATION CONSEQUENCE MODELS

This section describes assumptions, mathematical models and results of assessments to determine the public health impacts of transportation accidents that release hazardous materials. Separate subsections are provided for methanol, sodium hydroxide, chlorine, LPG and motor fuel anti-knock compound.

Consequence models described in this section use information describing conditions at potential accident locations in the CPSR to calculate a range of potential consequences due to HM releases. For materials that are sensitive to atmospheric conditions at the time of release, release size and atmospheric transport behavior are considered to estimate areas exposed to potentially fatal effects. For materials not significantly affected by atmospheric transport, fatality estimates are developed based on release sizes and the degree of contact hazard posed by the materials. Information in this section is combined in Section 7 with environmental information and shipping data from Sections 4 and 5 to calculate HM transportation risks for the CPSR.

6.1 METHANOL CONSEQUENCE ANALYSIS

Release probabilities and consequences for rail shipment of methanol were based on previous transportation risk analysis studies performed by Battelle-Northwest. Because the physical properties of methanol are similar to those of gasoline, release consequence models from PNL-2133 (Rhoads 1978) were used. These models were modified as necessary to account for the larger release sizes from a railroad tank car compared to the truck tanks analyzed in that study. Modifications were also made to account for the methanol releases occurring on railroad rights of way rather than highways and city streets used in the gasoline risk analysis study. Consequence estimates were made for methanol releases in both urban and rural areas.

Potential consequences from spills of methanol in urban areas include exposure of railroad personnel and fire fighters to fires and explosions, ignition of secondary fires in buildings near the accident location and exposure of people in nearby buildings to explosions. In rural areas, it was assumed that fires and explosions would affect only railroad workers and fire fighters.

TABLE 6.1. Estimated Consequences due to Methanol Releases

Estimated Fatalities (n)	P(n) Given that a Release Has Occurred		
	Consequences Due to Fire	Consequences Due to Explosion	
	Release in Urban Areas	Release in Rural Areas	Release in Urban Areas
1	1.9×10^{-3}	2.0×10^{-3}	2.3×10^{-3}
2	9.3×10^{-4}	1.0×10^{-3}	1.4×10^{-3}
3	1.2×10^{-4}	5.0×10^{-4}	7.0×10^{-4}
4	6.0×10^{-5}	3.0×10^{-4}	6.0×10^{-4}
5	4.5×10^{-5}	1.0×10^{-4}	4.0×10^{-4}
10	1.0×10^{-5}	1.0×10^{-5}	1.3×10^{-3}
15	3.3×10^{-6}	--	9.3×10^{-4}
20	--	--	7.9×10^{-4}
25	--	--	6.0×10^{-4}
30	--	--	4.0×10^{-4}
35	--	--	5.0×10^{-4}
40	--	--	5.0×10^{-4}
45	--	--	5.0×10^{-4}
50	--	--	5.0×10^{-4}
55	--	--	5.0×10^{-4}
60	--	--	5.0×10^{-4}
65	--	--	4.0×10^{-5}

TABLE 6.2. Release Frequency Estimates from Methanol Tank Cars

Release Mechanism	Probability, Given that an Accident Has Occurred
Impact Failure	
Tank Walls	3.6×10^{-4}
Tank End	3.3×10^{-4}
Puncture Failure	
Tank Walls	1.2×10^{-4}
Tank End	6.2×10^{-4}
Total	1.4×10^{-3}

A risk spectrum for methanol given that an accident has occurred is desirable for the risk calculations described in Section 7 of this report. Separate spectra are shown in Table 6.3 for urban and rural areas from Tables 6.1 and 6.2. The frequency of release given an accident in Table 6.2

can impair physical and mental performance and major exposures can produce respiratory problems and even blindness in some cases.

Consequence estimates presented for spills of methanol in railroad accidents are representative of consequences that could be expected from flammable liquid spills in general. Spills of other moderately volatile flammable liquids such as gasoline, alcohols, benzene, hexane, octane, methyl ethyl ketone, methyl methacrylate, toluene and acrolein would be expected to produce similar consequences. Highly volatile flammable liquids such as acetone, ether, carbon disulfide, ethyl chloride, pentane, propylene oxide and vinylidene oxide would also be expected to produce similar consequences, except that the chances of explosions or large vapor cloud deflagrations would be increased. Some of these materials such as benzene and acrolein also have toxic properties when inhaled, and ethyl chloride produces toxic combustion products, although the effects from fires and explosions are expected to be most important in releases of these materials.

6.2 SODIUM HYDROXIDE CONSEQUENCE ANALYSIS

This section discusses the consequences of a potential release of sodium hyroxide as a result of a rail, truck or marine accident.

6.2.1 Rail and Truck Transport

The probability of a release of sodium hydroxide (NaOH or caustic soda) in a rail or truck accident was estimated using the results of previous risk assessment studies performed at Battelle-Northwest for commodities carried in similar containers. NaOH is generally a semi-solid during transportation. Release consequences were estimated using selected portions of the consequence models from those studies together with information on the biological effects of exposure to sodium hydroxide. Tank cars used for rail shipments of NaOH are similar in construction to the tank cars used to carry methanol. NaOH cars are insulated and have heating coils that are used to raise the temperature of the cargo for easier unloading. These features do not significantly affect the response of the container to accident conditions. Therefore, the failure probabilities, developed previously for methanol tank cars (1.4×10^{-3} releases/accident) have also been used for NaOH cars.

summarized in Table 6.4. The overall risk from transporting these materials is obtained from the information provided in the table by combining it with data on accident frequencies from Section 5.

TABLE 6.4. Risks from Accidental Releases of Sodium Hydroxide During Truck and Rail Transport

Number of Fatalities (n)	Probability of n or More Fatalities, Given that an Accident Has Occurred	
	Truck	Rail
1	4.4×10^{-5}	1.5×10^{-8}
2	4.0×10^{-6}	1.4×10^{-9}
3	4.0×10^{-8}	1.4×10^{-11}

Consequence estimates and release probabilities presented for NaOH shipments should be representative of most materials in the corrosives class. These materials are all primarily contact hazards and are all transported in similar shipping containers.

6.2.2 Marine Transport

Marine accidents that result in large releases of NaOH could produce localized environmental damage, but are not expected to directly impact members of the public. A large NaOH release would be expected to dilute and dispense fairly rapidly in the ocean. Plant life and fish near the spill site could be killed during the period of time immediately following the spill when concentrations are high. Both the sodium and hydroxide ions are present naturally in sea water. Once the spilled NaOH has been diluted and dispersed, it should have no further harmful environmental effects.

6.3 CHLORINE CONSEQUENCES ANALYSIS

This section discusses the consequences of a potential release of chlorine as a result of a truck, rail or marine accident.

6.3.1 Truck and Rail Transport

Release probabilities and sizes for rail accidents involving liquid chlorine were developed in a previous risk assessment by Battelle-Northwest (Andrews et al. 1980). The primary pathway for a chlorine release to reach the public is

Five release categories were identifed from a fault tree analysis of chlorine tank car failure modes. These include:

- An instantaneous vapor release of 32% of the tank contents. The nominal release size for this release is 2.6×10^4 kg. This release could result from a catastrophic tank failure following exposure to a fire. Given that a transportation accident has occurred, this release size has a probability of 3×10^{-4}.
- An instantanous release of 17% of the tank contents. The nominal release size for this release is 1.3×10^4 kg. This release could result from a catastrophic tank failure at ambient temperature (21°C). This release size has a frequency of 6×10^{-3} per accident.
- A continuous release of 9.8 kg/sec. This represents a liquid discharge from a small opening in the tank shell. Flash vaporization from the release stream and vaporization from the material on the ground are included. This size release has a frequency of 6×10^{-5} per accident.
- A continuous release of 3.9 kg/sec. This represents a gaseous discharge from the relief valve at sonic velocity when the tank is involved in a fire. This release size is expected to occur in 6×10^{-3} of all accidents.
- Other small releases. These releases would result in small areas of toxic concentrations. It was assumed in this analysis that these releases were less than 0.1 kg/sec and have no consequences to the public.

Lethal areas were predicted using Gaussian atmospheric dispersion models modified for dense vapors. Areas used in this analysis are a function of atmospheric stability class, wind speed and release rates. They range from essentially no public hazard up to 7.2 km^2. An event covering areas of this magnitude is expected to occur once in 56,000 chlorine accidents in the CPSR.

Effective emergency response to chlorine spills can significantly reduce risk levels from this material. Response should include both protection of the public in surrounding areas and release control procedures. Public protection procedures for a chlorine spill are relatively straightforward. Chlorine

Chlorine is transported through the ports of Seattle, Tacoma and Everett. Standard barge shipments of 600 and 1200 tons are used (PSCOG 1980). Multiple tanks are provided for large barge shipments with capacities around 300 tons each.

For the purposes of this discussion, releases were divided into small and large. Small releases are anticipated to occur in loading/unloading operations from tank fixtures during transport and handling of less than bulk quantities. Onshore and shipboard chlorine handling equipment is designed to deal with this type of release. Therefore, no significant public consequences are anticipated.

Major releases of chlorine could arise from catastrophic events that cause major tank failures. In 1978 and 1979, 20 spills of hazardous chemicals were reported by the U.S. Coast Guard (USCG 1980). None of these incidents were in the Pacific region. Of the 20 incidents only 1 involved a chemical tank barge. Only 2 had releases in excess of 25 tons. From these statistics, it can be concluded that events causing large releases of hazardous chemicals are rare.

Consequences from a large release of chlorine in marine transport are potentially large. Liquid chlorine in contact with water will vaporize almost instantaneously. Thus, a major rupture of a 300-ton tank could result in an immediate release of 10 times as much vapor as the worst case rail accident.

Accidents at sea will be far enough from population centers to allow for significant dispersion before encountering land. The predominant North/South wind direction of the CPSR could help delay contact with the public. Water sprays could be used to help dispersion and sufficent time would be available to implement an evacuation plan. Successful evacuations have been carried out in response to chlorine barge accidents on the Mississippi River.

Based on the review of incidents in marine transport involving hazardous materials, it was concluded that large releases of chlorine with potential to impact public safety are very rare. While potential consequences from releases could be large, mitigation strategies such as water sprays and evacuation of onshore populations are available in a marine incident due to its relatively remote location. Once dispersed, chlorine vapor poses no long-term threat to the public or the environment. Marine transport of chlorine is not believed

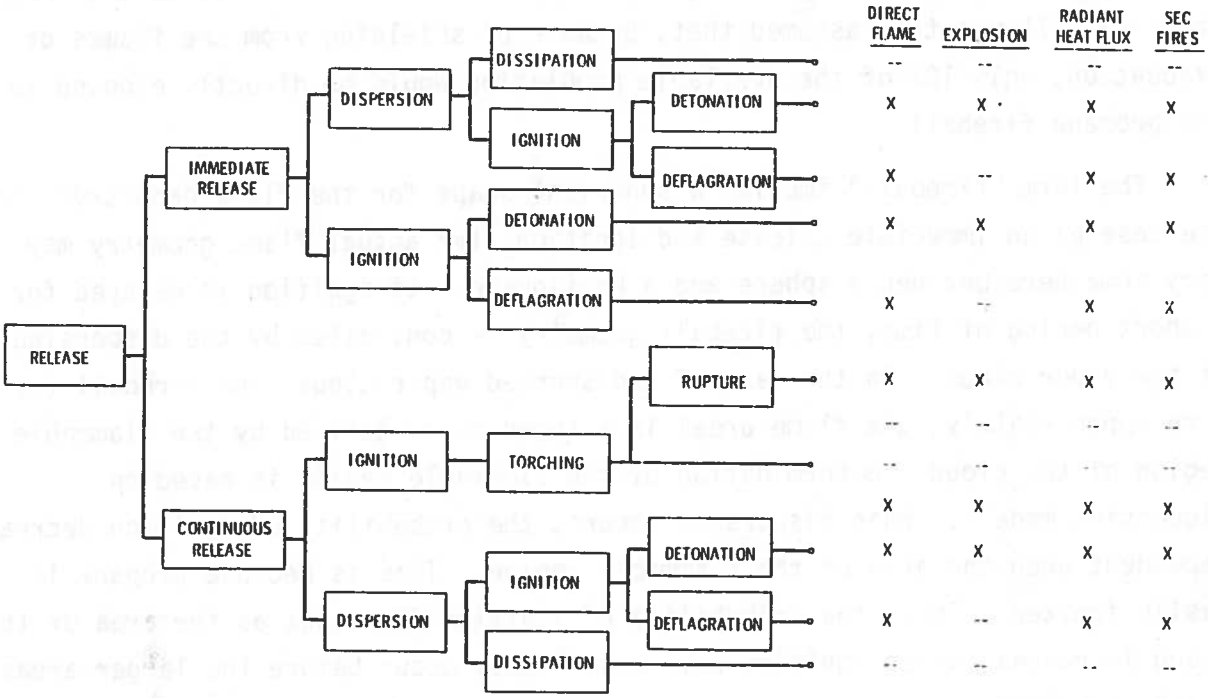

FIGURE 6.1. Propane Consequence Event Tree

The major health effects of the release scenarios considered in this analysis are direct flame exposure, explosion effects (overpressure and fragmentation), radiant heat flux, and secondary fires. The number of fatalities from each major health effect is estimated by determining a size and shape (range and geometry) for each effect and applying this information to population density information.

Typically, the general public does not reside immediately adjacent to major transportation rights of way. Thus, general public fatalities attributable to propane releases would occur at moderate distances from a release occurring on this pathway. To model this, a 15-meter exclusion zone on either side of the transportation right of way centerline was assumed for all releases.

It was assumed for this study that any person coming into direct contact with flames from a propane fire would not survive. However, portions of the general public will be shielded from the flames at the time of ignition by

Explosion effects were divided into two categories. These are overpressure and fragmentation. Overpressure effects are those deleterious effects caused by a radially expanding blast wave or pressure wave centered about the point of initiating energy release. The initiating energy release may be the result of chemical reaction or a mechanical reaction, hereafter referred to as a detonation or an explosive rupture, respectively. In this analysis, a chemical reaction, or detonation, refers to an explosion occurring after a vapor cloud has been formed. The flame front moves at supersonic speeds, creating pressure or shock waves. A mechanical reaction, on the other hand, refers to the explosion forces associated with tank rupture. The flame front moves at subsonic speeds (deflagration) and does not create pressure waves. Any shock wave or blast effects are a result of tank rupture. Fragmentation accounts for those effects caused by flying objects set in motion by the blast wave. The objects may be pieces of the propane tank or secondary objects in the neighborhood of the explosion.

Overpressure effects were estimated by assigning fatality percentages based on lines of constant overpressure magnitude (LCOM). It is assumed that 100% of the population within the 6.9×10^4 Pa LCOM will die. The 6.9×10^4 Pa limit was chosen because it defines the limit of probable total destruction. Areas inside the 1.7×10^4 Pa LCOM are assigned a fatality percentage of 10%. The 1.7×10^4 Pa limit was chosen because it represents the limit of serious structural damage. Distances to the 6.9×10^4 Pa and 1.7×10^4 Pa LCOM are found by calculating an equivalent TNT magnitude of the blast.

Fragmentation can also represent a significant explosion hazard. Fragments created during the rupture of a tank would most likely be portions of the tank itself. Although the direction of fragment flight is unknown, there would be a limited number of tank pieces that could act as missiles. Few people would actually be struck by the potential missile.

Fatalities from radiant heat were estimated by determining a distance from the fireball at which the threshold of second-degree burns exists. The threshold for second-degree burns was assumed to be 5 cal/cm^2. It is assumed that anyone within the area described by this distance will experience second-degree burns on all exposed surfaces. The amount of exposure would vary from person to

- An outflow of propane from activated safety relief valves in an accident where fire is present. This release was modeled as a continuous leak. Release rates of 5.23×10^{-2} m^3/sec for the tank truck and 1.04×10^{-1} m^3/sec for the rail tank car were used in this analysis.
- A small, continuous leak of propane in an accident situation with a fire present. The propane was assumed to be from a 2.5-cm diameter opening. A release rate of 9.16×10^{-3} m^3/sec was used.
- 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 of the tank are released almost immediately.
- 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 where 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.

Probabilities for each release category were developed based on statistical models of accident severity and calculations to predict propane tank response to transportation accident forces. Probabilities of release given a transportation accident for truck and rail transport of propane are given in Table 6.6.

TABLE 6.6. Propane Release Probabilities

Release Size (m^3/sec)	Probability of Release Given a Transportation Accident: Truck	Rail
1.96×10^{-2}	4.04×10^{-1}	6.47×10^{-1}
5.23×10^{-2}/1.04×10^{-2}	1.32×10^{-4}	1.86×10^{-4}
9.16×10^{-3}	1.41×10^{-2}	4.95×10^{-3}
Tank Contents-No Fire	9.16×10^{-3}	1.08×10^{-3}
Tank Contents-Fire Present	4.73×10^{-3}	5.64×10^{-4}

hazard to the public. MAKC is also flammable. A pool fire would increase release rates of vapor and poisonous combustion products.

Available toxicological information indicates that inhalation of 6 ppm concentrations is sufficient to cause death in rats. This represents a conservative level of fatal concentrations for acute exposures to releases from transportation accidents. For the purposes of this analysis, it was assumed that this concentration would cause death in 50% of those exposed.

Rail cars used to transport MAKC have characteristics similar to those of propane tank cars. For this reason, calculations were performed to determine their relative accident performance. While propane cars are roughly 3 times as large as the MAKC cars, the combination of density of the MAKC and wall thickness of the MAKC tank car make failure thresholds of propane and MAKC tank cars roughly equivalent. Based on this result, release categories defined for propane rail cars were assumed applicable to MAKC cars. Four release categories were used:

- A release from the car of 1×10^{-2} m^3/sec with fire present. Half of car contents were assumed released. This release has a probability of 5×10^{-3} per accident.
- A release of 9×10^{-3} m^3/sec with fire present. This release has a probability of 2×10^{-4} per accident.
- A release of the entire car contents with no fire. This release has a probability of 9×10^{-4} per accident.
- A release of the entire car contents with fire present. This release has a probability of 7×10^{-4} per accident.

A release duration was assumed to be 1 hour for all of the release categories. In the cases with fire present, this would be when all MAKC released from the tank car was consumed. If fire is not present, the release was assumed terminated by emergency response personnel. An evaporation rate of 2×10^{-4} g/cm^2 was assumed if fire was not present. Release rates and total releases for the four release categories are shown in Table 6.7.

Options to avoid exposure include evacuation and taking shelter. If the release is under control, shelter in available structures may be adequate. If evacuation is desirable, directions away from the spill should be given as MAKC vapor is not visible in low concentrations. Extensive spill site cleanup may be required prior to allowing public entry to avoid contact hazards. Once dispersed, MAKC vapor presents little hazard. It is a common air pollutant.

7.0 RISK OF TRANSPORTING SELECTED HAZARDOUS MATERIALS IN THE CENTRAL PUGET SOUND REGION

This section combines information presented in Sections 3, 4, 5 and 6 to calculate risk spectrums for the transport of hazardous material in the CPSR. Section 3 defined risk to be:

$$R = \sum_i P_i \times C_i$$

where R is total system risk, P_i are release event probabilities and C_i are the consequences of a hazardous material release.

For this study, P_i and C_i were calculated using the following relationships:

P_i = (Trips/Year) x (Accidents/Trip) x (Release/Accident) x (Weather Condition Probabilities) x (Population Density Probabilities)

C_i = (Lethal Area) x (Population Density) x (Evacuation Factor) x (Kill Rate).

The units of P_i and C_i are releases/year and deaths/release respectively. Each of the factors was evaluated for all hazardous materials, all release sizes and each subregion of the CPSR. All combinations of weather conditions that influence lethal areas and population density were evaluated to determine a distribution of consequences for each release size, location, and substance. The results of this calculation are presented in this section.

This section is divided into three subsections. The first presents total risk values (fatalities/year) and risk spectrums for each material considered in this study. The next section provides a discussion of sensitivity studies used to identify possible risk reduction strategies in the CPSR. The final section describes major conclusions from this study and identifies areas for further study.

corrosives. Results of this analysis indicate a total risk of 9.1×10^{-2} deaths per year, or one death every 11 years in the CPSR. This result indicates that the five commodities considered in this study are major risk contributors in the transport of HM by truck and rail in the CPSR.

Section 5 calculated that approximately 700,000 persons live within 3 km of the rights of way considered in this study. Based on this number, the annual average probability of an individual being killed by transport of the selected hazardous materials is 9.6×10^{-8}/year. This value is compared to average individual risks for other activities in the U.S. in Table 7.2. If the total U.S. values for chlorine and LPG are summed, the individual risk is 1.1×10^{-7}/year. This indicates that risks in the CPSR due to the transport of these materials are about the same as national averages. The risk of being killed due to accident forces in a transportation accident is 25,000 times greater than the risk of the hazardous nature of the cargo for motor vehicle transport and 40 times greater than the cargo risk for rail transport. The average individual risk is very low when compared to all accidental deaths in the U.S.

Figures 7.1 through 7.5 present risk spectra for individual commodities shipped in the CPSR. Similar spectra for each subregion are contained in Appendix A of this report. The vertical axis on each risk spectrum is the probability of an event causing n or more fatalities in one year. The horizontal axis is the number of fatalities from a hazardous material release. For example, in Figure 7.1, the probability of killing 5 or more persons in a single event involving LPG by truck is once in 1600 years.

The position of the risk spectrum on the vertical axis is determined by shipping volumes, distance traveled in the subregion, accident rates, and the probability of a release given an accident. Lowering of any of these factors will lower the position of the risk spectrum. Curve positions for Figures 7.1 through 7.5 range from events causing 1 or more deaths every 500 years for LPG by truck to once every 1.5 billion years for sodium hydroxide transport by rail.

The maximum consequence on a risk spectrum is determined by the maximum area of lethal concentration, maximum population density and assumed emergency

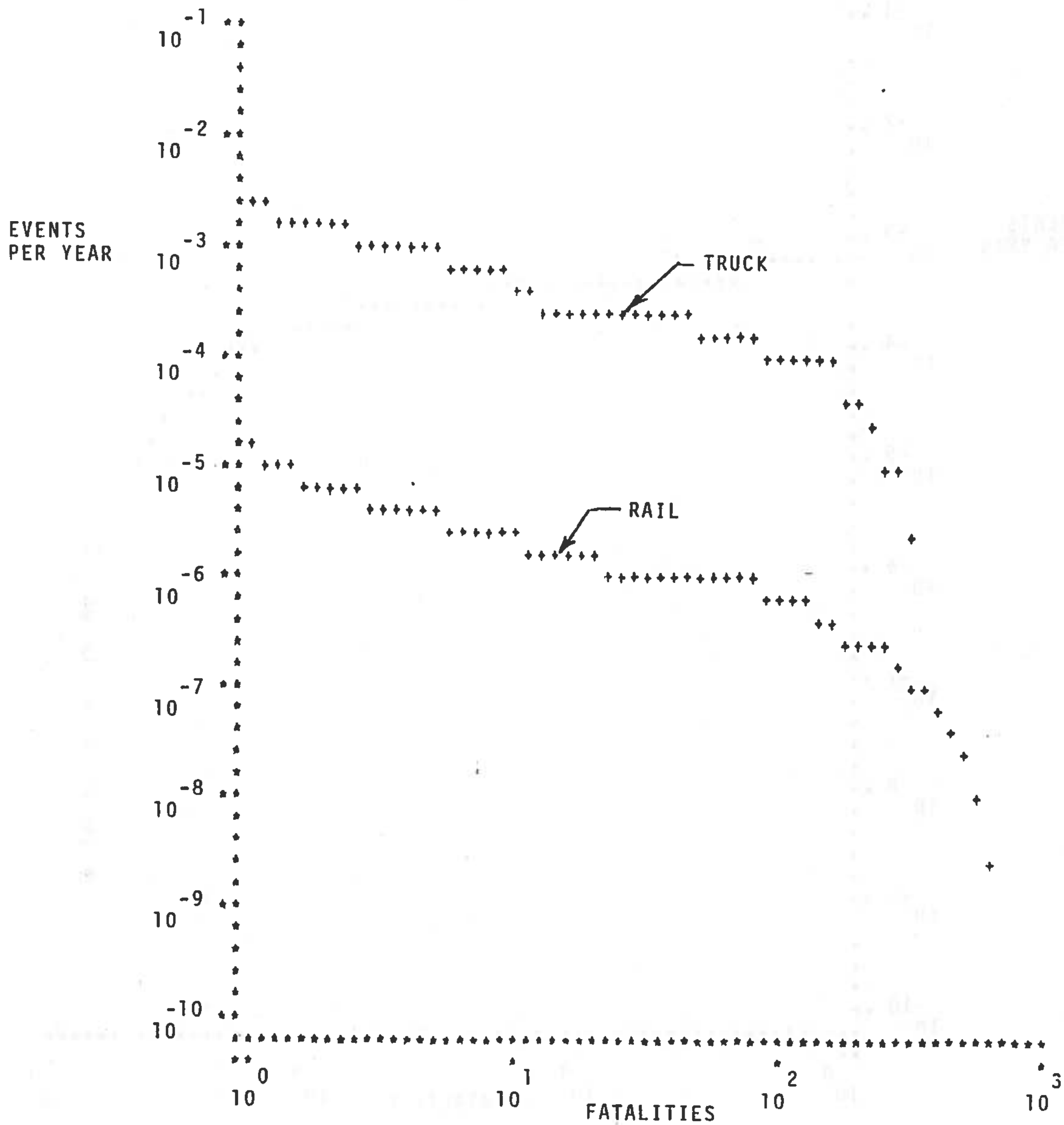

FIGURE 7.1. Risk Spectra for the Transport of LPG in the CPSR

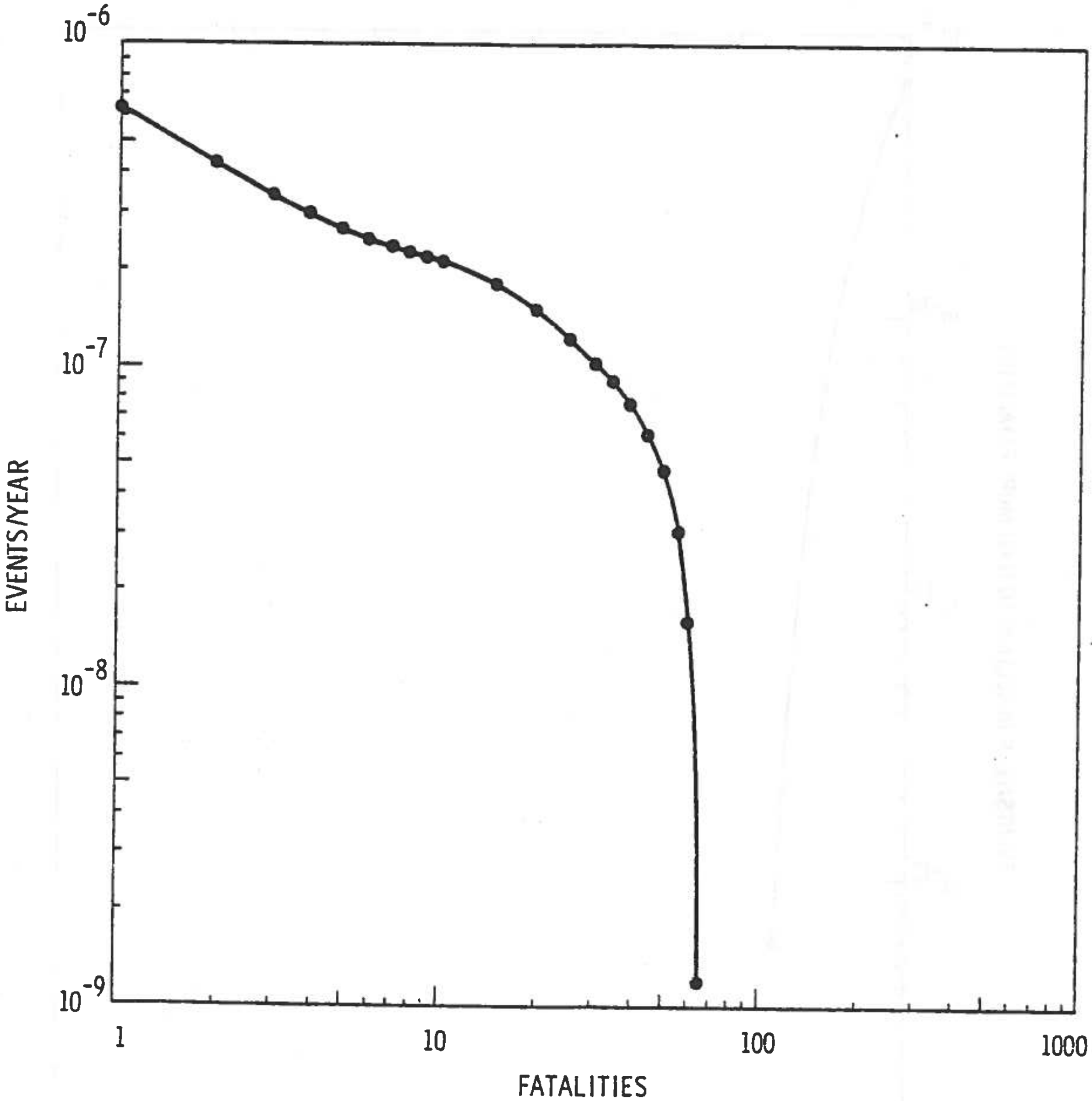

FIGURE 7.3. Methanol Risk Spectrum for Rail Transportation in the Puget Sound Region

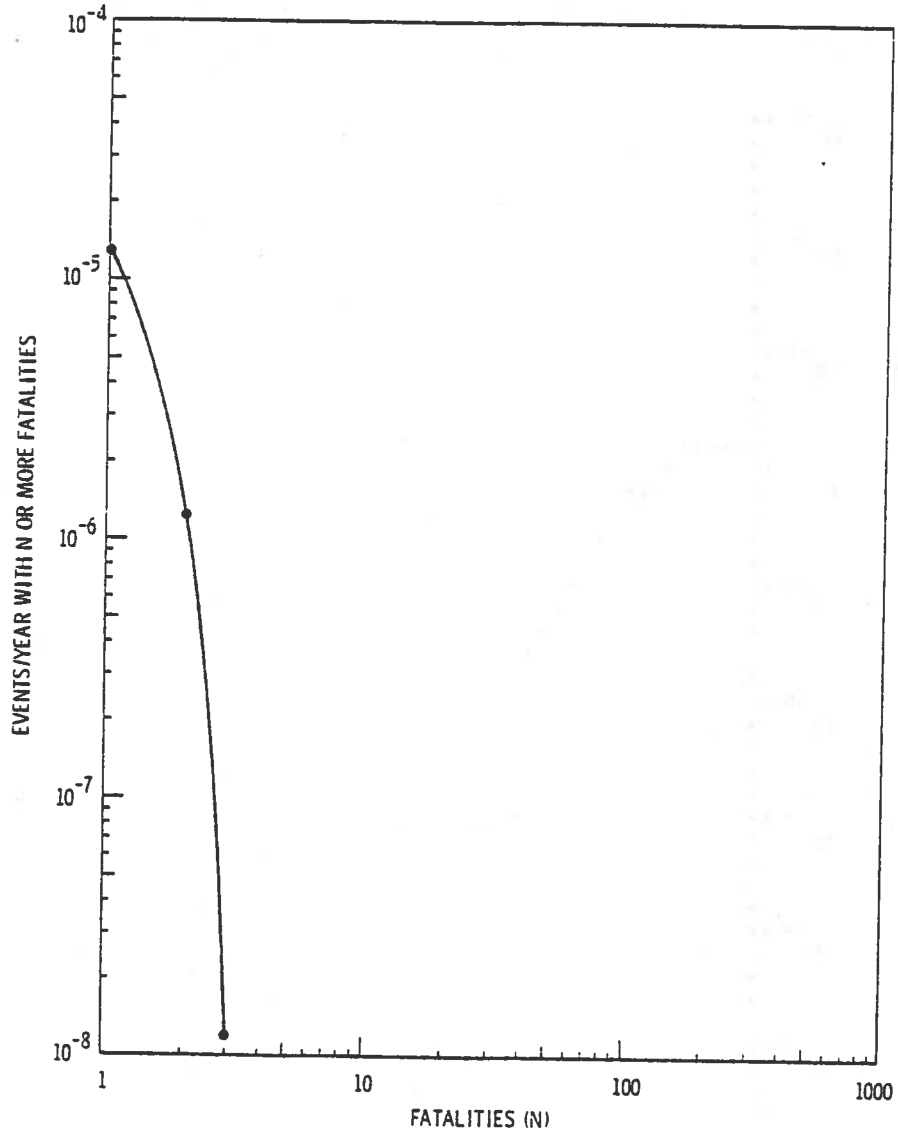

FIGURE 7.4b. Risk Spectrum for NaOH Shipments by Truck in the Central Puget Sound Region

The shape of the risk spectrum is determined by the relative frequency of large spill sizes, environmental conditions and population densities at the spill site. Given a spill location, population and environmental conditions are not controllable. Thus, to alter the shape of a risk spectrum, the probability of a large release size must change. Decreased probabilities will cause the slope of the curve to become steeper. Routing could be used to control accident location. Avoiding areas of high population or local conditions that intensify consequences would have the same effect as preventing large releases on the shape of the risk spectrum. Risk spectra for the CPSR generally indicate a rapidly decreasing chance of catastrophe.

Figure 7.6 presents the risk spectra for transporting hazardous material in the CPSR by truck and rail. The truck and rail curves are for only the commodities considered in this study. A spectrum is also shown for the total of truck and rail transport of the five commodities. The final spectrum is an estimate for all hazardous materials considered in the PSCOG study. The rail/truck risk spectra exhibit a crossover point at the consequence level of 12 fatalities. Below this level, truck risk dominates and above it rail is the largest contributor to total risk. That is, events involving truck transport are more likely to cause fewer fatalities than events involving rail transport. Both the truck and rail curves exhibit characteristics of their primary contributors: propane and chlorine respectively.

The risk spectrum for all CPSR hazardous material transportation considered in this study predicts an event with one or more fatalities on the average of once in 400 years. This declines relatively rapidly to events with 10 or more fatalities predicted every 1400 years.

The risk spectrum for all hazardous materials transported in the CPSR was developed by ratioing results of the five commodities considered in this study in the same way that was used to make a total risk estimate for the region. This curve predicts an event with one or more fatalities every 380 years. Events with 10 or more fatalities are predicted every 1100 years.

Figure 7.7 is included for comparison between risk spectra in the U.S. and hazardous material transportation in the CPSR. It shows that many man-caused

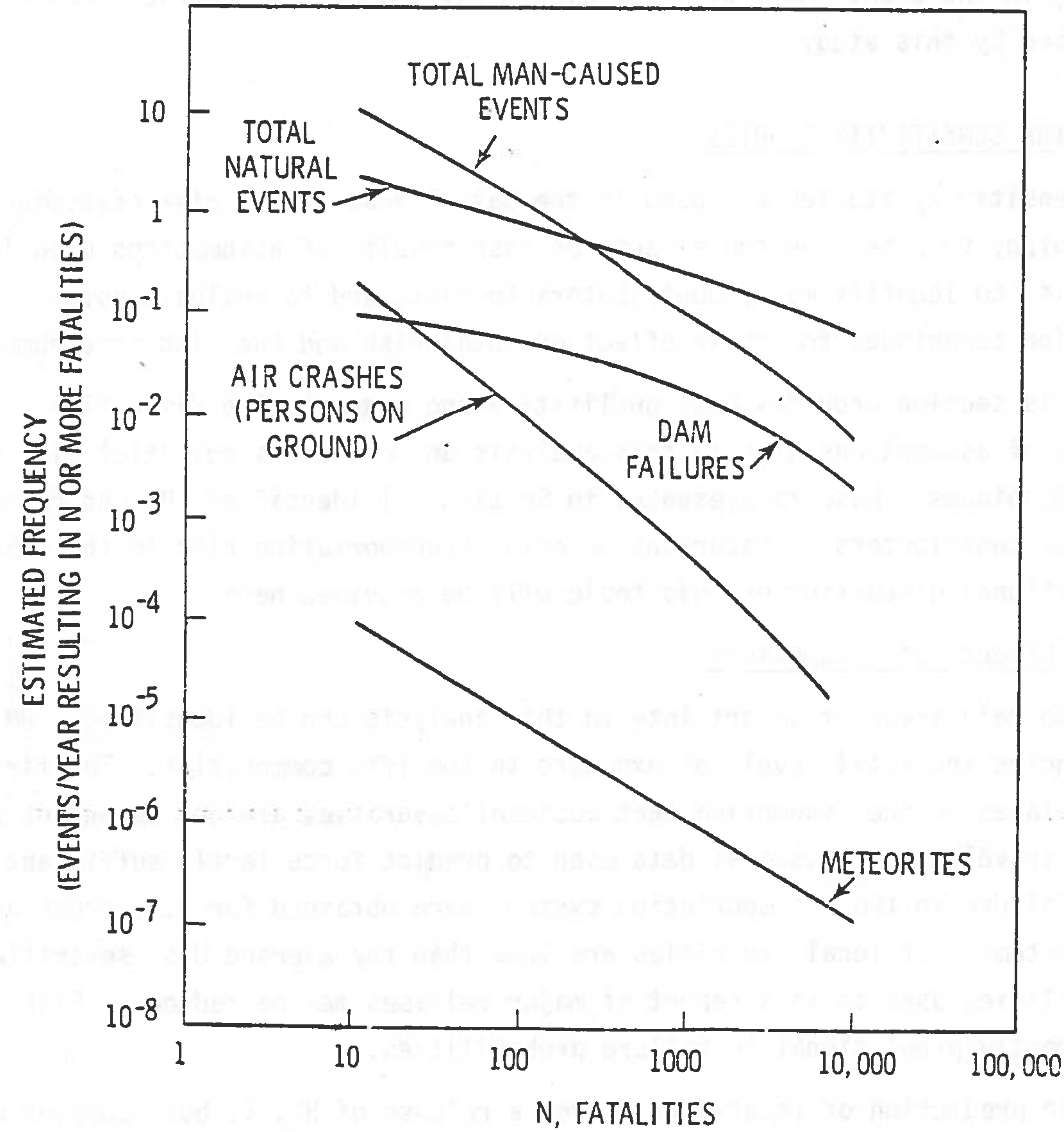

FIGURE 7.7. Risk Spectra for the Entire United States (WASH-1400)

areas was assumed. Chlorine risk levels are directly proportional to this factor. If a 95% evacuation were accomplished, chlorine risk would drop by 50% and risk levels in the CPSR would decline by almost 25%.

It is believed, based on comparisons with other risk assessment methodologies applied to chlorine transportation (Andrews et al. 1980) and historic data for other substances, that the Battelle-Northwest risk assessment methodology will yield conservative overestimates of public safety levels. Similar studies done by Battelle-Northwest for the entire U.S. indicate the relatively high level of safety that transport of hazardous material has achieved. The results of this study are consistent with these previous conclusions.

7.2.2 Risk Reduction Potential

Methods to reduce risk through consequence mitigation are qualitatively discussed under emergency response for specific commodities in Section 6. The effect of these emergency response procedures on the risk spectra is discussed in Section 7.1. In general, a reduction in release rates and less importantly release duration will reduce risk levels. This is due to the physics of atmospheric transport of pollutants and the energy available in combustion processes. Additional modeling could be used to evaluate changes in risk levels for specific emergency response procedures, but was beyond the resources of this study.

A second area of risk reduction technique is release and consequence prevention. Release prevention could address modifications to transport vehicles and alternative operating practices to avoid tank failures. These parameters are within the control of the U.S. Department of Transportation. For the purposes of this study, no specific regional problem in packaging has been identified, so it was decided not to study this area of risk reduction further.

Consequence prevention in this report means operating practices to avoid areas of high potential consequences in shipping hazardous material, assuming a release will occur. Rerouting of LPG shipments by truck to avoid the Seattle area is examined in the following representative example of this strategy.

Section 4 indicates a large number of LPG through shipments by truck through Seattle. These shipments flow from Alderwood Manor to north of Midway along Interstate Highway 5. In this study, the road segments were called 3B,

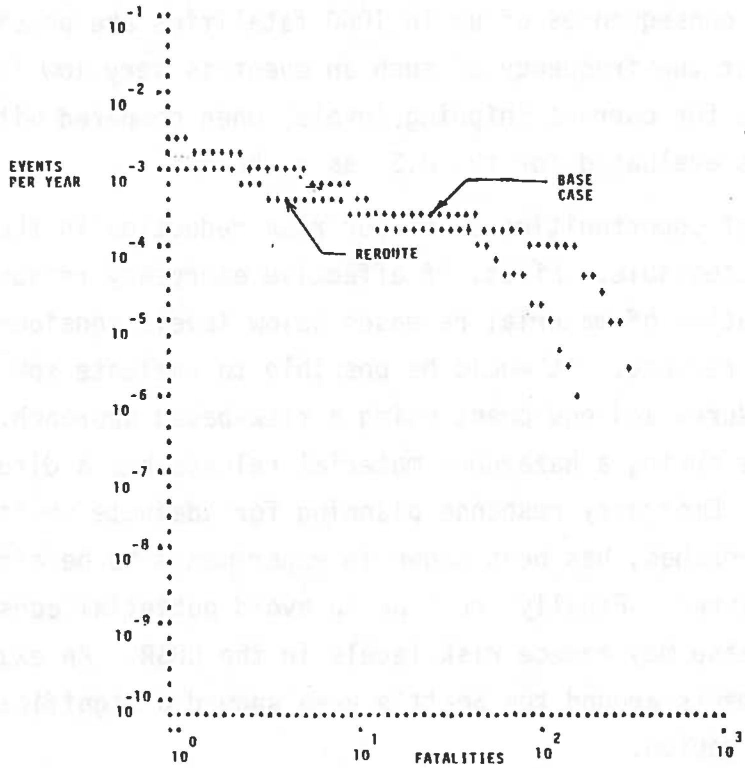

FIGURE 7.8. Risk Spectra for Rerouting Truck Shipments of LPG to Avoid Seattle

7.3.1 Conclusions

The scope of this study was limited to considering only transport of five commodities by truck and rail. Air shipping volumes are sufficiently low to preclude major risk contributors. Marine transport was examined in a cursory manner and appear to present relatively lower hazards. Pipeline transport was not addressed. Other commodities such as gasoline and anhydrous ammonia are shipped in sufficient quantity in the CPSR, but could not be specifically addressed with the resources available for this study.

Results of this study indicate that the expected numbers of fatalities or total risk due to the transport of the commodities considered in this report is low. The average individual living within 3 km of a transport route, has an annual risk of about 1 in 10 million of being killed due to the hazardous nature of these materials. This is comparable to similar previous results for the entire U.S.

levels, identify major risk contributors and evaluate the effect of risk reduction strategies. This study provides a benchmark for future studies in these areas.

Second, development of additional risk assessment modeling to examine detailed emergency response procedures is recommended to be used in planning, training and determining risk levels for emergency response personnel. The consequence models used in the current study provide insight on the range and frequency of hazardous material consequences as a function of environmental parmeters at the accident site. Mathematical models of emergency response procedures could be combined with existing consequence models to evaluate reductions in public safety and to quantify the risks to on-scene personnel participating in specific release mitigation actions. Similar models could also be used to compare emergency response equipment performance and identify needs for specialized training.

Finally, in support of decision making processes, uncertainties in risk levels should be examined. This study uses sensitivity studies to identify and evaluate major risk contributors. Rigorous statistical analyses could be performed on the data used in this analysis to quantify error estimates. Statistical significance could then be determined for comparisons between relative risk levels and alternative risk reduction strategies.

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APPENDIX A

SUBREGION RISKS OF TRANSPORTING SELECTED HAZARDOUS MATERIALS IN THE CENTRAL PUGET SOUND REGION

This Appendix is divided into two sections. The first contains a table of total risks for each commodity, transport mode and subregion. The second contains corresponding risk profiles.

A.1 TOTAL RISK IN SUBREGIONS OF THE CENTRAL PUGET SOUND REGION

Table A.1 contains total risk values for each subregion and commodity considered in this study. In general, risk levels for the transport of hazardous materials in the CPSR are low. Chlorine has the highest total risk with 1 death expected every 28 years. LPG by truck has the second highest risk level. One death is expected every 32 years.

Table A.1 shows subregions 3, 4, 5 and 10 to have the highest risk levels in the CPSR. This is due to the high population densities and hazardous material flows in these areas. Average individual risk for persons living within 3 km of a transportation right of way is more uniform than risk measured by deaths per year, with region 10 being the highest.

A.2 RISK PROFILES

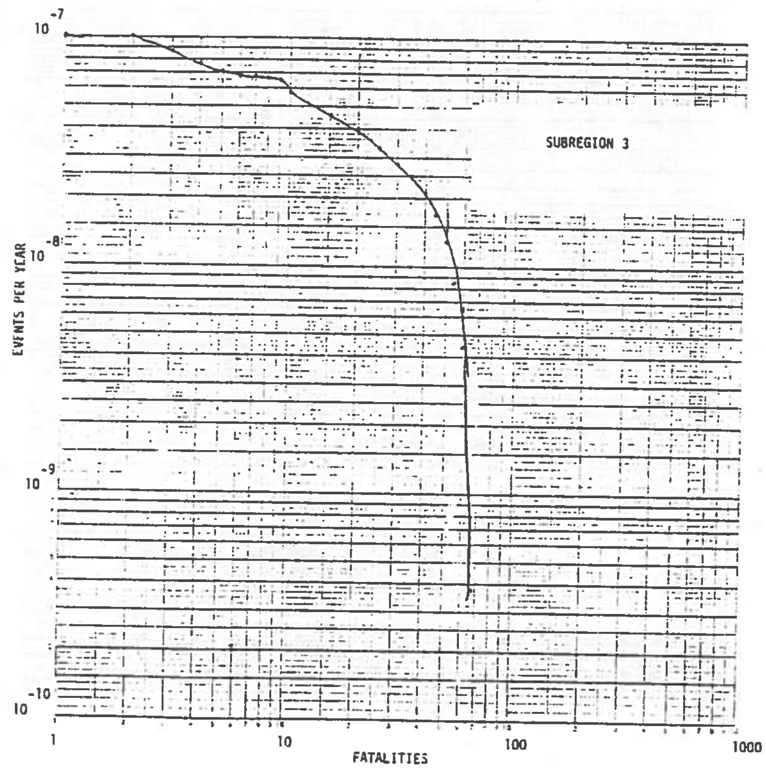
Figures A.1 to A.14 contain risk profiles for each subregion in the CPSR, transport mode and hazardous material considered in this study. Plots for sodium hydroxide have been combined into a single figure for each mode due to the low risk levels and similarity in consequences. Plots for Motor Anti-knock Compound in regions 3 and 9 were too small to draw on the axes.

The vertical axis on the risk spectra is the probability of an event causing n or more fatalities in one year. The horizontal axis is the number of fatalities from a hazardous material release. For example, in Figure A.1a, the probability of killing 5 or more persons in a single event involving methanol in subregion 1 is once in 100 million years, obviously a very low number.

TABLE A.1. Total Subregion Risks for the Central Puget Sound Region (deaths/years)

Commodity and Transport Mode	Subregion Number (See Section 4) 1	2	3	4	5	6	7	8	9	10	11	Total
LPG												
Truck	3.7×10^{-4}	0	4.1×10^{-3}	1.8×10^{-2}	2.6×10^{-3}	1.4×10^{-3}	0	0	1.1×10^{-3}	2.3×10^{-3}	1.3×10^{-3}	3.1×10^{-2}
Rail	6.9×10^{-6}	0	5.0×10^{-5}	4.6×10^{-5}	3.1×10^{-5}	1.5×10^{-5}	0	3.6×10^{-7}	4.8×10^{-6}	6.0×10^{-5}	4.6×10^{-9}	2.1×10^{-4}
Chlorine												
Rail	7.2×10^{-4}	2.6×10^{-5}	5.7×10^{-3}	5.3×10^{-3}	4.2×10^{-3}	2.1×10^{-3}	0	1.0×10^{-4}	1.9×10^{-3}	1.6×10^{-2}	1.4×10^{-5}	3.6×10^{-2}
Sodium Hydroxide												
Truck	4.3×10^{-7}	0	2.1×10^{-6}	3.5×10^{-6}	2.1×10^{-6}	2.3×10^{-6}	5.9×10^{-7}	0	9.4×10^{-7}	2.2×10^{-6}	2.6×10^{-7}	1.4×10^{-5}
Rail	0	1.5×10^{-10}	5.4×10^{-11}	1.6×10^{-11}	3.0×10^{-11}	2.7×10^{-11}	0	0	2.7×10^{-11}	4.3×10^{-10}	0	7.3×10^{-10}
Methanol												
Rail	3.0×10^{-7}	3.9×10^{-8}	2.0×10^{-6}	1.2×10^{-6}	1.3×10^{-6}	8.7×10^{-7}	0	0	3.0×10^{-7}	1.6×10^{-6}	0	7.6×10^{-6}
Motor Anti-knock Compound												
Rail	1.3×10^{-6}	5.6×10^{-8}	9.0×10^{-5}	8.4×10^{-6}	5.9×10^{-6}	2.9×10^{-6}	0	0	6.3×10^{-7}	1.4×10^{-5}	0	4.2×10^{-5}
Total	1.1×10^{-3}	2.6×10^{-5}	9.9×10^{-3}	2.3×10^{-2}	6.8×10^{-3}	3.5×10^{-3}	5.9×10^{-7}	1.0×10^{-4}	3.0×10^{-3}	1.8×10^{-2}	1.3×10^{-3}	6.7×10^{-2}
Average Individual Risk (Probability of death/yr)	1.2×10^{-7}	6.0×10^{-9}	7.8×10^{-8}	8.7×10^{-8}	1.0×10^{-7}	8.9×10^{-8}	3.1×10^{-11}	1.1×10^{-8}	1.0×10^{-7}	2.4×10^{-7}	2.4×10^{-8}	9.5×10^{-8}

Subregion 3



Subregion 4

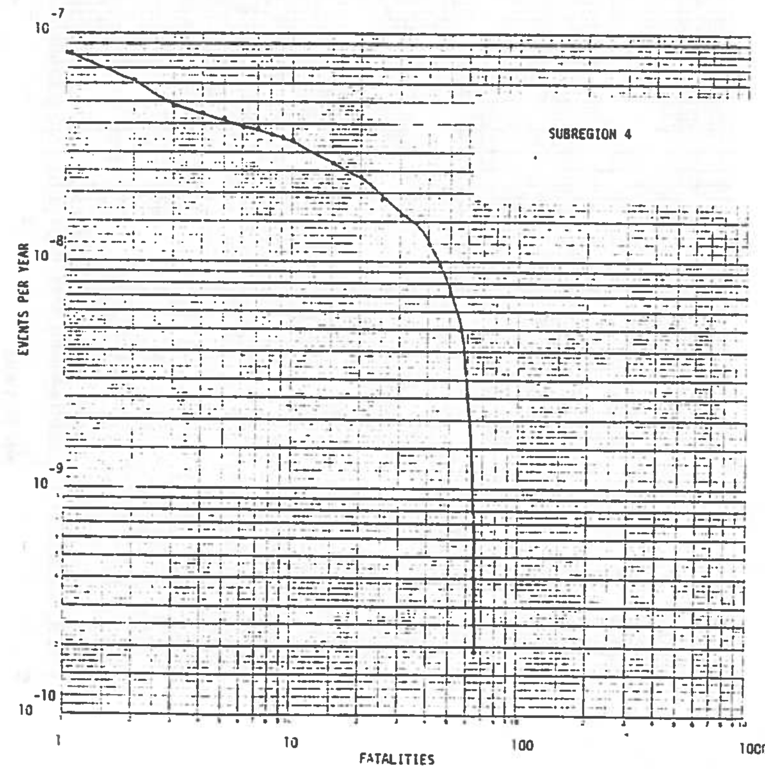
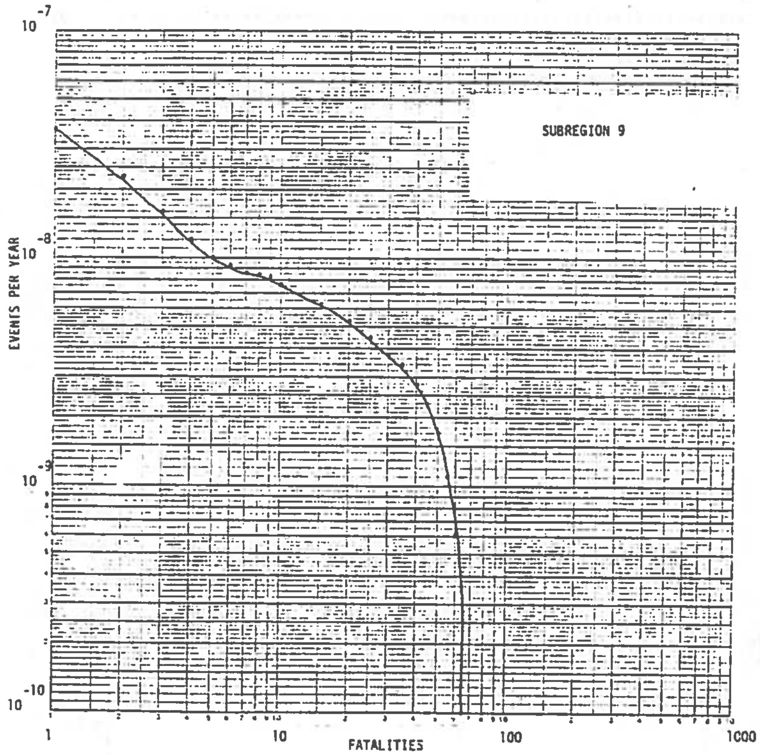


FIGURE A.1. (contd)

Subregion 9



Subregion 10

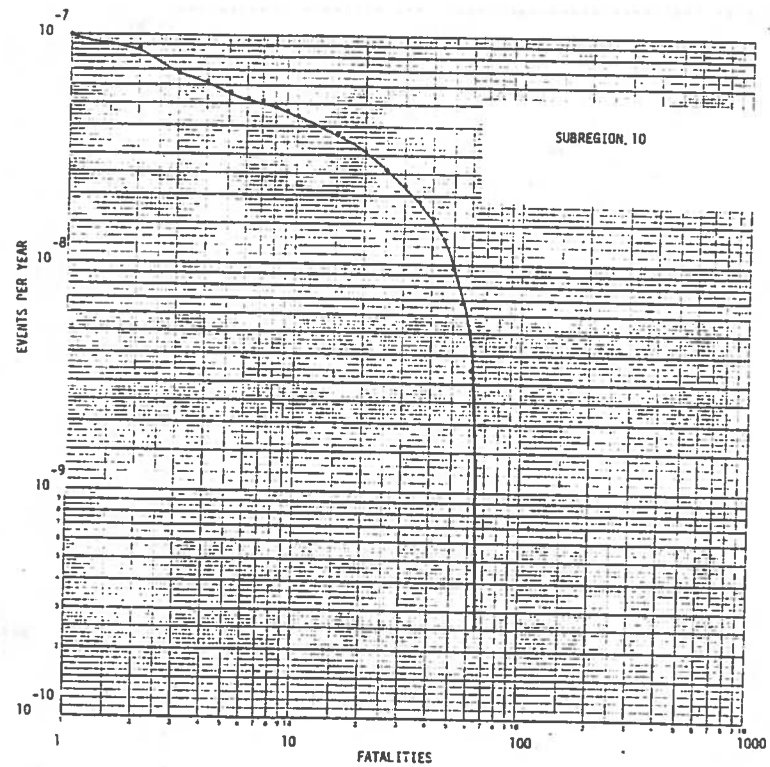
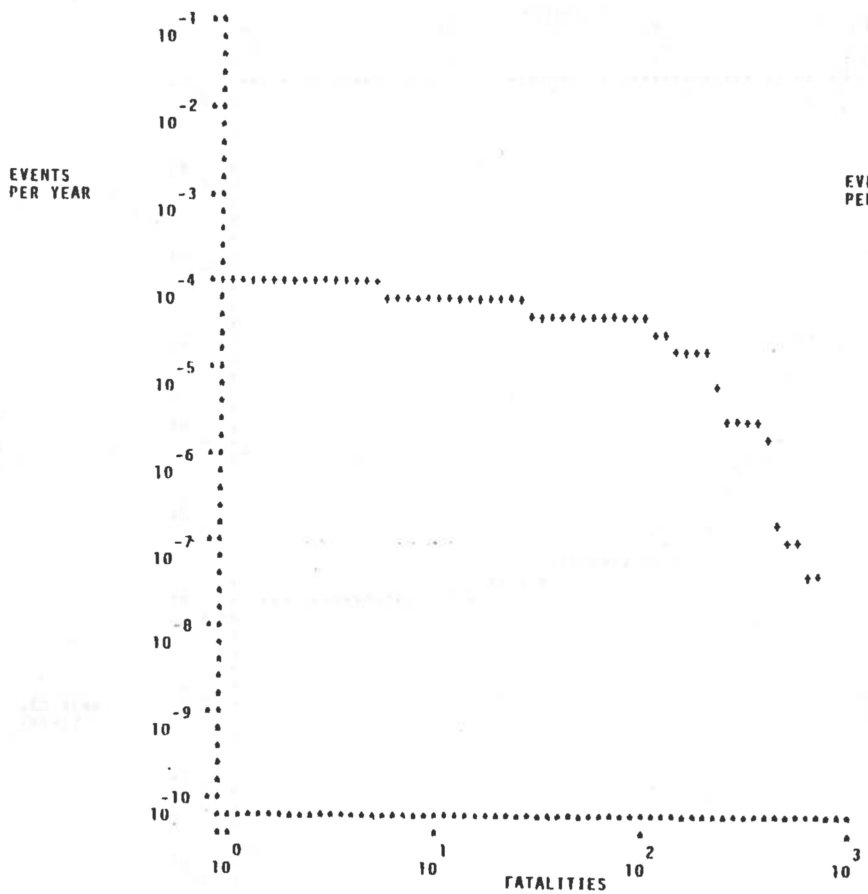


FIGURE A.2. (contd)

Subregion 3



Subregion 4

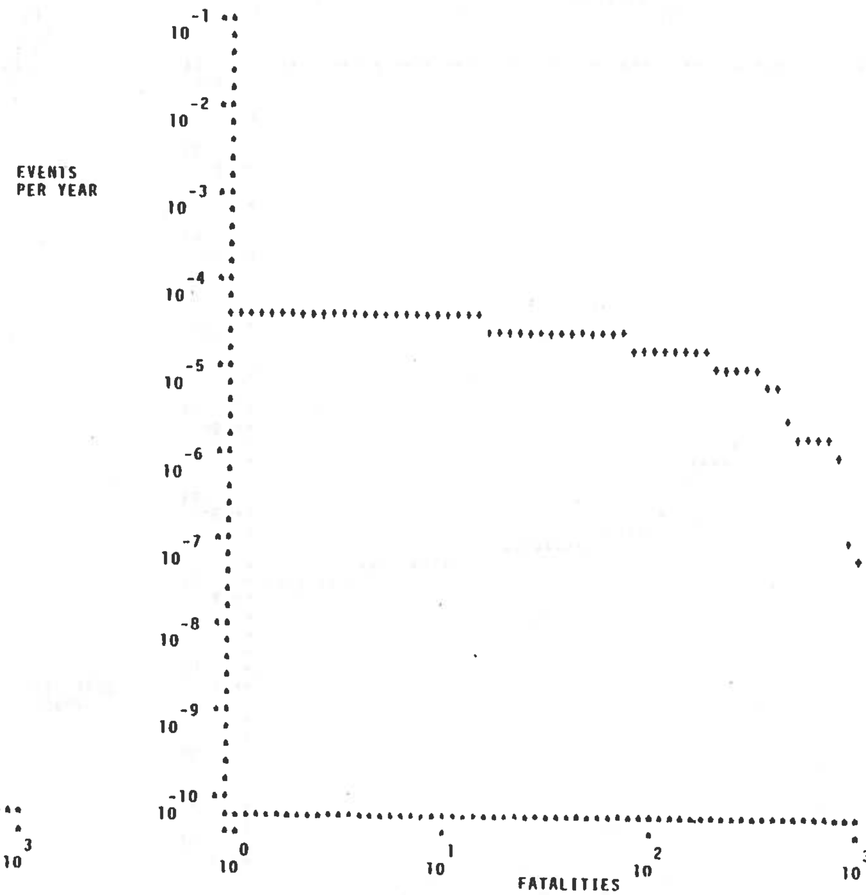


FIGURE A.3. (contd)

Subregion 8 Subregion 9

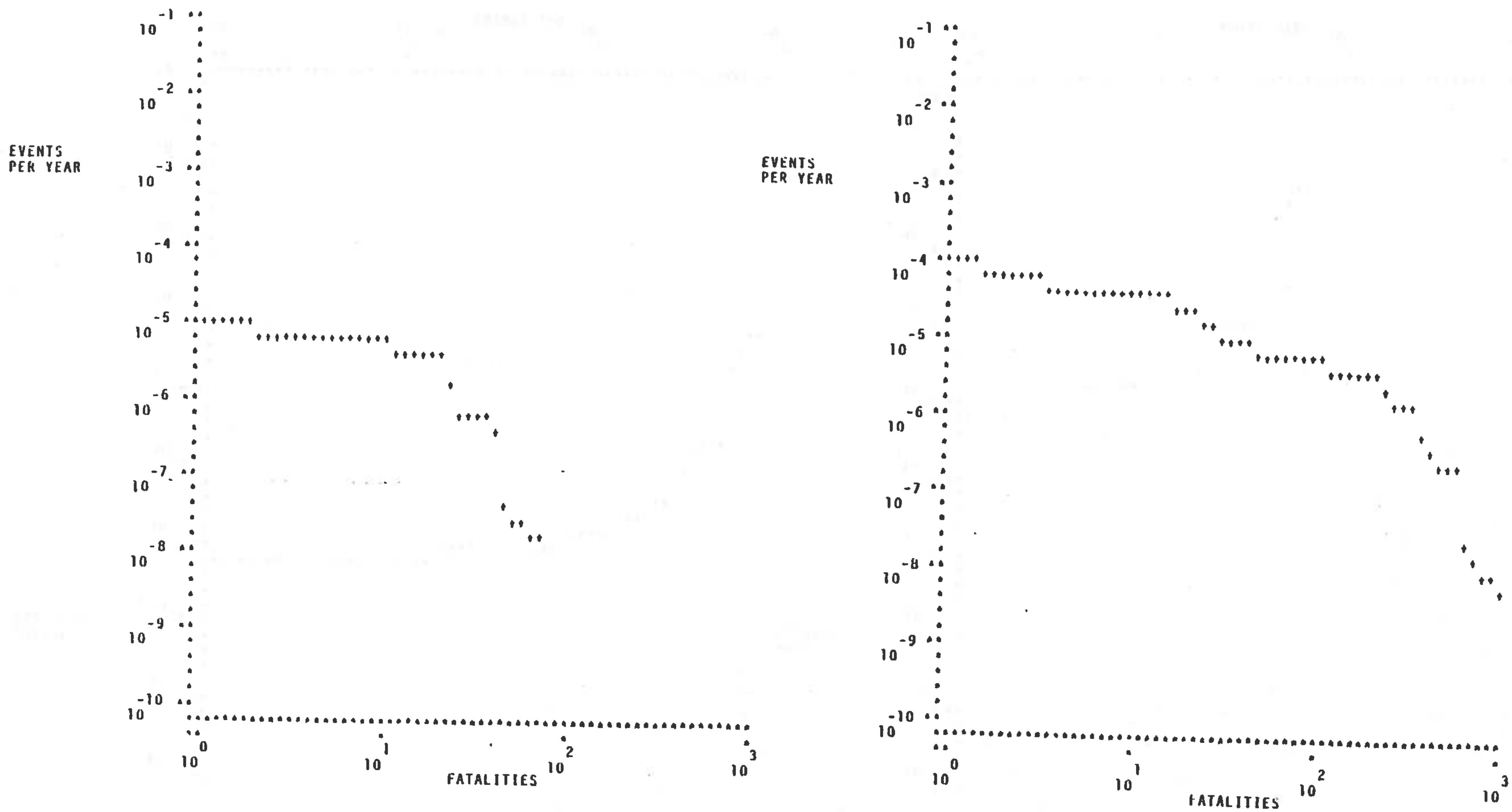


FIGURE A.4. (contd)

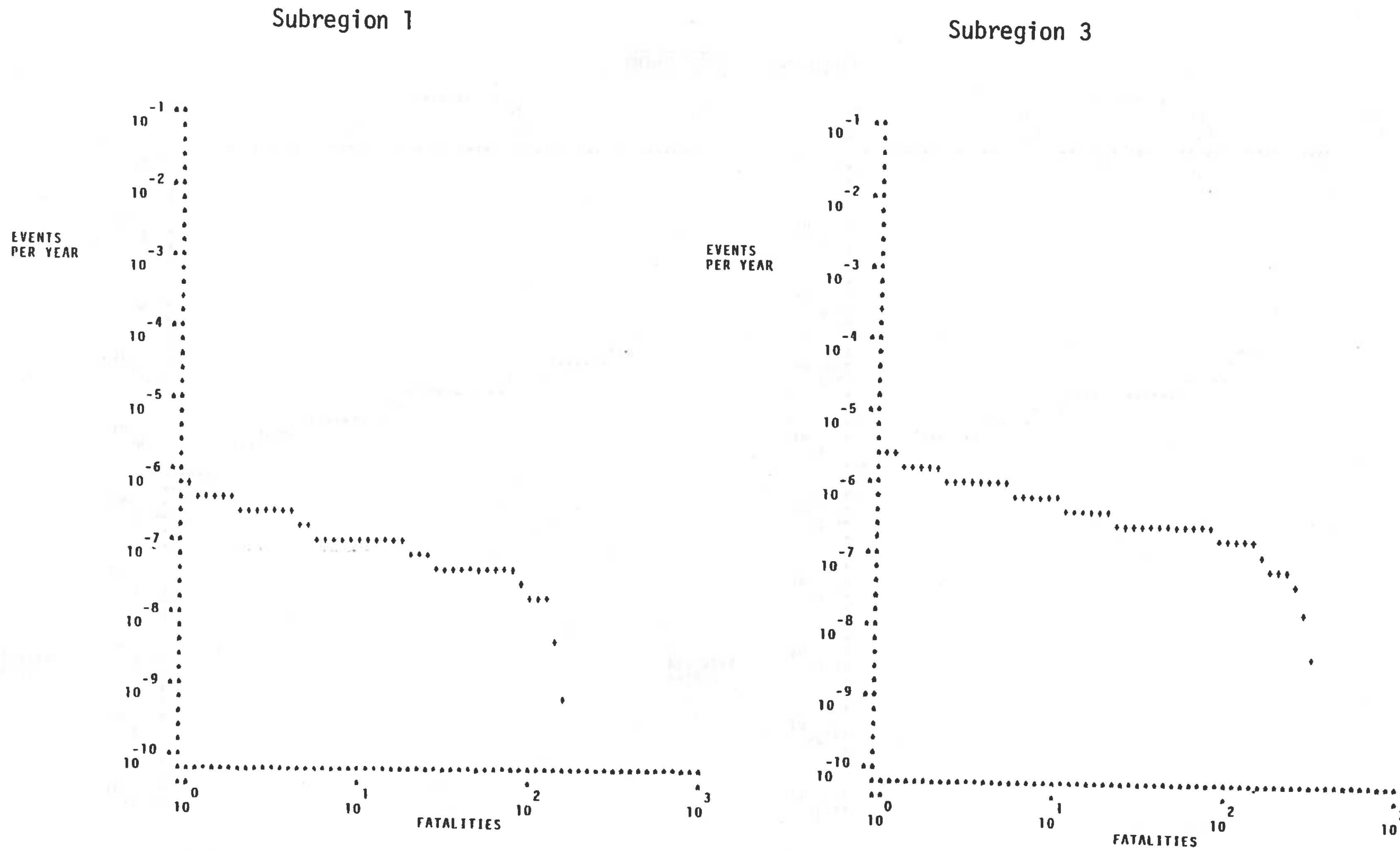
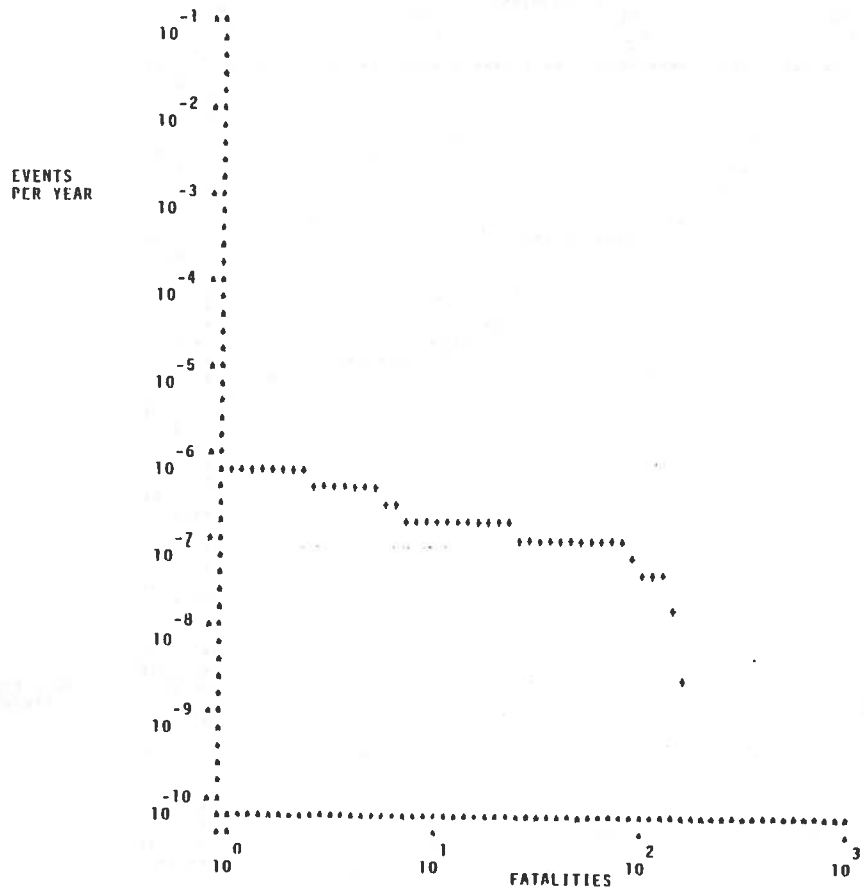


FIGURE A.6. Risk Spectra for the Transport of Propane by Rail in Subregions 1, 3, 4, 5

Subregion 6



Subregion 8

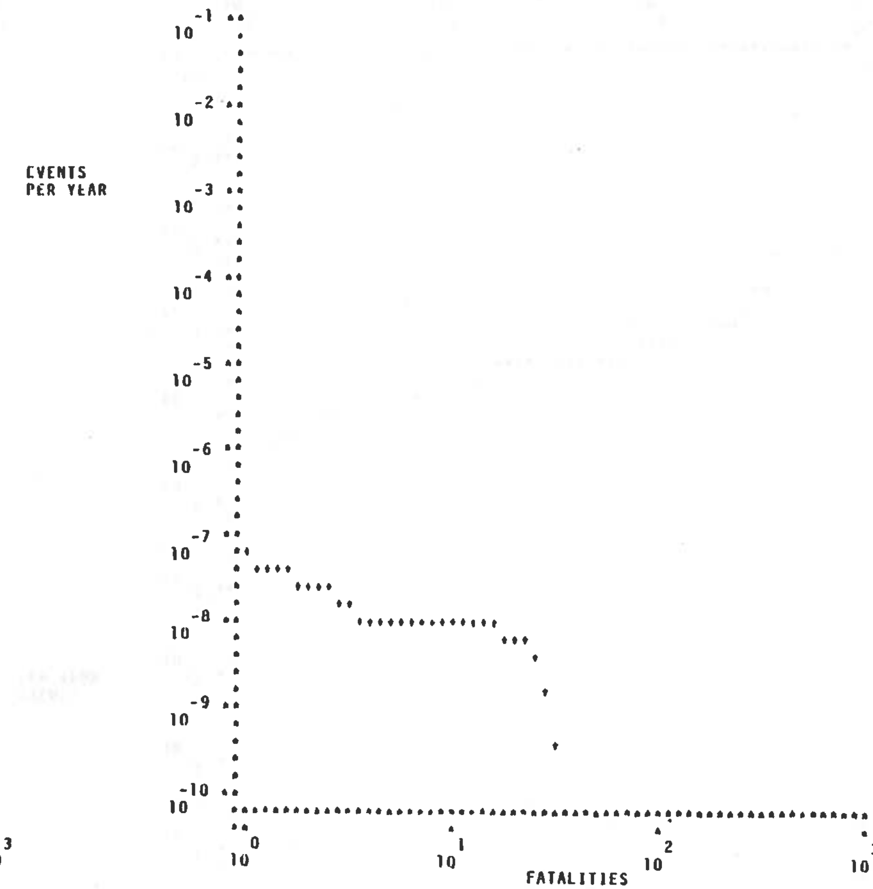


FIGURE A.7. Risk Spectra for Transporting Propane by Rail in Subregions 6, 8, 9, 10

Subregion 11

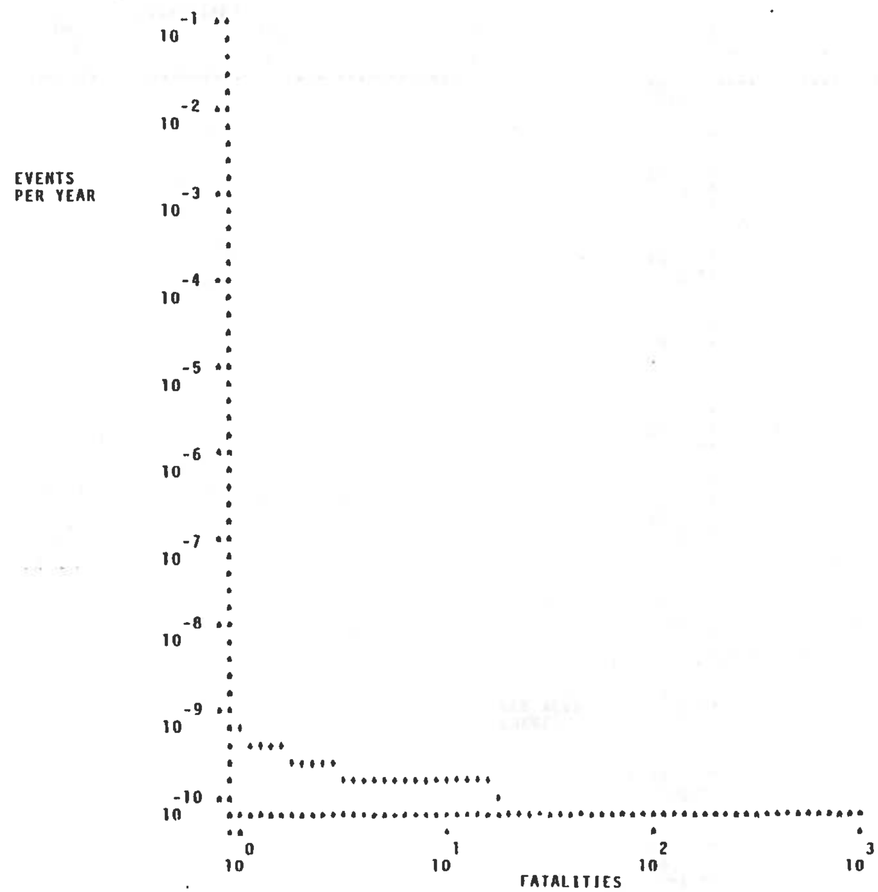


FIGURE A.8. Risk Spectrum for Transporting Propane by Rail in Subregion 11

Subregion 4 Subregion 5

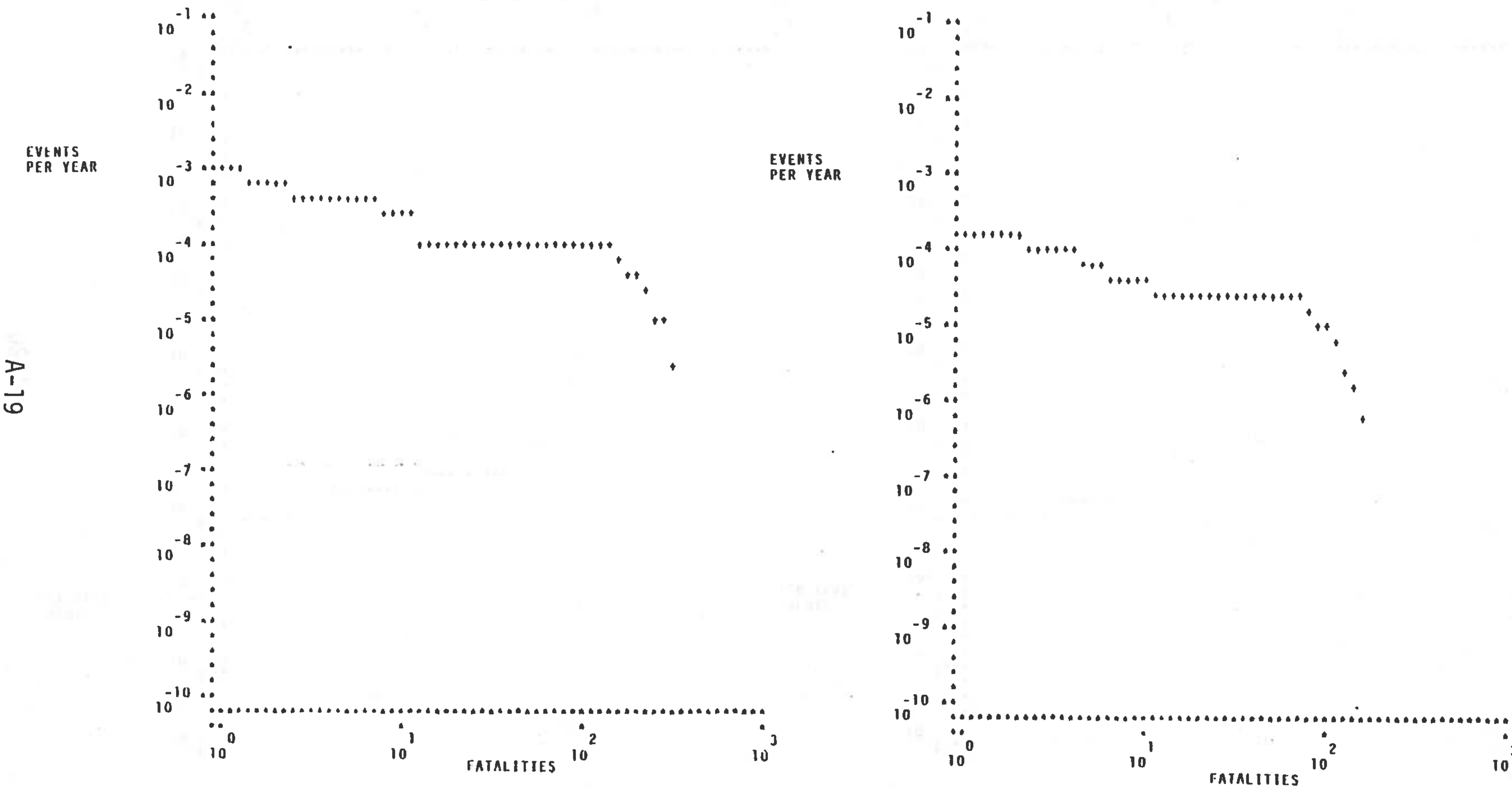


FIGURE A.9. (contd)

Subregion 10

Subregion 11

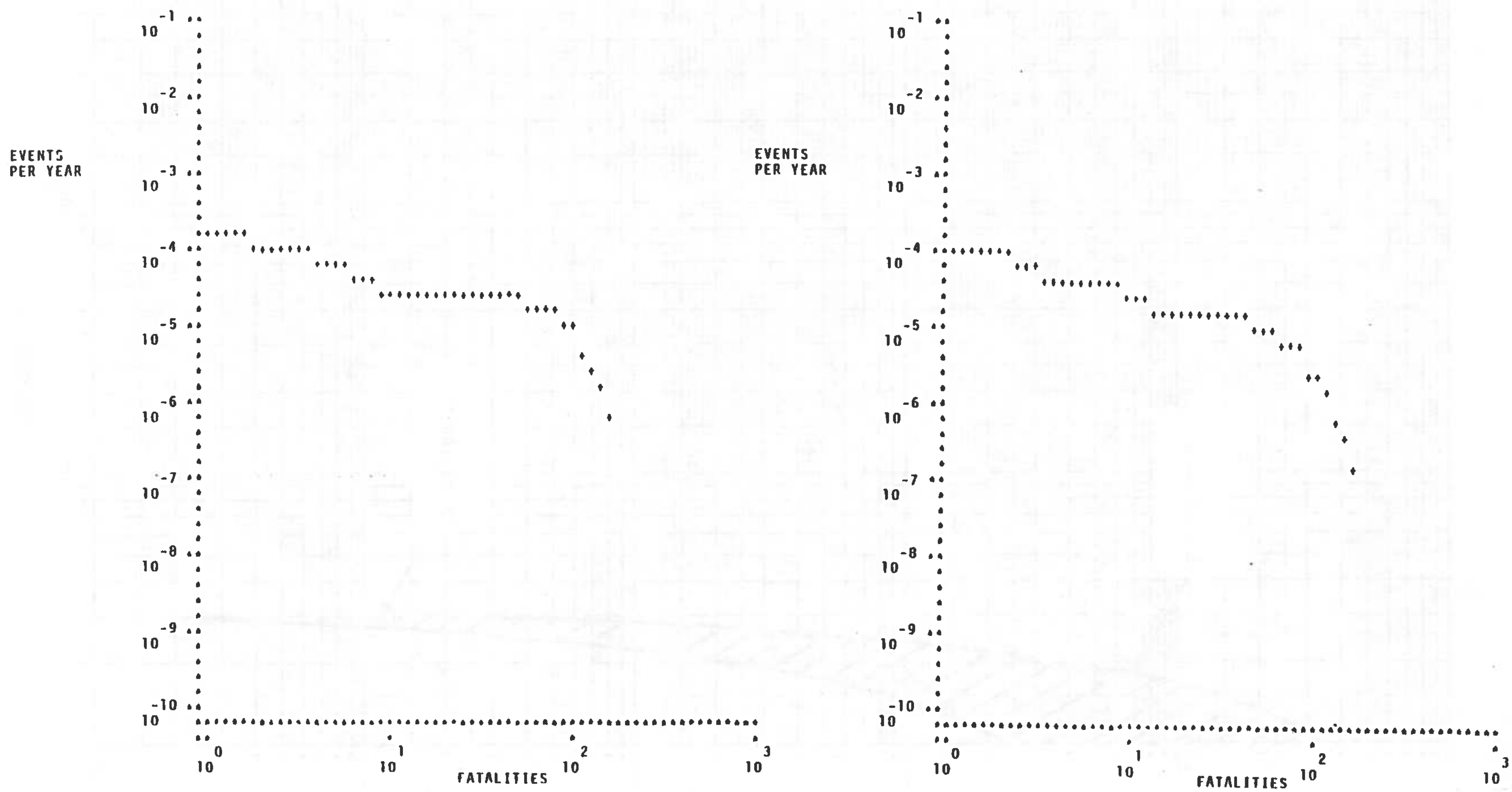


FIGURE A.10. (contd)

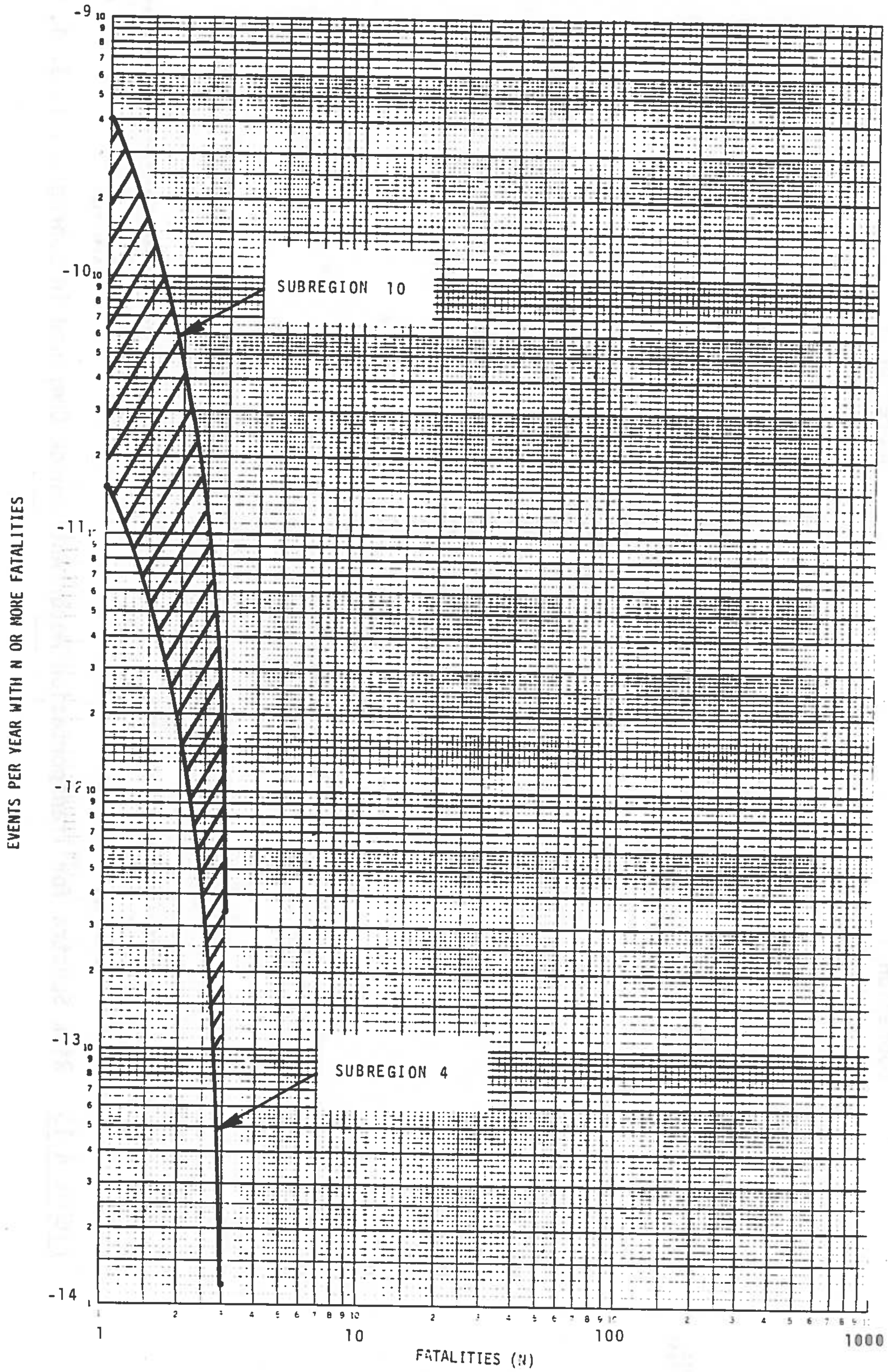
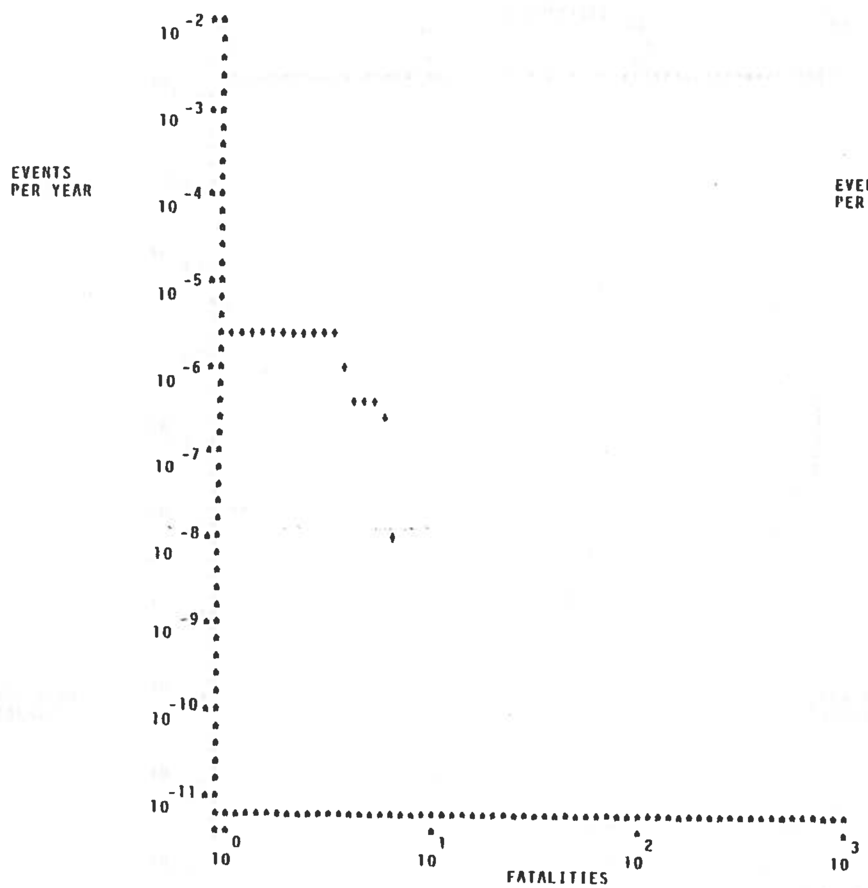


FIGURE A.12. Range of Subregion Risk Spectra for the Shipment of NaOH by Rail in the Central Puget Sound Region

Subregion 4



Subregion 5

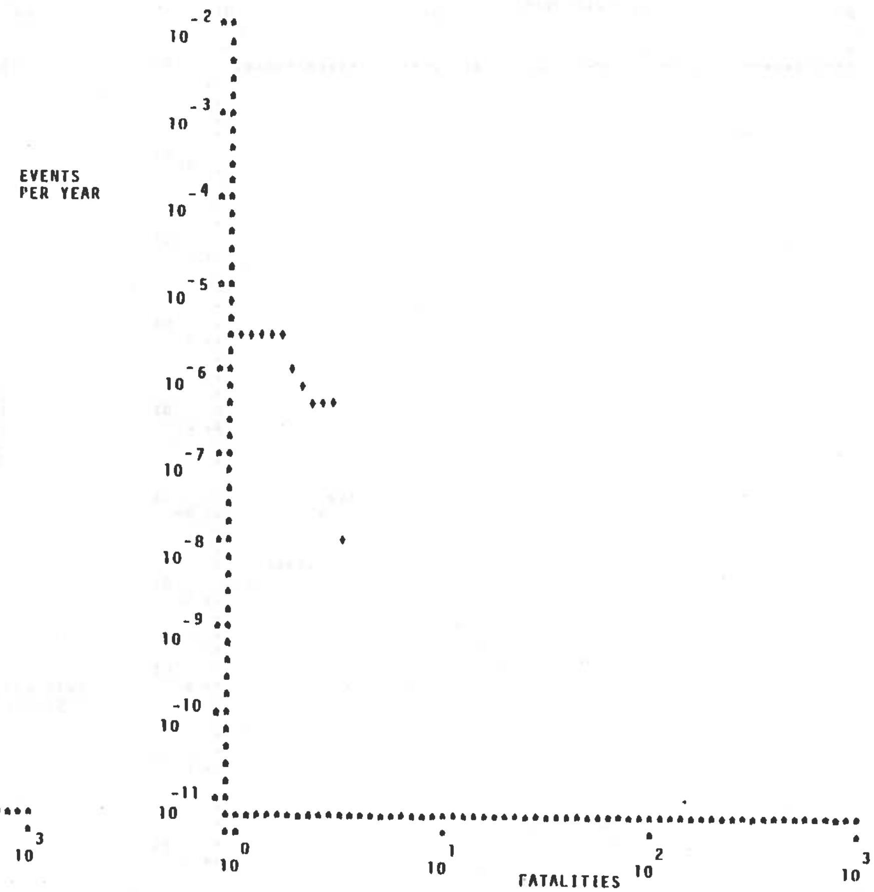


FIGURE A.13. (contd)

APPENDIX B

REPORT OF NEW TECHNOLOGY

The work performed under this contract has led to no new technology, although it does represent a significant application of a state-of-the-art risk analysis methodology to a practical situation.

110 copies