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ANALYSIS OF THE PROBABILITY  
OF A TOXIC GAS HAZARD FOR THE  
SAN ONOFRE NUCLEAR GENERATING STATION  
AS A RESULT OF TRUCK ACCIDENTS NEAR THE PLANT

February 28, 1981

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## 1.0 INTRODUCTION AND SUMMARY OF RESULTS

Transportation of toxic materials along Interstate 5 near the San Onofre Nuclear Generating Station (SONGS) presents the possibility that, as a result of an accident near the plant, toxic material may be released in sufficient concentration to incapacitate plant operators. A probabilistic assessment of toxic hazards to SONGS has been completed on the following basis:

- Probability is estimated for an event consisting of a sufficient concentration of a hazardous substance at the plant air intake to impair plant operation.
- The probability of a toxic hazard is estimated for each potentially significant toxic substance as discussed in FSAR Subsection 6.4.4.2.
- A significant hazard is defined as a substance for which the likelihood of a toxic hazard is greater than  $10^{-7}$ /year per the guidelines of Standard Review Plan 2.2.3.
- The Pasquill F weather stability category is assumed to exist at all times in accordance with Regulatory Guide 1.78.
- A Gaussian plume model is used with a correction made for modeling gases and vapors which are dense by comparison with air.
- Toxicity data, shipment frequency, and shipment size data were obtained from the report provided by Dames and Moore.

Four substances have been identified as a result of this probabilistic assessment for which the probability of a toxic hazard is near to or greater than  $10^{-7}$ /year:

- |                                       |              |                         |
|---------------------------------------|--------------|-------------------------|
| o The probability of a butane vapor   | hazard is    | $1 \times 10^{-6}$ /yr. |
| o The probability of a gasoline vapor | or hazard is | $1 \times 10^{-6}$ /yr. |
| o The probability of a propane vapor  | r hazard is  | $2 \times 10^{-6}$ /yr. |
| o The probability of a chlorine vapor | or hazard is | $1 \times 10^{-6}$ /yr. |

Although this report is considered a realistic analysis as far as acceptance criteria is concerned, certain conservatisms were maintained as follows:

- Plume blockage by existing structures, ground roughness, grade and other terrain-related effects are not considered.
- Hazardous material shipment quantities and frequencies reflect conservative estimates.
- No allowance is made for the effect of filtration or action by plant personnel to reduce "site" vulnerability in the event of an accident.

The following report is divided into three sections and several appendices:

Section 2: Probabilistic methodology

Section 3: Input data

Section 4: Quantification results

Appendix A: Dames and Moore data base

Appendix B: Quantification methodology for preparation of release source terms

Appendix C: Assessment of accidental release rates

Appendix D: Derivation of plume model mathematics

## 2.0 PROBABILISTIC METHODOLOGY FOR EVALUATING TOXIC AEROSOL RELEASE HAZARDS

Three sources of data were used to define candidates for evaluation

- Dames and Moore letter report (1) listing identified hazardous materials shipments local to the plant
- Data from a more complete Dames and Moore Survey as presented in the NUS-1942 Report on toxic hazards (2) and in the SONGS FSAR Section 2.2
- NRC's Regulatory Guidelines for evaluation of control room habitability problems (3)

The Dames and Moore letter report identified hazardous materials shipments local to the plant and is considered the basic data set for this analysis. This data, presented in FSAR Section 2.2, is listed in Table A.1. The 26 substances shown in Table 2.1 were identified for further evaluation using the probabilistic methodology discussed below.

### 2.1 THE TOXIC AEROSOL MODEL

Figure 2.1 presents the geometry of the highway passing the plant running nearly parallel to the shoreline. Should an accident occur and a release of hazardous material ensue, the plume, which travels with the wind, may pass near the plant. If the plume is drawn such that the plume boundary defines a level of toxic concentration,  $X_m$ , the hazardous condition is such that the plume "footprint" overlaps the air intake. Such a situation could result if the wind is blowing at an angle between  $\phi_1$  and  $\phi_2$ . Let  $P_m$  be the probability that the wind is blowing between the values, then the probability that the concentration exceeds  $X_m$  at the air intake is

---

\* footprint is defined as the projected area of the plume in which a concentration of the substance greater than the toxic limit exists. For a chronic release the footprint may be assumed to be fixed in time. For a puff release over an area, the footprint is the area enclosing a toxic concentration sometime during the passage of the plume.



Table 2.1

SONGS TOXIC HAZARD EVALUATION

Potentially Hazardous Materials Evaluated

Using Probabilistic Methodology\*

Chlorine	Methyl ethyl ketone
Ammonia (anhydrous)	Ethylene dichloride
Butane	Butyl acetate
Propane	Diacetone
Carbon dioxide	Hydrocarbon distillate (Shell M-75)
Methyl bromide	Methanol
Vikane	Methyl butyl ketone
Gasoline	Napthalene
Jet fuel (JP4/JP5)	Pentachlorophenol
Diesel fuel	Xylene
Benzene	Methylene chloride
Formaldehyde	Hydrochloric acid
Muriatic acid (bulk)	Sulfuric acid

\* See Table 3.2 for evaluated hazards and Tables 4.1 and 4.2 for evaluated probabilities.

$$P(X > x_m) = P_R P_m \quad (1)$$

where  $P_R$  is the probability of the release that caused the footprint.

A release producing accident could occur at any point along Interstate 5; therefore, it is convenient to segment the road and consider each segment separately as a release point. It is clear that if the wind is blowing at the angle,  $\phi$ , a release from only one of the segments will pass the air intake. If the release occurs in a different segment, the same angle,  $\phi$ , will not result in a plume passing the plant, but a slightly different wind direction could give such results. For a given plume size, for each segment, it is necessary to calculate the wind angle that would cause the cloud to cover the air intake. The plume itself is a function of many variables which are only known statistically. The large amount of research on atmospheric dispersion (4,5) has resulted in several models. Regardless of the details of the model used, the amount of exposure at some point away from the source is a function of many variables,

$$X = X(\bar{r}, \bar{U}, P, p, h, R, Q, t)$$

where  $\bar{r}$  is a vector from the source to the observer,  $\bar{U}$  is the average wind direction vector,  $p$  represents the atmospheric stability usually expressed in Pasquill categories A-G,  $h$  is the height of release, and  $R$  is the ground roughness that results in additional mixing.  $Q$  is the quantity of material released, if the material is released in a short time duration (a puff). The value of  $X$  is a function of time. If, however, the release occurs slowly so that a release rate,  $Q$ , is constant, the plume for constant meteorological conditions will reach equilibrium and the contour will appear as a static footprint.

In general, the probability that the plume contour,  $X$ , exceeds a critical concentration,  $X_m$ , is

$$P(X \geq X_m) = \sum_{\substack{\text{sum} \\ \text{over} \\ \ell, Q, P, \bar{U}}} P_{\ell} P_Q P_P P_{\bar{U}} \quad (2)$$

where  $P_{\bar{U}}$  is the probability that the wind will blow at an angle between  $\phi_1$  and  $\phi_2$ , at a wind speed,  $\bar{U}$ , given a Pasquill condition.  $P_P$  is the probability of this Pasquill condition;  $P_Q$  is the probability of releasing a quantity of material,  $Q$ , given an accident; and  $P_{\ell}$  is the probability of an accident in the  $\ell$ th segment of the highway. In this problem the effect of bouyancy is treated, the ground roughness,  $R$ , and the release height,  $h$ , are not considered as part of the plume algorithm. It is assumed that the problem can be treated as either a puff release in which  $X$  is the time integrated dose or a continuous release in which  $X$  is the maximum allowable concentration.

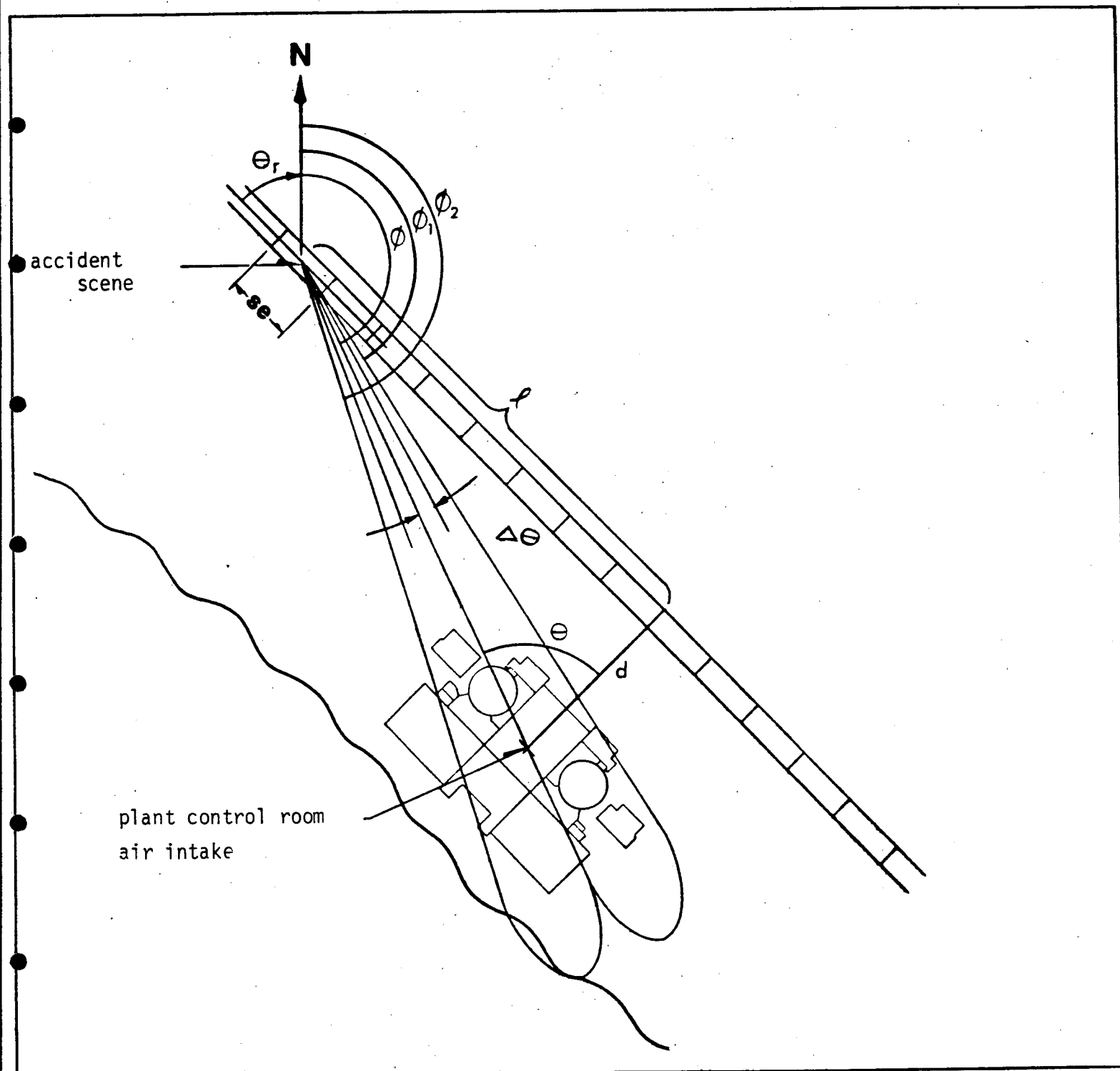


Figure 2.1 Site Geometry

## 2.2 GAUSSIAN PLUME MODEL

It has been found experimentally that the dispersion of aerosols into the atmosphere may be modeled as a Gaussian distribution. Qualitatively this suggests that there are many uncorrelated forces causing the dispersion, so that the mean value theorem is applicable\* and the result may be characterized by experimental parameters for the Gaussian distribution. In this model, for a puff release,

$$X(t) = \frac{2Q}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{x - \bar{U}t}{\sigma_x} \right)^2 - \frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right] \quad (3)$$

where  $x$  is a distance downwind from the release,  $y$  is a horizontal distance from the head of the  $x$  vector, and  $z$  is a vertical distance from the head of the vector.  $\sigma_x$ ,  $\sigma_y$ ,  $\sigma_z$ , are, respectively, parameters in the  $x$ ,  $y$ , and  $z$  directions that characterize the dispersion,  $\bar{U}$  is the average wind speed in the  $x$  direction, and  $Q$  is the puff release quantity.

A measure of the consequences of a toxic material spill is the dose or time integrated exposure

$$\bar{X} = \int_0^{\infty} X(t) dt.$$

Performing the integration (see Appendix D),

$$\bar{X} = \frac{Q}{\pi \sigma_y \sigma_z \bar{U}} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right]. \quad (4)$$

For a puff release of toxic gas the concentration at ground level has been shown to be adequately modeled by a Gaussian distribution in  $X$  and  $y$ :

\* The mean value theorem states that the sum of a large number of arbitrary distributions is Gaussian.

Considering a continuous release, the assumption can be made that if a toxic concentration occurs at the control room air intake, it will persist for a sufficient period of time to cause a hazard. Since the plume foot-print either does or does not encompass the plant air intake dispersion in the X direction as well as any time dependence in the dispersion equation is eliminated. Therefore, the dispersion equation for a continuous release has the same form as developed above except that the chronic source rate,  $\dot{Q}$ , is used and, with no integration over time, the incapacitating dosage,  $\bar{X}$ , is replaced by the toxic concentration,  $X$ .

Many of the substances considered here, because of their high molecular weight and the coldness of the vapor, do not rise as rapidly as more buoyant materials. An example of such a material is chlorine. Experiments conducted by the Bureau of Mines showed that the dispersion of chlorine vapor may be adequately described (5) by a Gaussian plume model such as those used for air pollutants (6). However, they found that the vertical dispersion is less than that observed for the usual air pollutants. Their data indicated that the vertical standard deviation (for concentration versus distance) is approximately 20 percent of the horizontal standard deviation.

Reference 3 addresses acceptable methods for calculating hazardous material releases for 27 chemicals. Figures 2.2 and 2.3 present their recommended  $\sigma_y$  and  $\sigma_z$  values for Pasquill conditions E, F, and G. It should be noted that  $\sigma_y(F)$  at 100 is 2.8 m and  $\sigma_z(F)$  at 100 is 1.2 m, giving a ratio of  $\sigma_z/\sigma_y$  of 0.55. Slade (7) provides values of  $\sigma_z/\sigma_y$  for stability at 100 meters of 0.57. Slade's data have been compared with several experiments (in particular the Project Prairie Grass experiment performed on grassland in Nebraska, p. 134) with good agreement.

To allow for the effect of heavy gases and vapors, a constant multiplicative scaling parameter is introduced into the code, SAITOX, adjusting  $\sigma_z$  for negative buoyancy. This scaling factor is approximately the ratio of the density of the aerosol to the density of the ambient air. The data from Reference 3 is digitized into 21 logarithmic spaced points and entered into the program where it is interpolated to provide the values of  $\sigma_y$  and  $\sigma_z$  appropriate for the x distance.

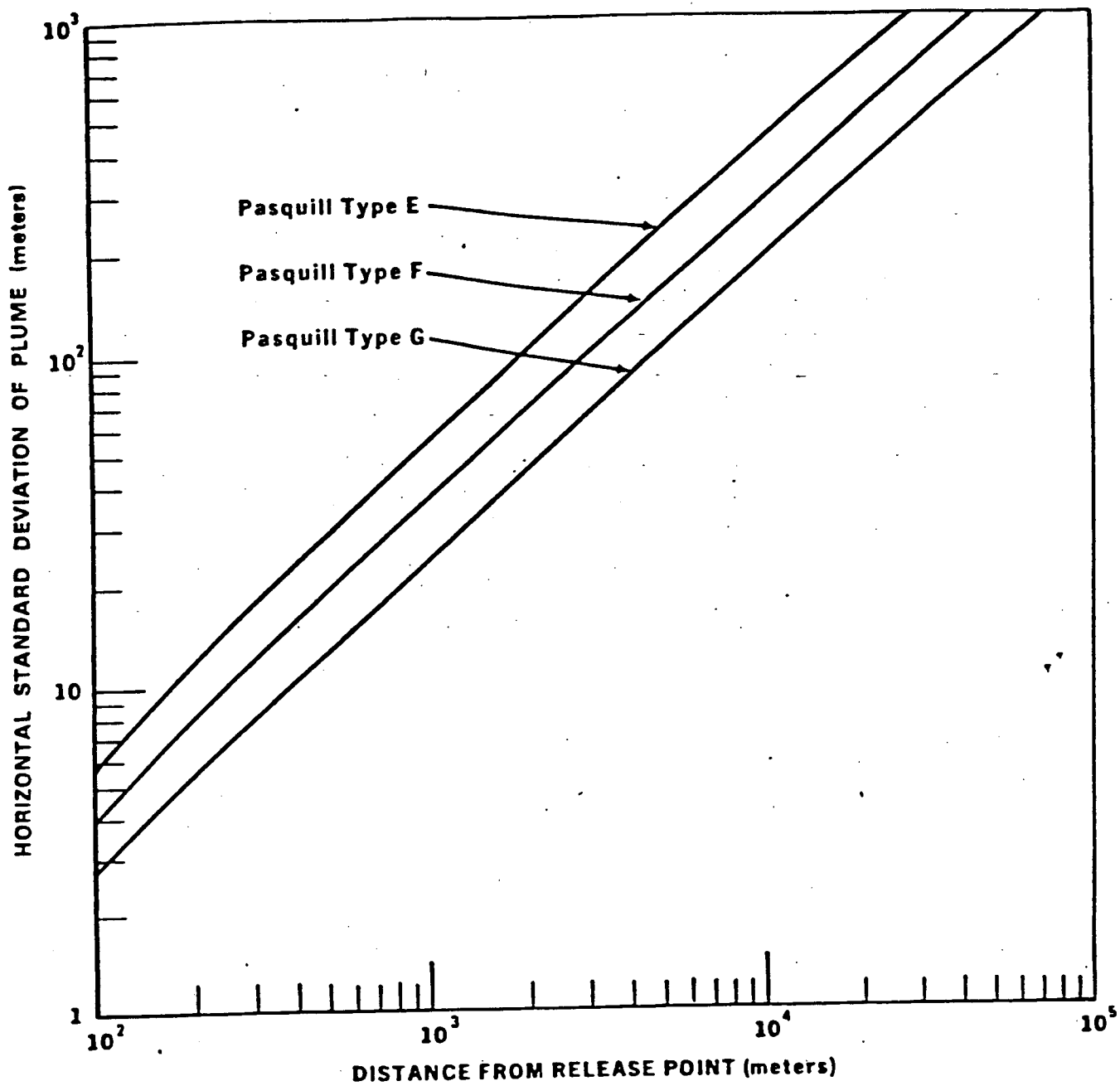


Figure 2.2 Horizontal Standard Deviation of Material in a Plume

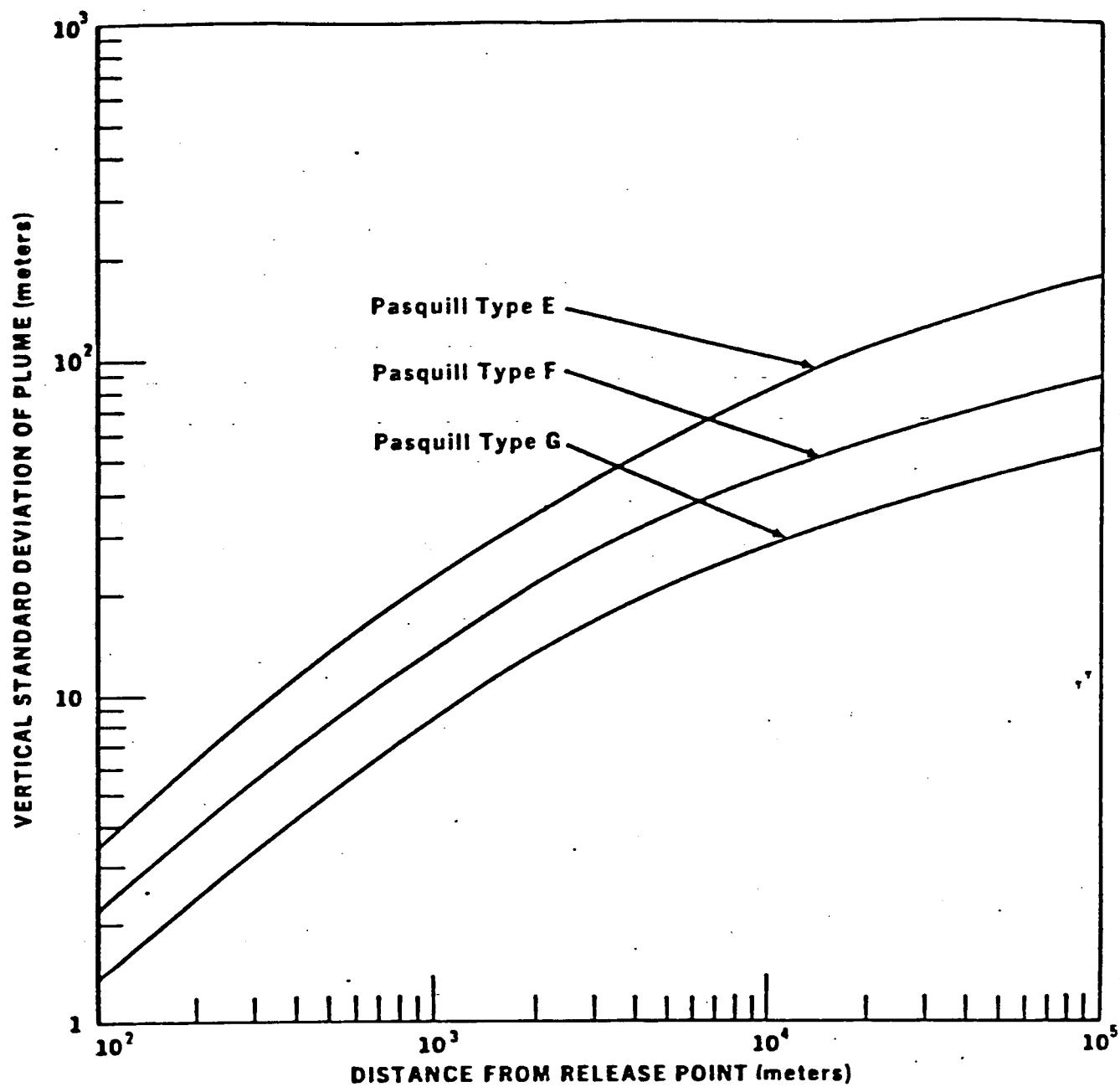


Figure 2.3 Vertical Standard Deviation of Material in a Plume



Equation 4 solved for y is

$$y(x, \bar{U}, P) = \sigma_y \sqrt{2 \ln \left( \frac{Q}{\bar{x} \pi \sigma_y(x, \bar{U}, P) \sigma_z(x, \bar{U}, P) \bar{U}} \right)} \quad (5)$$

where the dependency of  $\sigma_y$  and  $\sigma_z$  on  $x, \bar{U}, P$  is made explicit.

Returning to Figure 2.1, certain geometric relationships may be obtained:

$$\phi = 180^\circ - \theta_r + \tan^{-1} \frac{d}{\ell} \quad (6)$$

where  $\theta_r$  is the angle of the highway with respect to north, and  $d$  and  $\ell$  are defined in Figure 2.1. The allowable angular variations are

$$\phi_1 = \phi - \Delta\phi + 180^\circ \quad (7)$$

$$\phi_2 = \phi + \Delta\phi + 180^\circ. \quad (8)$$

The  $180^\circ$  is added to correct for the fact that the wind rose data are for wind direction and the theory requires wind bearing to be used.

If  $\phi_1$  or  $\phi_2$  are defined for each wind direction.

$$\Delta\theta = \tan^{-1} \frac{y}{x} \quad (9)$$

where  $y$  is obtained from Equation (5) and  $x = d^2 + \ell^2$ .

The computer code steps through incremental  $\ell$  values.

Having obtained  $\phi_1$  and  $\phi_2$ , the probability that the wind, given the speed,  $\bar{U}$ , and the Pasquill category,  $P_p$ , is blowing between these values is calculated by using the wind rose data in the FSAR (8) and computing the cumulative probability,  $P_\phi$ , of blowing between  $135^\circ$  and some angle,  $\phi_1$ .\* The probability of blowing between  $\phi_1$  and  $\phi_2$  is then obtained as

$$P_m(\ell, Q, X) = \sum_{\substack{\text{Sum} \\ \text{over} \\ \text{all} \\ \text{values} \\ \text{of } \bar{U} \\ \text{and } P}} |P_{\phi_1}(\bar{U}, P) - P_{\phi_2}(\bar{U}, P)|$$

$P_m$  is for one specific wreck site, for quantity of material,  $Q$ , released, having toxicity,  $\bar{X}$ .

Then, for a given toxic substance, the probability of exceeding its toxicity limit,  $X_m$ , is

$$P(X > X_m) = P_x P_T \Delta \ell \sum_{Q, \ell} P_Q P_m(\ell, Q, x)$$

where it is assumed that there is a constant accident probability,  $P_T$ , per unit length of highway and  $\Delta \ell$  is the length of the highway segment used in the analysis.  $P_x$  is the annual frequency of shipment of toxic material characterized by the toxic limit,  $X_m$ .

The next section discusses the frequency of toxic shipments past the makeup of release terms, accident probabilities and release probabilities.

\* This crossover point for the cumulative probability is chosen to avoid interpolation over the crossover. Wind blowing the plume away from the plant does not enter the calculation.

### 3.0 PROBABILISTIC ASSESSMENT INPUT DATA

Estimates of accident occurrence probabilities used in the interim project report (9) were compiled using Sandia data on truck accidents (10) and engineering judgment to establish the conditional likelihood of a spill given an accident.

#### 3.1 EVALUATION OF THE PROBABILITY OF A RELEASE

An accident rate of  $1.0 \times 10^{-8}/\text{mi}$  has been used in this report to estimate the likelihood that a truck accident will occur which results in some spillage of a hazardous material of the type shown in Table A.1. This probability is taken from the risk analysis of explosive hazards to SONGS (11) and is independently verified by the analysis shown in Appendix C which utilizes recent data on truck accidents for divided highways.

##### 3.1.1. Probability of a Complete Spill

The consequences as calculated using methodology for evaluating plume propagation are forecast based on the use of the entire contents of a container. Assuming that the entire contents of the container escape with a probability of 1 is viable for materials transported in gaseous form. For substances which are liquid or for which the flash fraction is small, the probability of a complete spill is likely to be less than 1. Table 3.1 indicates a statistical breakdown of conditional likelihoods for various amounts of material to be released. The resulting consequences of a release vary proportionally with the size of the release and, therefore (using the data in Table 3.3 a spectrum of source term sizes) could be used for each substance. For this analysis, however, an analytical simplification is used in that if more than half of the

Table 3.1

FREQUENCY AND PROBABILITY DISTRIBUTION  
OF FRACTIONAL CARGO LOSS  
IN TANK TRUCK LOSS-OF-LADING ACCIDENTS

Class Size of Fractional Cargo Loss	Frequency	Cumulative Frequency	Probability	Cumulative Probability
0.0-0.1	37	37	0.261	0.261
0.1-0.2	14	51	0.099	0.360
0.2-0.3	10	61	0.070	0.430
0.3-0.4	8	69	0.056	0.486
0.4-0.5	17	86	0.120	0.606
0.5-0.6	7	93	0.049	0.655
0.6-0.7	9	102	0.063	0.718
0.7-0.8	8	110	0.056	0.774
0.8-0.9	5	115	0.035	0.809
0.9-1.0	27	142	0.190	0.999

substance is released it is assumed that the release source is the same as for a release of the total container contents. Conversely if less than half of the contents are released no source is assumed to occur. Therefore, a scaling factor consisting of the cumulative conditional probability of releasing more than 50% of the cargo is used.

### 3.2 SOURCE TERM DATA

Three types of source terms are defined for use in the toxic hazard evaluation methodology:

- The amount of material flashed as a result of depressurizing high vapor pressure liquids such as chlorine and liquid CO<sub>2</sub> is estimated. This flash release comprises the "puff" portion of the source term for such liquids.
- The rate of vaporization of high pressure liquids after flashing is estimated. This boiling release is used as the chronic component of high vapor pressure liquid source terms.
- The rate of vaporization of a substance normally in a liquid state is estimated. This evaporative release comprises the entire source term for such substances.

The methodology for calculating each type of source term is discussed in Appendix B.

A listing of the source terms used in the analysis is shown in Table 3.2.

For continuous release calculations the threshold incapacitating concentration  $X_m(\text{mg}/\text{m}^3)$  was used directly. For a puff release a minimum of 2 minutes exposure to concentrations at or above the toxic concentration was required. Thus the minimum incapacitating dose was  $X_m \cdot 120 (\text{mg}\cdot\text{sec}/\text{m}^3)$ .

Table 3.2

## SONGS TOXIC HAZARD EVALUATION, PLUME MODEL INPUT DATA

Substance	Release Type(s) Expected	Source Terms				$x[\text{mg}/\text{m}^3]$	Frequency of Shipments[1/yr]
		Flash		Boil	Evap.		
		f	$Q_{fa}[\text{mg}]$ (1)	$Q_b[\text{mg}/\text{sec}]$	$Q_e[\text{mg}/\text{sec}]$		
Butane	F+B (2)	0.118	$1.9 \times 10^{10}$	$1.7 \times 10^6$		1750	2200
Carbon Dioxide	F+B	0.294	$8.9 \times 10^9$	$3.4 \times 10^6$		87400	260
Chlorine	F+B	0.168	$9.0 \times 10^8$	$1.3 \times 10^6$		43	754
Ammonia	F+B	0.152	$7.5 \times 10^9$	$5.9 \times 10^6$		27	108
Methyl Bromide	F+B	0.059	$8.2 \times 10^8$	$5.8 \times 10^5$		60	48
Vikane	F+B	0.62	$9.1 \times 10^7$	$3.8 \times 10^4$		40	43
Propane	F+B	0.33	$1.6 \times 10^{10}$	$3.7 \times 10^6$		1750	2200
Gasoline	E				$1.6 \times 10^7$	4000	17,000
Jet Fuel	E				$4.8 \times 10^6$	1355	910
Benzene	E				$9.8 \times 10^4$	30	430
Formaldehyde	E				$1.9 \times 10^6$	3	14
Hydrochloric Acid	E				$1.0 \times 10^5$	7	43
Muriatic Acid	E				$1.6 \times 10^5$	7	43
Methyl Ethyl-Ketone	E				$1.5 \times 10^6$	740	43
Ethylene Dichloride	E				$5.1 \times 10^6$	300	43
Butyl acetate	E				$4.9 \times 10^5$	950	43
Diacetone	E				$3.6 \times 10^4$	3,000	43
Distillates	E				$6.1 \times 10^5$	750	43
Methanol	E				$2.5 \times 10^6$	310	18
Diesel Fuel	E				$4.8 \times 10^6$	1,355	650
Methyl Butyl-ketone	E				$2.8 \times 10^5$	150	43
Napthalene	E				$3.6 \times 10^4$	75	43
Pentachlorophenol	E				$3.0 \times 10^4$	1.5	43
Xylene	E				$6.0 \times 10^5$	655	24
Methylene Chloride	E				$1.24 \times 10^7$	900	43
Sulfuric Acid	E				$8.93 \times 10^1$	1	43

(1) This is the assumed total amount of material available for flashing per shipment.

(2) For puff release a 120 second exposure time @ this concentration was assumed to constitute a hazard. The 120 second exposure is from Reference 3.

#### 4.0

#### CALCULATIONS OF THE PROBABILITY OF A HAZARD

Using the methodology and input data described above, estimates were made for individual substances chosen for evaluation of the probability of a toxic hazard at the plant. If significant hazards are assumed to be all substances with greater than  $10^{-7}$ /year probability of hazard occurrence, then from Table 4.1, chlorine, butane, propane, ammonia, and gasoline must be considered.

During plant operation, monitoring will be done at the control room air intake for butane, chlorine and ammonia concentrations in the inlet stream. Since the butane monitoring instrumentation has the capability of sensing other hydrocarbons, including gasoline, propane, jet fuel and diesel fuel, these substances will be monitored as well. The number of "significant" hazards is therefore, relatively insensitive to changes in toxic hazard likelihood. Removing all the monitored substances from consideration results in cumulative toxic hazard likelihood approximately  $10^{-7}$  per year.

Although the analysis presented here is intended to be a realistic estimate of the likelihood of toxic substance hazard, several effects have not been considered which make the results presented conservative. Effects not considered in this analysis include:

- blockage of the plume by plant structures which would tend to shield the air intake and break up a plume;
- dispersion effects such as ground roughness and terrain which enhance plume dispersion;
- short toxic exposure times of 2 minutes for "puff" releases which decrease the required toxic "dose" from a puff release, raising the probability of toxic hazard occurrence;

- no consideration of plant filtration system effects which diminish the level of concentration experienced in the control room over finite time periods;
- no consideration of plume pre-ignition which, for flammable substances overestimates the likelihood that a plume reaches the air intake.



Table 4.1

MAJOR TOXIC HAZARD CONTRIBUTORS<sup>(a)</sup>

CHEMICAL NAME	FREQUENCY OF HAZARD PER YEAR	DESCRIPTION
Propane	$2 \times 10^{-6}$	Compressed, Flammable liquid
Gasoline	$1 \times 10^{-6}$	Flammable liquid
Butane	$1 \times 10^{-6}$	Compressed, Flammable liquid
Chlorine	$1 \times 10^{-6}$	Compressed liquid
Ammonia	$9 \times 10^{-7}$	Compressed liquid
Benzene	$6 \times 10^{-8}$	Liquid
Formaldehyde	$5 \times 10^{-8}$	Liquid
Jet Fuel	$5 \times 10^{-8}$	Flammable liquid
Diesel Fuel	$3 \times 10^{-8}$	Flammable liquid

(a) substances which contribute greater than .1% of the cumulative likelihood of a hazard.

1. Letter Report, P. Gottlieb (Dames and Moore) to David Poole (SCE), dated April 28, 1977.
2. S.J. Nathan and J.M. Nieto, Determination of Acceptable Site Specific Frequency of Hazardous Chemical Shipments Passing San Onofre Units 2 and 3, NUS-1942, September 1977.
3. NRC, Assumptions For Evaluating the Habitability of A Nuclear Power Plant Control Room During a Postulated Hazardous Chemical Release, Reg. Guide 1.78, issued June 1979.
4. J.A. Simmons, R.C. Erdmann, and Barry Naft, Risk of Catastrophic Spills of Toxic Chemical, UCLA Report, PO-65037-0, for National Science Foundation, December 1973.
5. J.N. Murphy, M.E. Harris, and D. Burgess, Hazards of Marine Transportation of Liquid Chlorine, PMSRC Report No. S-4155, Bureau of Mines, Pittsburgh, Pennsylvania, March 1970.
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## APPENDIX A

### HAZARDOUS MATERIALS IN TRUCK TRANSPORT

The data presented in Table A.1 was obtained by Dames and Moore. The data were gathered\* by personnel at the truck weigh station near the plant. This information was recorded on a previously designed form. The explanation for the small amount of chlorine indicated is that the container is compartmentalized and this is the amount available for release.

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\* Information included is based on a private conversation between R. Fullwood (SAI) and Peter Gottlieb, February 5, 1981.

Table A.1

## CHEMICALS AND TOXICITY LIMITS

Chemical Name	Q, Gallons <sup>(a)</sup>	X <sub>TL</sub> , mg/m <sup>3</sup> <sup>(b)(c)</sup>	Annual <sup>(a)</sup> Shipments	Estimated Pool <sup>(b)</sup> Length, L (cm)	Description <sup>(a)</sup>
GASOLINE	4500	4000	17,000	1829	Liquid
DIESEL OIL	4500	1355	650	1829	Liquid
JET FUEL	4500	1000	910	1829	Liquid
ACETONE	7600	3000	43	1829	Liquid
DIACETONE	2600	360	43	1829	Liquid
XYLENE	3750	655	24	1829	Liquid
SHELL SOL M-75	2000		43	1829	See Standard Solvent
TOLU-SOL-6	2000		43	1829	See Standard Solvent
NAPHTA	2000		43	1829	(g)
METHANOL	2000	310	---	1829	Liquid
MS-20-H (NAPHTALENE)	4000	75	43	1829	Liquid
PENTACHLOROPHENOL	2000	1.5	43	1829	Liquid
ISOPROPHYL ALCOHOL	4500	1225	43	1829	Liquid
STANDARD SOLVENT	4500	750	43	1829	Liquid, Assumed to be TOLUENE
BENZENE	50	30	43	435	Liquid
MOTOR OIL	55		43	456	(g)
FORMALDEHYDE	6000	3	14	1829	Liquid
WEED OIL	4500		43	1829	(g)
CRUDE OIL	4500		43	1829	(g)
HYDRAULIC OIL	4500		43	1829	(g)

Table A.1 (Continued)

Chemical Name	Q, Gallons <sup>(a)</sup>	X <sub>TL</sub> , mg/m <sup>3</sup> <sup>(b)(c)</sup>	Annual <sup>(a)</sup> Shipments	Estimated Pool <sup>(b)</sup> Length, L (cm)	Description <sup>(a)</sup>
PERCHLOROETHYLENE	4000	1000	43	1829	Liquid
METHYL-BUTYL-KETONE	2000	150	43	1829	(e) Liquid
METHYLENE CHLORIDE	2000	900	43	1829	Liquid
METHYL ETHYL KETONE	2000	740	43	1829	Liquid
ETHYLENE DICHLORIDE	1000	300	43	1829	Liquid
BUTYL ACETATE	2000	950	43	1829	Liquid
EPOXY HB-151	1		43	61	(g)
METHYL ISOBUTYL KETONE	2000	510	43	1829	Liquid
NORMAL BUTYL KETONE	2000	150	43	1829	Liquid
FUEL ADDITIVE	2000			1829	(g)
BUTANE	8485	1750	2200	1829	Liquefied Gas
PROPANE	8485	1750	2200	1829	Liquefied Gas
LNG	9252		420	1829	(d), Liquefied Gas
HYDROGEN	8500		52	1829	(d), Liquid
HYDROGEN	11400 ft <sup>3</sup>		260	----	(d), Gas
ACETYLENE	219 ft <sup>3</sup>		200	----	(d), Gas
CO <sub>2</sub>	1500	87400	260	1829	Liquefied Gas
ARGON	330 ft <sup>3</sup>		200	----	(d), Gas
ARGON	8000		200	----	(d), Liquid
NITROGEN	226 ft <sup>3</sup>		2400	----	(d), Gas
NITROGEN	8000		2400	----	(d), Liquid
CHLORINE	153	43	754	761	Liquefied Gas
ANHYDROUS AMMONIA	2950	27	108	1829	Liquefied Gas
METHYL BROMIDE	125	60	48	690	Liquefied Gas
VIKANE	10.7	40	43	96.7	Liquefied Gas

Table A.1 (Continued)

Chemical Name	Q, Gallons <sup>(a)</sup>	$X_{TL}, \text{mg/m}^3$ <sup>(b)(c)</sup>	Annual <sup>(a)</sup> Shipments	Estimated Pool <sup>(b)</sup> Length, L (cm)	Description <sup>(a)</sup>
HYDROCHLORIC ACID	4600	7	133	1829	Liquid
SULFURIC ACID	6000	1	130	1829	Liquid
MURIATIC ACID	5000	7	43	1829	Liquid
NITRIC ACID	6000	10	130	1829	Liquid
USED BATTERIES	0.25		490	31	(f)

(a) Dames and Moore Report, Reference 1.

(b) NUC, Toxic Hazard For SONG Evaluation, Reference 2.

(c) NRC, Regulatory Guide 1.78, Reference 3.

(d) not evaluated, simple asphyxiant

(e) insufficient information available for evaluation

(f) non-toxic

(g) not evaluated, not readily formed into vapor cloud

## APPENDIX B

### SOURCE TERMS

Hazardous materials in transport may be solid, liquid or gaseous at ambient temperature. This Appendix provides the source terms to the atmospheric dispersion calculations performed by SAITOX. These source terms are based on the assumption that all of the material in transport shown in Appendix A is released while in fact not all may be released and the results should be scaled proportionally. This linear scaling, if used, would introduce a slight error that is conservative because a smaller size results in a smaller Reynolds number tending toward laminar flow.

Solid materials that have been considered are not sufficiently dispersible to reach 800 ft. or more from the accident. Materials that are liquid at standard conditions are treated in the next section (B.1.1), as evaporating due to air passage. Materials that are normally gaseous but shipped as pressurized liquids will flash to vapor when unconfined, thereby subcooling the remaining material which evaporates at a rate dependent on the heat flux. Gaseous material shipped as a gas is treated as adiabatically expanding and dispersing as a plume. Section B.2 presents the model for the flashing to vapor and Section B.3 presents the pool boiling model.

#### B.1 EVAPORATION RATE MODEL

##### B.1.1 Background

Bird, Stewart, and Lightfoot (B-1) define  $\phi$ , the rate factor, for mass transfer from the liquid surface to its vapor phase as:

$$\phi = \ln (1 + R) \quad (B-1)$$

where

$$R = \frac{X_{ao} - X_{a\infty}}{\frac{N_{ao}}{N_{ao} + N_{bo}} - X_{ao}}, \quad (B-2)$$

$$X_{ao} = \frac{P_a}{P}$$

$P_a$  = Partial pressure of species a (torr)

$P$  = Ambient pressure (atm or torr).

$X$  is the molar fraction and  $N$  is the molar flux (g-moles/cm<sup>2</sup>-sec). It is assumed that the material in the spill is not soluble in air and that none of the vapor is in the approaching air stream.

Then

$$X_{a\infty} = 0 \text{ and } N_{bo} = 0.$$

Using the definition of  $\phi$  (for  $N_{bo} = 0$ )

$$\phi = \frac{N_{ao}}{k_x}, \quad (B-3)$$

equations B-1 and B-2 may be solved for the molar flux

$$N_{ao} = k_x \ln \left( \frac{X_{ao}}{1 - X_{ao}} + 1 \right) \quad (B-4)$$

By including the surface area  $A$  (cm<sup>2</sup>) and the molecular weight  $M$  (g/g-mole), the mass transfer rate (evaporation rate) is found:

$$W_a = M_a A k_x \ln \left( \frac{P_a}{P - P_a} + 1 \right) \quad (B-5)$$

where  $k_x$  the mass transfer coefficient is found in the following.



The mass transfer coefficient ( $k_x$ ) is obtained by analogy with corresponding problems in heat transfer. That is, a correlation between Nusselt, Reynolds, and Prandtl numbers from heat transfer considerations may be used as the correlation between Sherwood, Reynolds, and Schmidt numbers for mass transfer.

For forced convection due to flow over a flat plate, Kreith (B.2) gives the following heat transfer correlations:

$$\overline{Nu}_L = 0.664 Re_L^{1/2} Pr^{1/3} \quad (B-6)$$

$$\overline{Nu}_L = 0.036 Pf^{1/3} (Re^{0.8} - 23200). \quad (B-7)$$

Equation B-6 is valid in the laminar flow regime ( $Re < 5 \times 10^5$ ), while equation B-7 holds for turbulent flows. Substituting the Sherwood number for the Nusselt number, and the Schmidt number for the Prandtl number for laminar flow, the following is obtained:

$$\overline{Sh}_L = \frac{k_x L}{c D_{ab}} = 0.664 Re^{1/2} Sc^{1/3} \quad (B-8)$$

Similarly, for turbulent flow, we have:

$$\overline{Sh}_L = \frac{k_x L}{c D_{ab}} = 0.036 S_c^{1/3} (Re^{0.8} - 23200) \quad (B-9)$$

Solving equations B-8 and B-9 for  $k_x$ , and using the definitions of the Reynolds and Schmidt numbers gives:

$$k_{x, \text{laminar}} = \frac{0.664 c D_{ab}}{L} \left( \frac{uL}{\nu} \right)^{1/2} \left( \frac{\nu}{D_{ab}} \right)^{1/3} \quad (B-10)$$

$$k_{x, \text{turbulent}} = \frac{0.036 c D_{ab}}{L} \left( \frac{\nu}{D_{ab}} \right)^{1/3} \left[ \left( \frac{uL}{\nu} \right)^{0.8} - 23200 \right] \quad (\text{B-11})$$

where  $u$  is the wind speed in cm/sec.

$$D_{ab}(P, T) = D_{ab}(P_o, T_o) \left( \frac{P_o}{P} \right) \left( \frac{T}{T_o} \right)^{3/2} \quad (\text{B-12})$$

where  $P_o, T_o$  are the pressure and temperature at which the diffusivity are reported.

Theoretical predictions of the diffusivity are based on the Chapman-Enskog kinetic theory of gases (B-3). This theory predicts the diffusivity as:

$$D_{ab} = 0.0018583 \frac{\sqrt{T^3 \left( \frac{1}{M_a} + \frac{1}{M_b} \right)}}{P \sigma_{ab}^2 \Omega_{D,ab}} \quad (\text{B-13})$$

The Lennard-Jones parameters  $\sigma_{ab}$  and  $\epsilon_{ab}/k$  are estimated by combining parameters for the individual species:

$$\sigma_{ab} = 1/2 (\sigma_a + \sigma_b) \quad (\text{B-14})$$

$$\epsilon_{ab}/k = \sqrt{(\epsilon_a/k) (\epsilon_b/k)} \quad (\text{B-15})$$

The Lennard-Jones parameters for the individual species may be obtained from tabulations (B-4 through B-6) or estimated from the properties of the fluid at the critical point (subscript c) or liquid at the normal boiling point (subscript B), by means of empirical correlations (B-7),

$$\epsilon/k = 0.77 T_c \quad (\text{B-16})$$

$$\sigma = 0.841 v_c^{1/3} \quad (B-17)$$

$$\sigma = 2.44 \left( \frac{T_c}{P_c} \right)^{1/3} \quad (B-18)$$

$$\epsilon/k = 1.15 T_B \quad (B-19)$$

$$\sigma = 1.166 v_{B, liq}^{1/3} \quad (B-20)$$

$c$  = Molar concentration of air (the value used in this analysis was  $3.88 \times 10^{-5}$  g-moles/cc)

$v$  = Kinematic viscosity of air (the value used in this analysis was  $0.1671 \text{ cm}^2/\text{sec}$ ).

### B.1.2 Summary Evaporation Rate

The evaporation rate, as a function of wind speed and spill size, is obtained by substituting equation B-10 or B-11 into equation B-5 and multiplying by 1000 (to obtain mg/sec).

$$Q = M_a \cdot 3.471 \times 10^{-2} A D_{ab}^{2/3} \sqrt{\frac{u}{L}} \left( \ln \frac{P_a}{P-P_a} + 1 \right) \text{ mg/sec} \quad (B-21)$$

(laminar)

$$Q_{wa} = M_a \cdot 1.397 \times 10^{-3} A D_{ab}^{2/3} (2.305 u^{0.8} L^{-0.2} - 12800/L) \ln \left( \frac{P_a}{P-P_a} + 1 \right) \text{ mg/sec} \quad (B-22)$$

(turbulent)

The characteristic length ( $L$ ) is determined by assuming the spill area is square. The surface area of the spill is based on a minimum pool thickness of 1 cm. The maximum surface area of the pool is limited to  $3600 \text{ ft}^2$  ( $60^2$ ) based on considerations of the road topography.

The results of applying equation B-24 for the hazardous materials in transport are presented in Table B.1. These results are for turbulent flow at a wind speed of 11 m/sec (equation B-22). The turbulent flow regime is chosen for

TABLE B.1  
EVAPORATION RATES FOR LIQUID CHEMICALS

Chemical Name	(a) $D_{ab}$ , (cm <sup>2</sup> /s)	(b) $M_a$ , (g/g-mole)	(c) $P_a$ , (torr)	(d) $Q_o$ , (mg/s)
GASOLINE	.09	114.23	517	$1.62 \times 10^7$
DIESEL OIL	.09	170.3	155	$4.82 \times 10^6$
JET FUEL	.09	128.25	155	$3.63 \times 10^6$
ACETONE	.134	58.1	400	$7.02 \times 10^6$
DIACETONE	.2	116.2	1.1	$3.55 \times 10^4$
XYLENE	.2	106.2	20	$5.98 \times 10^5$
METHANOL	.17	32.0	260	$2.54 \times 10^6$
MS-20-H (NAPHTALENE)	.2	128.6	1	$3.57 \times 10^4$
PENTA CHLOROPHENOL	.2	266.4	40	$3.04 \times 10^6$
ISOPROPYL ALCOHOL	.106	60.1	105	$1.24 \times 10^6$
STANDARD SOLVENT	.1	92.13	36.7	$6.06 \times 10^5$
BENZENE	.1	78.11	100	$9.79 \times 10^4$
FORMALDEHYDE	.2	30	198	$1.91 \times 10^6$
PERCHLOROETHYLENE	.2	165.85	15.8	$7.36 \times 10^5$
METHYL-BUTYL-KETONE	.2	100.16	10	$2.80 \times 10^5$
METHYLENE CHLORIDE	.2	84.94	380	$1.24 \times 10^7$
METHYL ETHYL KETONE	.2	72.10	71.2	$1.50 \times 10^6$
ETHYLENE DICHLORIDE	.2	99	165	$5.12 \times 10^6$
BUTYL ACETATE	.2	116.16	15	$4.89 \times 10^5$
METHYL ISOBUTYL KETONE	.2	100.2	16	$4.50 \times 10^5$
NORMAL BUTYL KETONE	.2	100.16	10	$2.80 \times 10^5$
HYDROCHLORIC ACID	.2	36.5	10	$1.02 \times 10^5$
SULFURIC ACID	.1038	98.08	.005	$8.93 \times 10^1$
MURIATIC ACID	.186	36.47	16	$1.56 \times 10^5$
NITRIC ACID	.2	63	10	$1.76 \times 10^5$
MURIATIC ACID (POOL CHEMICAL)	.186	36.47	16	$1.41 \times 10^2$
GEL COAT & RESIN	.08	104.14	15	$1.74 \times 10^4$
ROOFING RESIN	.08	104.14	15	$2.38 \times 10^5$

NOTES:

- (a) Diffusion coefficient for air-chemical pair
- (b) Molecular weight of chemical
- (c) Vapor pressure of chemical at 100F
- (d) Reference Evaporation Rate at 100% spill, 11 m/s wind speed.

its wider range of applicability and its more conservative results. The computer program SAITOX includes a factor on  $Q$  of  $(u/11)^{0.8}$  so that the values in Table B-1 may be directly used as the source term for evaporative chemicals with this factor providing the wind speed correction for the wind rose superposition.

## B.2 Flash Evaporation Model

When a liquified gas is rapidly depressurized, a portion will flash to vapor taking away the heat of vaporization and cooling the remainder to sub-boiling temperature. A heat balance is written as:

$$M_L C_p (T_o - T_B) = M_v h_{fg}.$$

If  $M_L + M_v = M$  and  $f$  is the fraction flashing to vapor, then  $f = M_v/M$  and  $M = M_L + M_v$

$$f = \frac{1}{1 + \frac{h_{fg}}{c_p (T_o - T_B)}} \quad (B-23)$$

where  $c_p$  is the specific heat (approximated or being constant)  $T_B$  is the boiling temperature.  $T_o$  is the ambient air temperature at the accident site (294°K, 70°F) and  $h_{fg}$  is the heat of vaporization.

Table B.2 presents the parameters necessary to evaluate equation B-23 for the hazardous liquified gases in transport near the plant and gives the flashing fractions and puff release quantities.

## B.3 POOL BOILING MODEL

The heat balance for a boiling pool is :

TABLE B.2

FLASHING FRACTIONS AND RELATED PARAMETERS ( $T_a = 70^\circ\text{F}$ )

Chemical	Boiling Temp ( $T_B$ °K)	$C_p$ (Cal/ °C.gm)	$h_{fg}$ (Cal/gm)	f	$Q_f$ (mg)
BUTANE	272	0.56	91.9	0.118	$2.2 \times 10^9$
CARBON DIOXIDE	195	0.147	35	0.294	$2.6 \times 10^9$
CHLORINE	239	0.114	31	0.168	$1.5 \times 10^8$
ANHYDROUS AMMONIA	240	1.09	327	0.153	$1.2 \times 10^9$
METHYL BROMIDE	276	0.21	60.2	0.059	$4.9 \times 10^7$
VIKANE	218	0.975	45.0	0.622	$5.7 \times 10^7$
PROPANE	186	0.389	83	0.336	$5.4 \times 10^9$

$$Mh_{fg} = Q_c + Q_a + Q_s \quad (B-24)$$

where

M = Mass of liquid spilled (lb),  $h_{fg}$  is the heat of vaporization of the spilled liquid (Btu/lb),  $Q_c$  is the heat supplied by the roadway by conduction (BTU),  $Q_a$  is the heat supplied by connective air flow over the pool (BTU), and  $Q_s$  is the solar heat (BTU).

### B.3.1 Conduction From the Highway

The total heat conducted from highway (concrete) slab to the liquid pool during the time required to evaporate all the liquid is given by (B-8):

$$Q_c = 2K_c A(T_c - T_o) \sqrt{\frac{\theta}{\pi \alpha}} \quad (B-25)$$

where

$T_c$  = Temperature concrete (°F),

$T_o$  = Boiling point of liquid (°F)

A = Area of spill (ft<sup>2</sup>)

$K_c$  = Thermal conductivity of concrete (the value used in this analysis was 0.54 (Btu/hr-ft-°F)

$\alpha$  = Thermal conductivity of concrete (the value used in this analysis was 0.19 ft<sup>2</sup>/hr).

### B.3.2 Convection From Air

The total heat transfered to the pool by convection, during the same time period, is given by (B-9):

$$Q_a = \bar{h}_a A(T_a - T_o) \theta \quad (B-26)$$

where

$T_a$  = Temperature of Air (F) and  $\bar{h}_a$  is defined below:

The film coefficient ( $\bar{h}_a$ ) is determined from correlation between Nusselt, Reynolds, and Prandtl numbers as (B-10, B-11):

$$\bar{h}_a = \frac{\overline{Nu}_L K_a}{L} \quad (B-27)$$

where

$L$  = Characteristic length of spill (cm). For simplicity the pool was assumed square.

$K_a$  = Thermal conductivity of air (The value used in this analysis was 0.0154 (Btu/hr-ft-°F))

and the Nusselt number has several forms depending upon the flow regime:

$$\overline{Nu}_L = \frac{\bar{h}_a L}{K_a} = 0.664 Re_L^{1/2} Pr^{1/3} \quad (B-28)$$

$$\overline{Nu}_L = 0.036 Pr^{1/3} (Re_L^{0.8} - 23200). \quad (B-29)$$

Equation B-28 is applicable to the laminar flow regime ( $Re_L < 5 \times 10^5$ ), while equation B-29 is applicable to turbulent flows using a Prandtl number of .72 and all other parameters as previously defined.

$$\bar{h}_a = 0.279 (Re_L)^{.5}/L \quad (\text{laminar}) \quad (B-30)$$

$$\bar{h}_a = 0.0151 (Re_L^{0.8} - 23200)/L \quad (\text{turbulent}) \quad (B-31)$$

$$Re_L = uL/0.1671 \quad (B-32)$$

where

$u$  = wind speed (cm/sec), and the Reynolds number ( $uL/v$ ) includes a value for the air viscosity  $v$  of  $0.1671 \text{ cm}^2/\text{sec}$ .



### B.3.3 Solar Insolation

The total heat addition due to solar insolation during the time required to evaporate all the liquid is:

$$Q_s = 365 A \theta \quad (B-33)$$

based on 365 BTU/hr-ft<sup>2</sup> solar insolation at the plant latitude (B-12) and A. The area is in square feet.

### B.3.4 Evaporation Rate

Substituting equations B-25, B-26 and B-33 into B-23 gives

$$Mh_{fg} = 2K_c A (T_c - T_o) \sqrt{\frac{\theta}{\pi \alpha}} + \bar{h}_a A (T_a - T_o) \theta + 365 A \theta \quad (B-34)$$

This may be solved for the time,  $\theta$ , as

$$\sqrt{\theta} = \frac{-b \pm \sqrt{b^2 + 4ac}}{2a} \quad (B-35)$$

$$b = 4.45 (T_c - T_o) \quad (B-36)$$

$$a = \bar{h}_a (T_a - T_o) + 365 \quad (B-37)$$

$$c = Mh_{fg}/A \quad (B-38)$$

and the average evaporation rate is:

$$\dot{Q}_o = 126 M/\theta \quad (B-39)$$

where

$\dot{Q}_o$  = average rate of vaporization (mg/sec) and the 126 arises from the units.

It should be noted that the evaporation rate for large Reynold's numbers (well into the turbulent region) goes as the wind speed to the 1.6 power; for small Reynold's numbers (laminar) the evaporation rate is linearly proportional to the wind speed. The evaporation rates after flashing

presented in Table B.3 for liquified compressed gases in shipment are based on an 11 m/s windspeed. These values are used as reference. SAITOX contains a factor  $(u/11)^{1.6}$  to correct for different evaporation rates at different windspeeds. The 1.6 power corresponds to the turbulent regime which is the more conservative since it corresponds to higher evaporation rates.

## B.6 REFERENCES

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TABLE B.3

## EVAPORATION RATES OF COMPRESSED GASES AFTER INITIAL FLASHING

Property	Butane	CO <sub>2</sub>	CL <sub>2</sub>	NH <sub>3</sub>	Methyl Bromide	Vikane	Propane
T <sub>o</sub> (boiling) (°F)	31.1	-109.3	-29.3	-28	38.4	-67.7	-43.9
P (g/cc) (a)	0.602	1.569	1.558	0.674	1.730	2.24	0.5
h <sub>fg</sub> (BTU)/lb (b)	166	247	124	589	108	81	150
$\dot{Q}$ (Tc=150°F)(mg/sec) (c)	2.1x10 <sup>6</sup>	4.4x10 <sup>6</sup>	1.8x10 <sup>6</sup>	7.6x10 <sup>5</sup>	8.1x10 <sup>5</sup>	4.6x10 <sup>4</sup>	5.8x10 <sup>6</sup>
$\dot{Q}$ (Tc=120°F)(mg/sec) (c)	1.8x10 <sup>6</sup>	3.8x10 <sup>6</sup>	1.5x10 <sup>6</sup>	6.7x10 <sup>5</sup>	6.0x10 <sup>5</sup>	3.9x10 <sup>4</sup>	4.1x10 <sup>6</sup>
$\dot{Q}$ (Tc=70°F)(mg/sec) (c)	1.4x10 <sup>6</sup>	3.0x10 <sup>6</sup>	8.5x10 <sup>5</sup>	5.5x10 <sup>5</sup>	3.4x10 <sup>5</sup>	3.0x10 <sup>4</sup>	2.1x10 <sup>6</sup>
$\dot{Q}$ (this study)(mg/sec) (d)	1.8x10 <sup>6</sup>	3.7x10 <sup>6</sup>	1.3x10 <sup>6</sup>	6.6x10 <sup>5</sup>	5.8x10 <sup>5</sup>	3.8x10 <sup>4</sup>	4.0x10 <sup>6</sup>

(a) Liquid density at boiling point

(b) Latent heat of vaporization at boiling point

(c) Boiling rate at 11 m/s wind speed is used as a reference value. SAITOX changes the reference according to the windspeed.

(d) Average of 150°F and 70°F values.

## APPENDIX C

### PROBABILITY OF AN ACCIDENTAL RELEASE

Reference C-1 describes in detail transportation accident severities including general highway accident environments. However, it lumps travel over all types of road systems (interstate, primary, secondary, etc.) into one general statistical conglomerate. A motivating factor for the construction of the interstate highway system is to save lives and reduce highway accidents. These mixed statistics are probably inappropriate to the accident rate on I-5 near the plant. This conclusion regarding the accident reduction of the interstate highway system is supported by an analysis of truck accidents conducted by the University of Michigan Highway Safety Research Institute (C-2) for the National Highway Traffic Safety Administration.

Sandia Laboratories (C-3) has performed an analysis of data from five different types of highway segments:

1. Flat and straight interstate similar to that over a large portion of the western and mid-western U.S.
2. Wide sweeping curves and hilly interstate highway which is characteristic of much of the U.S. from the Mississippi River eastward and also descriptive of a large part of the mountainous west
3. Mountainous segments of interstate such as encountered in going over mountain passes. These constitute a very small percentage of the total interstate system.
4. Interstate routes through urban or highly populated areas. The urban descriptions presented here are applicable when the traffic volume over the segment is above about 20,000 vehicles per day.
5. An uncontrolled access FAP (Federal aid primary) segment in heavily mountainous terrain. This segment represents the type of road which might be employed to bypass tunnels on mountainous interstate through which transport of hazardous materials is prohibited.

Table C.1 presents the finding of the Sandia study (C-3).

Table C.1

ACCIDENT RATES FOR VEHICLES SIMILAR TO THOSE USED FOR  
TRANSPORT OF HAZARDOUS MATERIALS FOR  
DIFFERENT TYPES OF REPRESENTATIVE ROADWAY

<u>Segment Category</u>	<u>Type of Terrain and Highway</u>	<u>Injury Accidents per Truck Mile</u>	<u>Truck Accidents per Truck Mile</u>
1	Flat, straight (interstate)	$3.3 \times 10^{-7}$	$1.1 \times 10^{-6*}$
2	Gentle hills and curves (inter- state)	$2.1 \times 10^{-7*}$	$6.3 \times 10^{-7}$
3	Mountainous (interstate)	$1.4 \times 10^{-6}$	$4.5 \times 10^{-6*}$
4	Urban (interstate)	$8.7 \times 10^{-7}$	$2.8 \times 10^{-6*}$
5	Mountainous (FAP)	$1.6 \times 10^{-6}$	$5.2 \times 10^{-6*}$

\*Based upon 0.31 ratio of injury or fatality accidents to total number of truck accidents.

Out of these studies, it seems that Category 4, the interstate urban route, is most appropriate for this study. The segment studied is I-70 passing through urban Denver. In fact, this choice may be overly conservative since many urban vehicles, such as delivery trucks, which marginally meet minimum safety requirements also travel this route.

This statistic, however, is for the probability of an accident of any severity; it is necessary to determine the probability of an accident of severity sufficient to cause a spill. The Federal Register, dated May 22, 1980, addresses the "Transportation of Hazardous Wastes and Substances." While package tests are specified for radioactive material shipments (C-4) such survivability tests are not specified for other hazardous wastes. Generally speaking, small containers survive better than large containers. The reasons include the amount of material surrounding the package, use of tie-downs, and the enclosed shipping compartment. It therefore seems that large shipments, such as gasoline or LGP, could provide a conservative criteria for other types of shipment.

Reference C-5 (Appendix D) provides calculations on failure thresholds of gasoline shipping containers. The conclusions are summarized in Table 6.1 of Reference C-5 indicating a minimum impact velocity perpendicular to an unyielding surface of 30.6 mph. The 30 ft. drop test onto an unyielding surface is the same as the collision with a like object with a closing velocity of 60 mph.

Returning to Table 6.1 of Reference C-5, it is also indicated that a perpendicular side impact at a closing velocity into an unyielding surface at 18.7 mph or greater would fail the container. By the image analysis, this corresponds to 37.4 mph; however, this makes no allowance for the protection provided by the bed of the truck and the undercarriage.

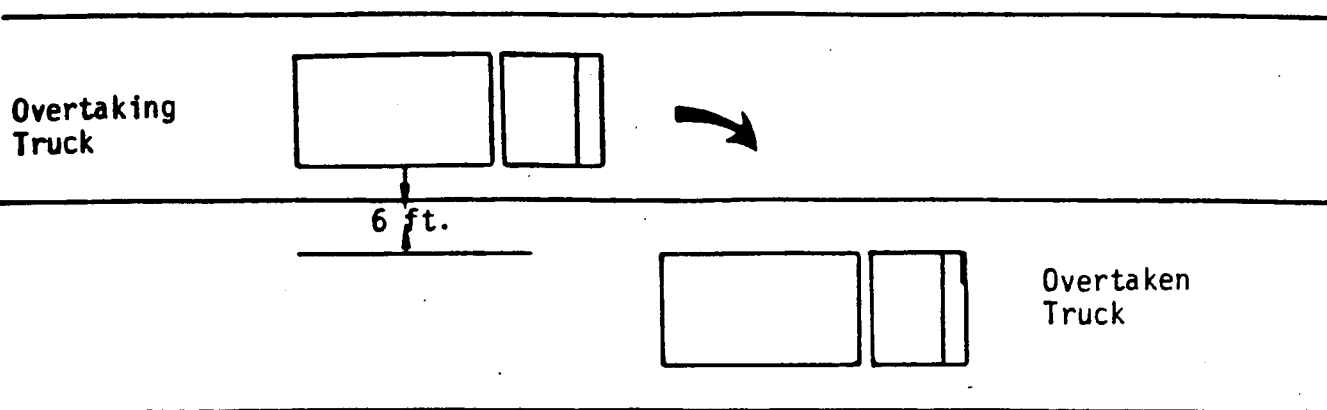


Figure C.1 Collision Geometry for Perpendicular Side Impact

Figure 3.1 presents a sketch of the collision geometry. It is necessary to estimate the maximum angle at which one truck can collide with the other. The center of gravity of a truck is taken to be 4 ft. above the ground, and the treadwidth is 7 ft., hence, the roll-over radius is:

$$r = \frac{4}{3.5} \frac{v^2}{g} .$$

At 60 mph (88 ft./sec.), this rollover radius is 176 ft.. Considering the 6 ft. separation between trucks and this radius of curvature, the angle of impact is  $11.9^\circ$ . The impact velocity to provide the same perpendicular force vector as the 18.7 mph perpendicular into the side of the container is obtained by energy scaling, i.e., scaling as the square of the velocity. This equivalent velocity is:

$$\frac{v_{\text{equiv.}}^2}{(18.7)^2} = \frac{1}{\sin 11.9^\circ}$$

or  $v_{\text{equiv.}} = 41.2$  mph into a solid wall or flat surface. The closing velocity into a similar object, like another truck, is obtained by the image theory as 82.2 mph; therefore, the rear-end collision has the lower critical closing velocity.

When the damage threshold, the effect of side barriers, and the high required closing velocity for side-on impact are considered, it is reasonable to say that the criteria for non-radiological hazardous material is about the same as that for radiological material.

A further stipulation should be placed on the analysis because most truck accidents are not with like objects (i.e., trucks) but with cars. Because of the lighter weight the forces in truck-car interactions for the same closing velocities will be much less than truck-truck interactions. Equating the impulse\* of the two types of collisions gives

$$M\Delta V_{TT} = m\Delta V_{CT} - (M-m)V_2$$

where M is the truck mass, m is the car mass,  $\Delta V_{TT}$  is the truck-truck closing velocity and  $\Delta V_{CT}$  is the car-truck closing velocity, and  $V_2$  is the overtaken truck velocity before collision.

Rearranging,

$$\frac{\Delta V_{CT}}{\Delta V_{TT}} = \frac{M}{m} + \frac{(M-m)V_2}{m\Delta V_{TT}}$$

Assuming 6000 lbs. for the weight of the car (or light truck) and 36,000 lbs. for the weight of the truck, and using  $\Delta V_{TT} = 60$  mph as before, and  $V_2 = 15$  mph, the equivalent car-truck velocity is

$$\frac{\Delta V_{CT}}{60} = 6 + 0.75$$

and  $\Delta V_{CT} = 405$  mph; thus, truck-car collisions may be excluded from consideration.

---

\* The interaction times are assumed to be the same for truck-truck as for car-truck.



The data in Table C.2 shows that in only 7% of the cases on the Colorado Interstate is the weight of the side-on on sideswiped vehicles greater than 6000 lbs., and only 6% of the rear-end collisions is the weight of the overtaken vehicle in excess of 5000 lbs. The data also show that in only 7% of the cases is the side-on closing velocity in excess of 50 mph and, in rear-end collisions, only 5% of the accidents had closing velocities greater than 40 mph. This also indicates that 40% of the accidents occurred under icing or snow road conditions which would not be expected at the SONGS site.

In summary, the estimated probability of releasing hazardous material is:

$$\text{Probability of Release (per mile)} = 2.8 \times 10^{-6} \times 0.07 \times 0.07 \times 0.6 = 8.2 \times 10^{-9} / \text{mile}$$

Base type	Probability	Other	Weather
4 prob-	of sideswipe	vehicle	like I-5
ability	at closing	weighing	near SONGS
(Table I)	velocity	6,000 lbs.	
	50 mph		

TABLE C.2

VELOCITY AND WEIGHT DISTRIBUTIONS FOR  
COLLISION ACCIDENTS WITH OTHER VEHICLES

A. HEAD-ON COLLISIONS WITH OTHER VEHICLES					
Velocity (Relative velocity between vehicles at impact in miles per hour)					
Utah Interstate		Colorado Interstate		Colorado FAP	
Insufficient Data		Insufficient Data		Sparse Data	
<u>Number of Accidents</u>	<u><math>\Delta V</math> (mph)</u>	<u>Number of Accidents</u>	<u><math>\Delta V</math> (mph)</u>	<u><math>\Delta V</math> (mph)</u>	<u>% Less Than This Value</u>
1	45	1	50	20	14
1	55	1	105	40	43
1	60			60	57
				80	72
				100	86
				120	100
Weight of Other Vehicle (in pounds)					
Utah Interstate		Colorado Interstate		Colorado FAP	
Insufficient Data		Insufficient Data		Sparse Data	
<u>Number of Accidents</u>	<u>Weight (lbs)</u>	<u>Number of Accidents</u>	<u>Weight (lbs)</u>	<u>Weight (lbs)</u>	<u>%</u>
1	< 3000	2	3000 - 4000	< 3000	30
2	3000 - 4000			3000 - 5000	53
				> 5000 *	17

\* Collision with another semi- at  $\Delta V = 75$  mph.

TABLE C.2 (Continued)

B. REAR-END COLLISIONS WITH OTHER VEHICLES					
Velocity (Relative velocity between vehicles at impact in miles per hour)					
Utah Interstate		Colorado Interstate		Colorado FAP	
13% of these accidents involved the other vehicle running into the truck; 87%, the truck running into the other vehicle.		22% of these accidents involved the other vehicle running into the truck; 78%, the truck running into the other vehicle.		Insufficient data	
<u>Velocity</u>	<u>% Less Than Average</u>	<u>Velocity</u>	<u>% Less Than Average</u>	<u>Number of Accidents</u>	<u>ΔV (mph)</u>
10	28	10	17	1	25
20	50	20	67	1	30
30	71	30	90		
40	93	40	95		
50	100	50	100		
Weight of Other Vehicle (in pounds)					
Utah Interstate		Colorado Interstate		Colorado FAP	
<u>Weight</u>	<u>% Less Than Weight</u>	<u>Weight</u>	<u>% Less Than Weight</u>	<u>Number of Accidents</u>	<u>Weight (lbs)</u>
3000	19	3000	11	1	3000
4000	50	4000	44	1	3000 - 4000
5000	88	5000	94		
6000	94*	7000	100		

\* Remaining collision is with tractor trailer at 10 mph.

TABLE C.2 (Continued)

C. SIDE-ON OR SIDESWIPE COLLISIONS WITH OTHER VEHICLES					
Velocity (Relative velocity between vehicles at impact in miles per hour)					
Utah Interstate		Colorado Interstate		Colorado FAP	
<u>Same Direction</u>	<u>Opposite Direction</u>	<u>Same Direction</u>	<u>Opposite Direction</u>	<u>Same Direction</u>	<u>Opposite Direction</u>
<u>% Less V Than V</u>	<u>Insuffic. Data</u>	<u>% Less V Than V</u>	<u>None</u>	<u>1 Accident with <math>\Delta V = 15.</math></u>	<u>% Less V Than V</u>
10 50	1 Accident	10 36			20 14
20 88	with	20 79			40 42
30 94	$\Delta V = 80.$	30 86			60 57
40 100		50 93			80 71
		80 100			100 100
Weight of Other Vehicle (in pounds)					
Utah Interstate		Colorado Interstate		Colorado FAP	
<u>Same Direction</u>	<u>Opposite Direction</u>	<u>Same Direction</u>	<u>Opposite Direction</u>	<u>Same Direction</u>	<u>Opposite Direction</u>
<u>% Less W Than W</u>	<u>Insuffic. Data</u>	<u>% Less W Than W</u>	<u>None</u>	<u>Insufficient Data</u>	<u>% Less W Than W</u>
3000 31	1 Accident	3000 14		1 Accident	4000 57
4000 50	with	4000 50		with	5000 100
5000 81	5000 - 6000	5000 86		4000 < 5000	
6000 88		6000 93			
7000 100		7000 93			
		8000 100			

## REFERENCES

- C-1 R.K. Clarke, J.T. Foley, W.F. Hartman, and D.W. Larson, Severities of Transportation Accidents, SLA74-001, Sandia Laboratories, Albuquerque, New Mexico.
- C-2 Statistical Analysis of Truck Accident Involvements, PB-208 139, University of Michigan Highway Safety Research Institute, December 1971.
- C-3 W.F. Hartman, C.A. Davidson, and J.T. Foley, Statistical Description of Heavy Truck Accidents on Representative Segments of Interstate Highway, SAND-0409, January 1977.
- C-4 10 CFR 71, Title 10, Code of Federal Regulations -- Energy, Part 71, Packaging of Radioactive Material for Transport and Transportation of Radioactive Material under Certain Conditions.
- C-5 R.W. Rhodes, "An Assessment of the Risk of Transporting Gasoline by Truck," PNL-2133, November 1978.

## APPENDIX D

### DERIVATION OF GAUSSIAN PLUME DOSAGE MODEL

For the "puff" release source considered in Section 2.0, the integrated "dosage" from a Gaussian plume passing over the plant is derived as follows. Starting with the time dependent concentration at ground level downstream of the source,

$$x(t) = \frac{2Q}{\sqrt{2\pi}^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[ -1/2 \left( \frac{x-Ut}{\sigma_x} \right)^2 - 1/2 \left( \frac{y}{\sigma_y} \right)^2 \right] \quad (D-1)$$

and integrating over time such that dosage is

$$\bar{x}(t) = \int_0^{\infty} x(t) dt \quad (D-2)$$

and assuming that  $\sigma_x$ ,  $\sigma_y$  and  $\sigma_z$  are constant over time, then

$$\bar{x} = \frac{2Q}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \left[ \exp -1/2 \left( \frac{y}{\sigma_y} \right)^2 \right] \int_0^{\infty} \exp \left[ -1/2 \left( \frac{x-\bar{U}t}{\sigma_x} \right)^2 \right] dt. \quad (D-3)$$

Using a change of variables

$$u = \frac{-x + \bar{U}t}{\sigma_x}, \quad du = \frac{\bar{U}}{\sigma_x} dt \quad (D-4)$$

$$\int_0^{\infty} \exp \left[ -1/2 \left( \frac{x-\bar{U}t}{\sigma_x} \right)^2 \right] dt = \frac{\sigma_x}{\bar{U}} \int_{-\frac{x}{\sigma_x}}^{\infty} \exp \left( -1/2 u^2 \right) du \quad (D-5)$$

$$= \frac{\sigma_x}{\bar{U}} \left[ \int_0^{\infty} \exp \left( -\frac{1}{2} u^2 \right) du + \int_{-\frac{x}{\sigma_x}}^0 \exp \left( -\frac{1}{2} u^2 \right) du \right]$$

In equation D-5,

$$\int_0^{\infty} \exp \left[ -\frac{1}{2} u^2 \right] du = \frac{\sqrt{\pi}}{\sqrt{2}}$$

For distances along the line of plume travel far distant from the release source, the value of  $x$  is large compared to the  $x$  direction standard deviation and in the limit

$$\lim_{x/\sigma_x \rightarrow \infty} \int_{-x/\sigma_x}^0 \exp \left( -\frac{1}{2} u^2 \right) du = \frac{\sqrt{\pi}}{\sqrt{2}} \quad (D-6)$$

Therefore,

$$\int_0^{\infty} \exp \left[ -\frac{1}{2} \left( \frac{x - \bar{U}t}{\sigma_x} \right)^2 \right] dt = \frac{2\sigma_x}{\bar{U}} \sqrt{\frac{\pi}{2}} \quad (D-7)$$

and

$$\bar{X} = \frac{Q}{\pi \sigma_y \sigma_z \bar{U}} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right], \quad (D-8)$$

which is the same form as the concentration equation from a chronic source

$$X = \frac{\dot{Q}}{\pi \sigma_x \sigma_z \bar{U}} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right]. \quad (D-9)$$

Equation D-9 can be compared with the 'puff' Gaussian plume model in Reg. Guide 1.78:

$$X = \frac{Q}{\sqrt{2} \pi^{3/2}} \left[ (\sigma_{x,y}^2 + \sigma_I^2) (\sigma_z^2 + \sigma_I^2)^{1/2} \right]^{-1} \exp \left[ -\frac{1}{2} \left( \frac{(x - \bar{U}t)^2}{\sigma_x^2 + \sigma_I^2} + \frac{y^2}{\sigma_y^2 + \sigma_I^2} + \frac{z^2}{\sigma_z^2 + \sigma_I^2} \right) \right] \quad (D-10)$$

On the following basis:

- initial dispersion of the 'puff'

$$\sigma_I = \frac{Q}{\sqrt{2} \pi^{3/2}} X_0 \quad (D-11)$$

is essentially zero.

- only concentration @ ground level is considered
- $\sigma_x$  and  $\sigma_y$  are independent.

Considering a continuous release, the assumption can be made that if a toxic concentration occurs at the control room air intake, it will persist for a sufficient period of time to cause a hazard. Since the plume footprint either does or does not encompass the plant air intake, dispersion in the X direction, as well as any time dependence in the dispersion equation, is eliminated. Therefore, the dispersion equation for a continuous release has the same form as developed above except that the chronic source rate  $\dot{Q}$  is used with no integration over time, and the incapacitating dosage  $\bar{X}$  is replaced by the toxic concentration  $X$ .