HAZARD ANALYSIS OF FLAMMABLE COMPRESSED GAS

SHIPMENTS ON THE ILLINOIS CENTRAL GULF RAILROAD

NEAR THE CLINTON POWER STATION

(Safety Evaluation Report - Outstanding Issue No. 1)

Illinois Power Company

Clinton Power Station - Unit 1

TABLE OF CONTENTS

I. INTRODUCTION

The Nuclear Regulatory Commission (NRC) has required an evaluation of the risk associated with rail transportation of hazardous materials in the vicinity of the Clinton Power Station (CPS). The NRC position was stated in the CPS Safety Evaluation Report (NUREG-0853 - Outstanding Issue No. 1):

> "The nearest railroad is a line of the Illinois Central Gulf Railroad which runs parallel to State Route 54 and traverses the site approximately 0.75 mile (1.21 km) north of the station. The Illinois Central Gulf Railroad also has a line approximately 3.5 mi (5.6 km) south of the station. The hazards associated with rail transportation of toxic and explosive materials are still being evaluated. Based on 1976 and 1980 transportation data obtained from Illinois Central Gulf Railroad, the applicant has identified several materials requiring further analysis. These will be addressed in a future SER supplement."

It is the purpose of this report to give a detailed discussion of the calculations required to determine the probability of a delayed detonation giving rise to an overpressure greater than 1 psi at the plant. It will be shown that the probability of such an incident causing an overpressure greater than 1 psi is acceptably low. The methodology used is similar to that used in NUREG-0014 (Reference 1).

Flammable compressed gas (FCG) is transported on the Gilman Line of the Illinois Central Gulf (ICG) Railroad which passes approximately three-quarters of a mile north of the CPS. In case of an accidental release of FCG into the atmosphere near the station, a hazard to the structural integrity of the plant could result. Such a hazard would be from the detonation of the FCG with resulting overpressures on the plant structures. According to Regulatory Guide 1.91, overpressures of 1 psi or less are considered safe. Explosions which give rise to overpressures greater than 1 psi must be analyzed further. In particular, the safety of the Seismic Category I plant structures can be demonstrated by showing that they can actually withstand the overpressure of the explosion, or that the probability of such an occurrence is acceptably low.

Regulatory Guide 1.91 provides a method for calculating the safe stand off distance which insures overpressures of 1 psi or less. For detonations which would occur at any point <u>on</u> the rail line near the station, the separation is sufficient to guarantee overpressures of less than 1 psi and therefore no further analysis is necessary. However, in the case of

accidentally released FCG, the formation of a vapor cloud which drifts toward the plant with subsequent detonation is a possibility.

II. SITE CONDITIONS

The two rail lines in the vicinity of the CPS are owned and operated by the ICG Railroad. The ICG line approximately 3.5 miles south of the station is not used to transport hazardous materials. Therefore, no additional evaluation of this line will be made. Further, the railroad is considering abandoning this line. The ICG line parallel to State Route 54, the Gilman Line, is used to transport numerous commodities including flammable compressed gas. At its closest point, this line is approximately 3,400 feet northwest of the plant. Figure 1 shows the location of the plant and surrounding facilities.

Illinois Power (IP) made a comprehensive survey of the Gilman Line from ICG shipping records for the period of December 1, 1981 to November 30, 1982. During this period, a total of 1673 trains were operated over this line. Shipments of FCG were identified on shipping records by a 49-05 series Standard Transportation Commodity Code number. From this survey, summarized in Table 1, 3472 carloads of FCG were shipped via the Gilman Line during the time period studied.

Measurements of local meteorological data were taken over a 5-year period, from April 1972 through April 1977. Joint frequency distribution of wind according to stability class, speed, and direction were taken from the CPS FSAR (Reference 2). The data encompass seven stability conditions (A through G), six speed ranges, and 16 discrete directions. The stability Categories A through G are defined in Regulatory Guide 1.23. Table 2 defines the various categories.

After the meteorological measurements were taken, a man made lake, Lake Clinton, was formed. Lake Clinton surrounds three sides of the plant and covers approximately 5,000 acres. Most of the year the temperature of the lake is greater than the surrounding air. Therefore, it would have a destabilizing effect on the air mass. That is, the air layer in contact with the lake would be heated and would tend to rise, thus causing additional movement. Since any escaping gas would be dispersed faster in increasingly unstable air, the lake would probably reduce the potential for a damage-causing explosion. For conservatism, any effects of the lake are disregarded.

III. BASIC ASSUMPTIONS

In this study, the hazard due to the transportation of FCG is considered. The railroad transports numerous gases in

this category. However, for this case, propane was chosen as the representative cargo. It was further assumed that the liquefied propane was transported in tank cars holding 160,000 lbs. of the fuel (Reference 3).

A loaded tank car loss of lading rate was determined in an Association of American Railroads Report (Reference 4) to be 0.152×10^{-6} loss of ladings per tank car mile. This spill rate is based on data from 1965 through 1970 (6 years) where a total of 49 loss of lading accidents were observed. During this period, the average loaded pressurized tank car traffic (flammable gases) was 5.38×10^{7} car miles per year (from 1% Waybill statistics). Thus, the nationwide loss of lading rate for loaded tank cars was:

$$Pr = \frac{49 \text{ accidents}}{5.38 \times 10^{7} \frac{\text{car miles}}{\text{year}} \times 6 \text{ years}} = 0.152 \times 10^{-6} \frac{\text{accidents}}{\text{car miles}} \quad (3.1)$$

A detonation rate given a loss of lading was determined to be 1.11×10^{-2} explosions/accident using a review of the University of Southern California report (Reference 5) AAR - RPI reports (References 6,7), FRA report (Reference 8) and DOT reports (Reference 9). The determination of this value is from an analysis of LPG tank car accident data from the period of 1965 through 1977 (13 years). During this time period 163 losses of ladings caused by mechanical damage resulted in three explosive incidents. This type of incident could be caused by a major rupture of the containment vessel resulting in a gross spill without ignition. The result could be the formation of a very large vapor cloud. If this cloud would be ignited after an explosive fuel-air mixture had been formed, a maximum incident explosion could result. This type of incident is characterized by an unconfined fuel/air detonation. In addition to mechanical damage induced loss of lading, exposure to fire can lead to an explosive incident. From an analysis of LPG tank car accident data for the period of 1965-1970 (6 years), 49 losses of ladings caused by fire resulted in no explosive incidents.

Thus, the nationwide detonation rate given a loss of lading for FCG is:

$$P(D/R) = \frac{3 \text{ explosions/13 years} + 0 \text{ explosions/6 years}}{163 \text{ accidents/13 years} + 49 \text{ accidents/6 years}} \quad (3.2)$$

$$= 1.11 \times 10^{-2} \frac{\text{explosions}}{\text{accident}}$$

NUREG/CR-0075 by Eichler & Napadensky (Reference 10) contains information on accidental discharge of gases from tank cars. In that report, puncture hole sizes of 23-1/2" and 7-1/2" in diameter were recommended for analysis purposes. Openings of this size would discharge gas at the constant rates of 2,667 lbs/second and 266.7 lbs/second, respectively. In this work, a 14-1/2" opening and a 4-3/4" opening were also used. The latter two have corresponding gas release rates of 888.9 lbs/second and 102.6 lbs/second, respectively. A summary of the assumed puncture hole sizes, release rates, and durations of release are given in Table 3. In the analysis, it was assumed that as the liquefied gas escaped, it immediately flash-vaporized in its entirety. This is a very conservative assumption since only about one-third of the contents would vaporize immediately, with the remainder staying as liquid droplets (Reference 10).

In evaluating the detonation potential of the escaping gas, it was assumed that the limits of flammability for propane are between 2.8% and 7% by volume of the gas-air mixture. To assess the probability of a detonation, given that an accidental discharge of FCG has occurred, a negative exponential probability density function for ignition time was used. That is, the probability of detonation between time equal to T_1 and time equal to T_2 is given by the following expression:

$$P_d(T_1,T_2) = \exp(-T_1/\beta)-\exp(-T_2/\beta) \qquad (3.3)$$

where β is the mean time to detonation.

When applying Equation (3.3) eight discrete time intervals were selected such that for a given rupture size, the time range covered the time needed to discharge the contents of the tank and to dissipate the flammable concentrations of gas. In all cases, the range was increased until the computed probability showed no increase for the increase in total time. Based on the observed time to ignition reported in Reference 8 for two rail tank car accidents, the mean time to detonation used in the analysis is nearly 300 seconds. In addition, for the 23.5- and 14.5-inch diameter ruptures, average times to detonation of 90 and 120 seconds, respectively, were used in the analysis because of rapid dumping of tank contents at these rupture sizes.

In order to evaluate the overpressure from an explosion of FCG, it was necessary to convert the explosive potential of the gas to that of TNT. According to Regulatory Guide 1.91, the product of 2.4 times the weight of the hydrocarbon involved will give an equivalent weight of TNT. Based on an equivalent weight of TNT and assuming ground level detonation, the distance from the explosion beyond which the overpressure will not exceed 1 psi is given in Regulatory Guide 1.91 as:

$$r_b = 45W^{1/3} \tag{3.4}$$

where: r_b = separation for 1 psi or less (ft)
W = equivalent weight of TNT (lbs)

IV. PROBABILITY CALCULATION

In this section, a step-by-step procedure is used to explain the calculation of the probability of exceeding the 1 psi overpressure at the plant due to an accident on the ICG Railroad. As each step is explained, numerical examples are used for clarity.

A. Division of Railroad into Segments

An approximately 2.6-mile-long section of the railroad line just north of the plant was considered. This portion of the line was used because preliminary calculations indicated that using a longer section would not make a significant contribution to the hazard probability. The 2.6-mile portion was divided into 26 segments of varying lengths: 300, 400, and 800 feet. While an accident is equally possible at any point in any of the segments, it was assumed that an accident would occur at the point in each segment which was closest to the plant. As an example, consider Segment 8 (see Figure 2). The segment is 400 feet in length; therefore, the probability that an accident occurs in the segment within a year is computed as follows:

$$P_a = 0.152\times10^{-6} \frac{\text{accidents}}{\text{car mile}} \times 400 \text{ ft} \times \frac{1}{5280} \frac{\text{miles}}{\text{ft}}$$

$$\times 3472 \frac{\text{FCG cars}}{\text{yr}} = 4.00\times10^{-5} \frac{\text{accidents}}{\text{year}} \tag{4.1}$$

If a detonation were to follow an accident right at the point of accident on the railway line, the resulting overpressure at the plant would be less than 1 psi. To see this, consider the location of the assumed accident point on Segment 8. Its distance from the plant is given by:

$$r = \sqrt{2350^2 + 2650^2} = 3542 \text{ ft} \tag{4.2}$$

In addition, the stand off distance prescribed by Regulatory Guide 1.91 is found to be:

$$r_b = 45 (160{,}000 \times 2.4)^{1/3} = 3271 \text{ ft} \tag{4.3}$$

Since the stand off distance is less than the actual

distance to the assumed point of accident on the line, the conditions of Regulatory Guide 1.91 are fulfilled and there would be no additional concern. Since the rail line is approximately 3400 feet from the plant at its closest point, the safe stand off distance is always less than the actual distance to the assumed point of accident. However, in the case of a material such as propane, the possibility of a vapor cloud moving toward the plant and subsequently exploding must be examined. To do this, a study of cloud diffusion dynamics is necessary.

B. Cloud Dynamics

As the propane escapes from the damaged tank car, it is assumed that turbulent mixing with the air occurs. It is further assumed that the entire amount of released propane vaporizes immediately. The resulting cloud then moves with the prevailing wind. As the cloud moves away from the source, it diffuses so that the concentration becomes less and less. The concentration of vaporized propane at any point downwind from the accident point is given by the following expression:

$$\Psi(x,y,z) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right);\ u(t-T) \leq x \leq ut \qquad (4.4)$$

$$= 0 \quad x < u(t-T) \text{ and } x > ut$$

where the following symbols are used:

Ψ	=	gas concentration
Q	=	gas release rate (ft^3/sec)
u	=	wind velocity (ft/sec)
x	=	distance downwind (ft)
y	=	horizontal distance normal to drift direction (ft)
z	=	vertical distance normal to drift direction (ft)
σ_y	=	dispersion coefficient in horizontal direction (ft)
σ_z	=	dispersion coefficient in vertic direction (ft)
t	=	time after initial rupture (sec)
T	=	time required for total content of car to be released (sec)

The previous expression represents the distribution of concentration associated with a Gaussian Dispersion Process. The diffusion coefficients σ_y and σ_z depend on the distance the vapor has travelled from the source and are given graphically in Figures 3 and 4

(Reference 1). From an examination of the dispersion equation itself and the curves showing the dispersion coefficients, it is evident that the vapor concentration at any point is dependent upon wind speed, wind stability class, and time after the initial discharge of gas. In this analysis, calculations were made for each stability class and for each wind speed range. The average speed was used for each of the first five speed groups. A speed of 36.7 fps (25 mph) was used for the highest speed range.

The calculations were carried out for several different total time durations. Hazard probabilities were calculated for a given gas discharge rate and mean time to ignition, increasing the total time on each successive cycle. Although the cloud formation and drift are continuous processes, the numerical computations were only carried out for discrete time points. Flammable gas volumes and centroid drift distances were calculated at eight times over the duration. The probability of detonation was also evaluated for eight time intervals, the intervals being chosen such that the times of flammable volume and centroid travel calculation fell at the mid-points of the intervals. Figure 5 gives an example of the time steps used in a 1600 second total time calculation.

It is noted from Figures 3 and 4 that the dispersion coefficients σ_y and σ_z are dependent upon the distance from the source. Since the curves representing the coefficients do not admit values for zero distance from the source (that is, at the source itself), a device is needed which will allow use of the dispersion equation in conjunction with the dispersion coefficient curves and still yield a concentration of 100% at the source. The device most often used to accomplish this is the computation of a virtual source distance. That is, it is assumed that a source exists somewhat behind the actual source. The actual distance between the real source and the virtual source is chosen to give dispersion coefficients which, when utilized in the dispersion equation, give a 100% concentration on the centerline at the source.

For example, consider wind stability Class D and wind speed of 7.4 fps. If the dispersion coefficients are assumed equal at the source, then a straightforward calculation shows that if the discharge rate is 2667 lbs/second, the dispersion coefficients must be equal to 22.3 feet:

$$\psi(0,0,0) = \frac{Q}{2\pi u \sigma^2} \quad \text{(Reference 1)} \qquad (4.5)$$

where $\sigma_y = \sigma_z = \sigma$ It follows that:

$$1.0 = \frac{\left(\frac{2667}{0.1154}\right)}{2\pi(7.4)\sigma^2} \tag{4.6}$$

where a specific weight of 0.1154 lb/ft^3 is assumed for propane.

Hence:

$$\sigma = 22.3 \text{ ft.} \tag{4.7}$$

Note that in the proceeding calculation the factor 2π appears in the denominator, while in Equation 4.4, the factor is π. Equation 4.4 is intended for the calculation of concentrations at spatial points located at distances from the source which are much greater than the elevation of the source above ground. In that case, the ground surface forms a boundary preventing diffusion downward. On the other hand, when determining the virtual source location, it is assumed that diffusion occurs in all directions normal to the cloud drift direction.

The lateral diffusion coefficient is given in the form:

$$\sigma_y = 0.18 \; x^{0.825} \tag{4.8}$$

Since σ_y = 22.3 ft, the distance to the virtual source is given by:

$$d_y = \left(\frac{22.3}{0.18}\right)^{\frac{1}{0.885}} = 232 \text{ ft} \tag{4.9}$$

Even though the graphical representation of the variation of dispersion coefficient in the vertical direction is not a set of straight lines, as is the case for the lateral dispersion coefficients, the same form of analytical expression was still used to approximate the vertical dispersion coefficients. Specifically, the form of the variation for wind stability Class D may be written as:

$$\sigma_z = 0.13 \; x^{0.825} \tag{4.10}$$

Using the same steps as before, it is determined that the virtual source distance for computation of the vertical dispersion coefficient is approximately 511 feet. In subsequent calculations for this wind

stability class and wind speed, the two distances just calculated must be added to the actual distance from the source when determining the two dispersion coefficients. Values used for calculating σ_y and σ_z for all wind stability classes are given in Table 4.

The dispersion equation allows computation of the concentration of the gas at any location downwind from the assumed point of tank car puncture. Figures 6 and 7 show contours of concentration at ground level and in a vertical plane passing through the centerline of the cloud. Using contour data of this type, the volume contained in the flammable region and the downwind centroid location of this volume can be calculated. The volume of flammable gas and its downwind location of the centroid are shown on each curve. Similar curves can be calculated for each different combination of wind stability class, wind speed and time. It is noted that no rise of the centroid of the gas volume is considered. That is because propane has a greater density than air and therefore will not be lifted by buoyant force. It is further noted that in case of gases which are lighter than air, such as natural gas, a rise of the entire cloud, independent of the upward diffusion, would be taken into account.

C. Critical Wind Directions

For a given wind stability class, wind direction, and time, a flammable volume of gas and a downwind centroid location can be obtained as shown in the previous section. The next step in the analysis is to convert the flammable gas volume into an equivalent weight of TNT. The volume is multiplied by the specific weight of propane (in this study it was taken to be 0.1154 lbs/ft^3) and subsequently multiplied by the 2.4 equivalency factor stated in Regulatory Guide 1.91. Next, the equivalent weight of TNT is used in the stand off equation given by Regulatory Guide 1.91 to determine a 1 psi explosion radius, that is, a radius within which the overpressure will be at least 1 psi if the calculated gas volume were to explode. Since the centroid of the detonating gas volume is displaced downwind from the source of gas release, a geometric calculation will show whether the centroid lies inside or outside the 1 psi damage circle. Figure 8 shows the various items involved in calculations of this type.

For Segment 8 the point of assumed accident is located 2,350 feet west and 2,650 feet north of the nearest plant structure. For stability Class D, a wind speed of 7.4 fps and for 520 seconds following the break, a flammable gas volume of 17,350 cubic feet is formed, and the centroid of the flammable volume is located

3,600 feet downwind from the point of break. Consequently, the weight of gas involved, based on a specific weight of 0.1154 lbs/ft^3, is approximately 2,002 pounds. The equivalent weight of TNT is 2.4 times the weight of gas or 4,805 pounds. It follows that the 1 psi damage radius obtained on the basis of the equation from Regulatory Guide 1.91 is:

$$r_b = 45\ (4805)^{1/3} = 757 \text{ feet} \qquad (4.11)$$

From Figure 8 it can be seen that for wind directions between 306° and 331° the centroid of the exploding gas will fall within the 1 psi damage radius. For all other wind directions the centroid will fall outside the 1 psi radius. Figure 9 shows that for the range of winds giving an unfavorable result (that is, causing the centroid to fall within the 1 psi circle), only the northwest and north-northwest sections need be considered. Reference 2 gives the probability of wind from all directions for the six wind speed increments for stability Class D. For winds in the speed range of 1.5 to 3.0 meters per second (average 7.4 fps), it is observed that the probability of winds from the northwest is 0.41% and for winds from north-northwest it is 0.38%. Therefore, the total probability of having winds from a direction which will cause the centroid of the detonating gas to be inside the 1 psi damage radius is 0.79%.

Next, the probability of detonation at the time under consideration is calculated. In the case under consideration here, the average time to detonation is taken as 300 seconds. Therefore, the probability of detonation in the time interval between 410 seconds and 610 seconds following detonation is given by the following:

$$P_d = \exp(-410/300) - \exp(-610/300) = 0.1241 \qquad (4.12)$$

D. <u>Combined Probability for a Single Segment</u>

The following probabilities are now used to obtain the results for Segment No. 8:

Probability of an accident in Segment 8 = 4.00×10^{-5}
Probability of unfavorable wind direction = .0079
Probability of detonation given an accident = 0.0111
Probability of detonation in time interval = 0.1241

Finally, the product of the four probabilities just stated is the probability that a detonation will occur on Segment No. 8 during wind of stability Class D, with speed of 7.4 fps in the critical directions and that detonation will occur in the 410 to 610 second time interval. The result is 4.35×10^{-10} per year.

E. Total Probability of an Explosion Hazard

Using the same steps just presented for all segments, wind stability categories, wind speeds and time intervals, then summing the results gives the total probability of an explosion hazard at the plant.

The result is expressed formally by:

$$P = P_r x P(D/R) \text{ x } F \text{ x } \sum_{N=1}^{NP} \sum_{S=1}^{7} \sum_{V=1}^{6} \sum_{I=1}^{NT} \sum_{D=1}^{16} P_w(S,V,D) x P_d(T_{I-1},T_I) x L(N) x d(S,V,D,I,N$$

where:

P_r = probability of rupture per tank mile
P(D/R) = probability of detonation (explosion) given a rupture
F = frequency of shipment of tanks carrying FCG, in shipments per year
$P_w(S,V,D)$ = probability that wind of stability class S, speed V, and direction D is blowing when detonation occurs
$P_d(T_{I-1},T_I)$ = probability that detonation occurs between times T_{I-1} and T_I, given that a rupture has occurred
L(N) = length of railroad segment N, in miles
NP = number of railroad segments considered in analysis
NT = number of detonation time intervals
d(S,V,D,I,N):
= 1 if overpressure exceeds the one psi criterion for S,V,D,I,N
= 0 if overpressure does not exceed the one psi criterion

Each total probability calculation must be based on:

a) gas discharge rate
b) mean time to detonation
c) total time after puncture occurs

As indicated earlier, four different discharge rates corresponding to four different size puncture holes were considered. In addition, the mean time to detonation was varied between 90 and 300 seconds and the time following rupture of the tank was varied from 900 to 3120 seconds, depending on the time required to empty the tank of its contents. Table 5 gives a list representative of the cases studied, including the worst cases. This list shows the results for a series of assumed conditions. As shown by the two cases in Table 5, the maximum probability calculated for all of

the cases studied was 2.3×10^{-7} per year and was distributed over the 26 segments of the rail line as shown in Table 6. According to Regulatory Guide 1.91, this probability is sufficiently low, less than 10^{-6} per year, provided conservative estimates were used. The following conservatisms were used in the evaluation:

1. The entire contents of the tank has been assumed to flash-vaporize. Actually, only 1/3 of the contents might vaporize, the remaining 2/3 staying in the form of liquid droplets.

2. Destabilizing effects of the lake have been neglected.

3. No rise of the plume due to buoyancy has been assumed.

4. The equivalent weight of TNT has been taken as 240% of the gas contained in the flammable cloud region. Regulatory Guide 1.91 indicates that the 240% represents an upper limit for hydrocarbons.

5. The safe overpressure for the safety-related structures has been taken as 1.0 psi, whereas the maximum safe overpressure for CPS is 1.65 psi, which is one-half the total tornado wind design load of 3.3 psi.

6. Statistics used for tank car accidents rates have been taken from a time period (1965-1977) before recently mandated design changes were completed. Specifically, tank cars used to transport flammable combustible gases are mandated by 49CFR173 and 179 to have a combination of the following safety features: coupler restraint systems, tank head puncture resistance systems, thermal protection systems, and safety relief valves. Tank cars not built with the mandated safety features were required to be backfitted under a timetable (1977-1982) specified in 49 CFR.

7. Exceeding the specified overpressure will not necessarily cause any radioactivity release, much less one sufficient to exceed 10CFR100 guidelines.

V. CONCLUSIONS

This study evaluated the effects on the Clinton Power Station of the accidental discharge and detonation of flammable compressed gases transported by the Illinois Central Gulf Railroad. Using conservative estimates, the probability of exceeding a 1 psi overpressure was shown to be less than 10^{-6} per year. According to Regulatory Guide 1.91, this probability is sufficiently low and, therefore, the hazards associated with FCG shipments near CPS do not need to be considered as design basis events.

VI. REFERENCES

1. NUREG-0014, "Safety Evaluation Report for Hartsville Nuclear Plants," April 8, 1976.

2. Clinton Power Station, Final Safety Analysis Report, Tables 2.3-15 through 21, "Joint Frequency Distribution, Distribution of Wind Directions and Speeds".

3. Considine, D. M., Energy Technology Handbook McGraw-Hill, 1977.

4. "Final Phase 02 Report on Accident Review", Railroad Tank Car Safety Research and Test Project, Association of American Railroads and Railway Progress Institute, Report No. RA-02-2-18. August, 1972.

5. Jones, G. P., et al, "Risk Analysis in Hazardous Materials Transportation," report by the University of Southern California Institute of Aerospace Safety and Management for the Department of Transportation, NTIS Report No. PB-230 810, March 1973.

6. "Phase 02 Report on Dollar Loss Due to Exposure of Loaded Tank Cars to Fire - 1965 through 1970," Association of American Railroads and Railway Progress Institute, Report No. RA-02-1-10, August 11, 1972.

7. "Final Phase - 01 Report on Summary of Ruptured Tank Cars Involved in Past Accidents," Association of American Railroads and Railway Progress Institute, Report No. RA-01-2-7, July 1972.

8. Federal Railroad Administration. "Unpublished Summary List of Tank-Car Accidents--Hazardous Materials Section."

9. "Hazardous Material Incident Reports," Material Transportation Board, DOT.

10. Eichler, T.V. and H. S. Napadensky, "Accidental Vapor Phase Explosion on Transportation Routes Near Nuclear Power Plants," report prepared for the NRC, NUREG/CR-0075, April 1977.

MIS '8

List of Tables

TABLE 1

FLAMMABLE COMPRESSED GAS SHIPMENTS OVER THE ILLINOIS CENTRAL GULF-GILMAN LINE, 12/1/81 to 11/30/82

STCC No.	Description of Commodity	Carloads	Tons
4905702	Butane (butane, impure for further refining)	9	675
4905703	Butadiene, inhibited (butadiene, impure for further refining)	1	75
4905706	Butane	443	31,146
4905707	Liquefied Petroleum Gas (butene gas, liquefied)	345	24,459
4905711	Liquefied Petroleum Gas (butylene, impure for further refining)	13	875
4905741	Liquefied Petroleum Gas (NIC)	1	75
4905747	Isobutane	793	57,001
4905748	Isobutylene	1	75
4905750	Isobutane (Isobutane for further refinery processing)	8	523
4905752	Liquefied Petroleum Gas	885	61,816
4905761	Methyl Chloride	3	141
4905781	Propane	164	11,559
4905782	Propylene	801	57,132
4905785	Trifluorochloroethylene	1	75
4905792	Vinyl Chloride	4	300
	Total	3472	245,927

STCC: Standard Transportation Commodity Code

NIC: Not in Code - commodity was coded with a STCC number which could not be identified from the STCC tariff. Commodity was assumed to be of the same family of nearest identifiable commodity by STCC number.

Table 2 Classification of Atmospheric Stability

Stability Classification	Pasquill Categories	σ_θ*	Temperature change with height (°C/100m)
Extremely unstable	A	25.0°	-1.9
Moderately unstable	B	20.0°	-1.9 to -1.7
Slightly unstable	C	15.0°	-1.7 to -1.5
Neutral	D	10.0°	-1.5 to -0.5
Slightly stable	E	5.0°	-0.5 to 1.5
Moderately stable	F	2.5°	1.5 to 4.0
Extremely stable	G	1.7°	4.0

*σ_θ - Standard deviation of horizontal wind direction fluctuation over a period of 15 minutes to 1 hour.

Table 3 Puncture Size and Related Gas Release Quantities

Puncture Diameter (in.)	Release Rate (lbs./Sec)	Discharge Time (Sec.)
23½	2667	60
14½	888.9	180
7½	266.7	600
4 3/4	102.6	1560

Table 4 Analytical Representations for Dispersion Coefficients

STABILITY CLASS	$\sigma_y = A_y x^{B_y}$*		$\sigma_z = A_z x^{B_z}$*	
	A_y	B_y	A_z	B_z
A	0.52	0.885	0.031	1.27
B	0.39	0.885	0.097	1.02
C	0.27	0.885	0.097	0.95
D	0.18	0.885	0.13	0.825
E	0.14	0.885	0.097	0.815
F	0.094	0.885	0.058	0.815
G	0.052	0.900	0.038	0.815

* x, σ_y, σ_z in feet

Table 5 Probability of Exceeding 1 psi Overpressure Based on Various Assumed Conditions

Discharge Time[1] (Min.)	Duration[2] (Sec.)	Mean Detonation Time[3] (Sec.)	Probability (per yr.)
26	3120	300	1.7×10^{-9}
1	180	300	5.1×10^{-8}
10	1200	300	1.5×10^{-8}
1	180	90	6.6×10^{-8}
3	400	120	2.9×10^{-8}
1	600	90	1.3×10^{-7}
1	900	300	2.3×10^{-7}
3	1500	300	1.1×10^{-7}
1	1125	300	2.2×10^{-7}
1	1500	300	2.3×10^{-7}

1 "Discharge Time" is defined as the time required, from when the car is punctured, to release the entire contents of the car.

2 "Duration" is total time modeled by the computer program, taken from when the car is punctured.

3 "Mean Detonation Time" is defined as the mean time elapsed, from when the car is punctured, until a detonation occurs.

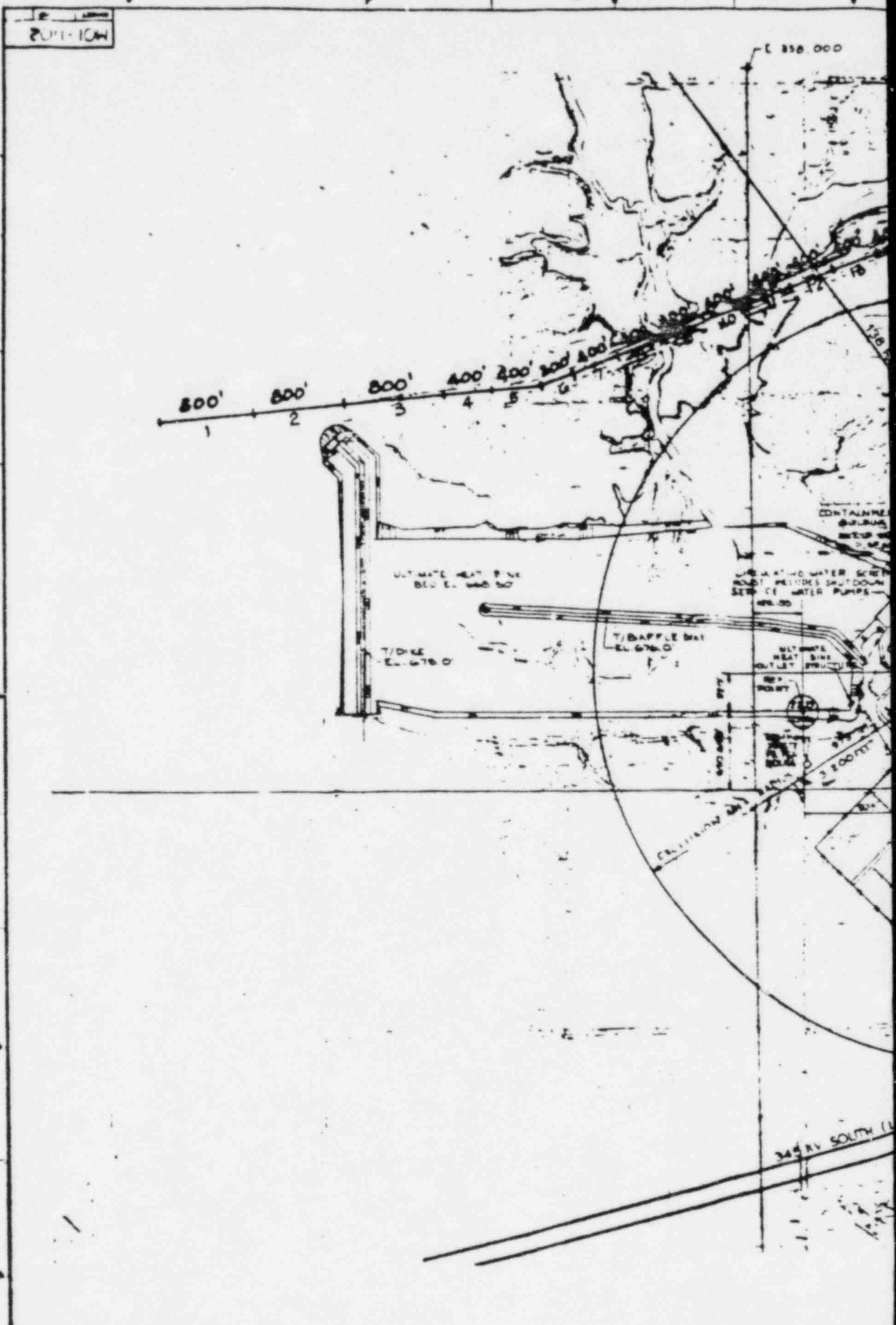
TABLE 6

CONTRIBUTION OF EACH RAILROAD SEGMENT TO TOTAL PROBABILITY

Duration: 1500 seconds
Mean Duration Time: 300 seconds

Segment Number	Contribution (%)
1	1.0
2	2.9
3	3.9
4	3.3
5	4.0
6	3.4
7	5.5
8	6.4
9	6.0
10	7.6
11	8.3
12	8.2
13	6.6
14	5.2
15	4.8
16	4.2
17	3.5
18	2.4
19	2.8
20	2.5
21	2.7
22	2.2
23	1.2
24	0.7
25	0.4
26	0.3
TOTAL	100.0 = 2.3×10^{-7} per year

List of Figures



800'
800'
800'
400'
400'
T/DIKE
T/BAFFLE DIKE
345 KV SOUTH

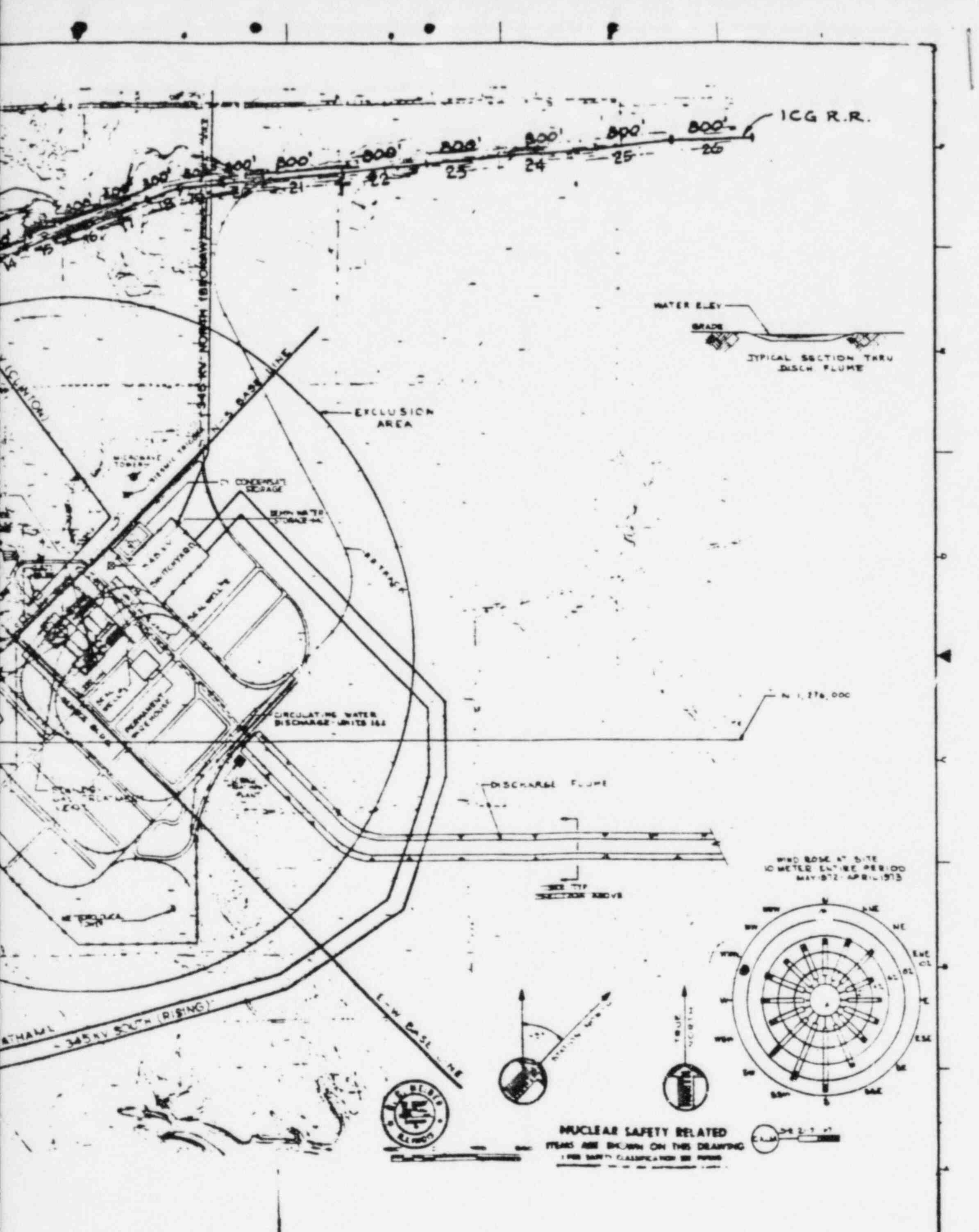


Figure 1 - Site Plan

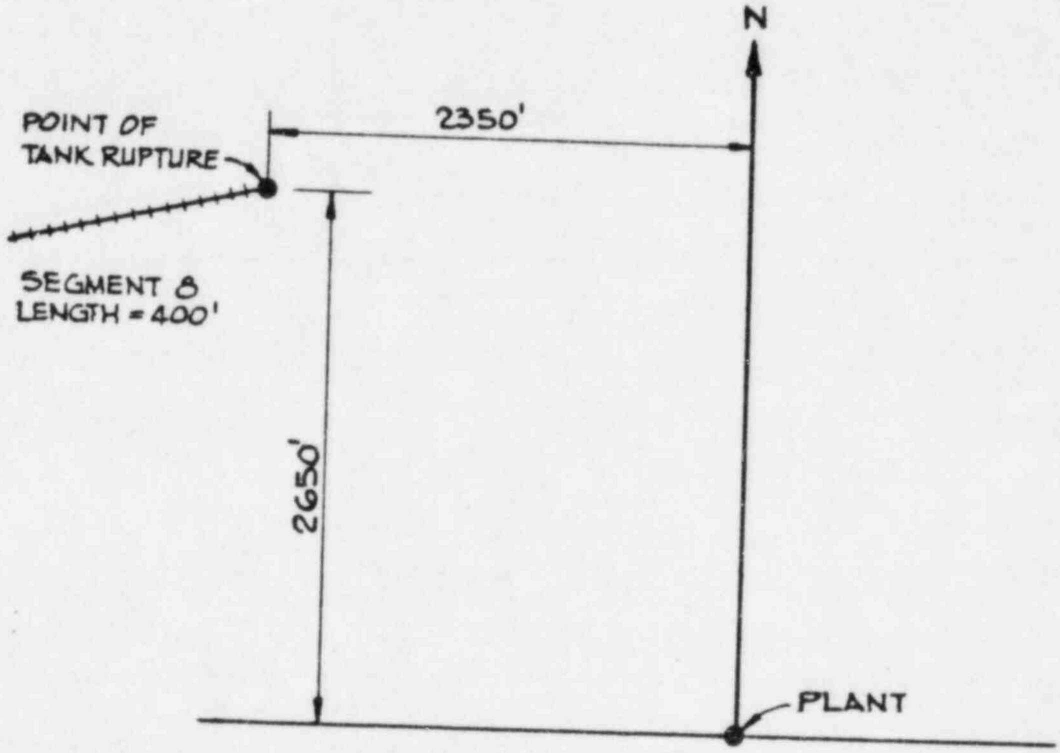


Figure 2: Isolated Segment 8 of Railroad Line

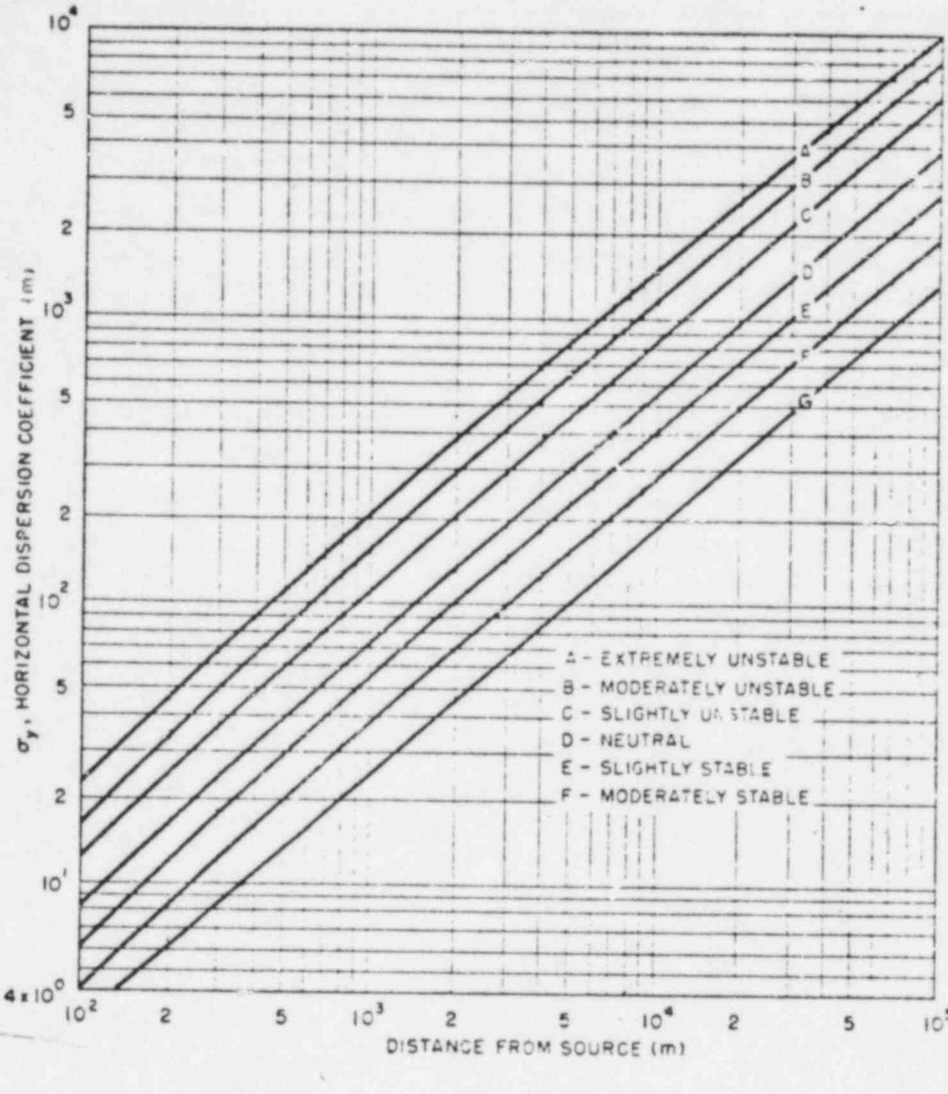


Figure 3: Horizontal Dispersion Coefficients

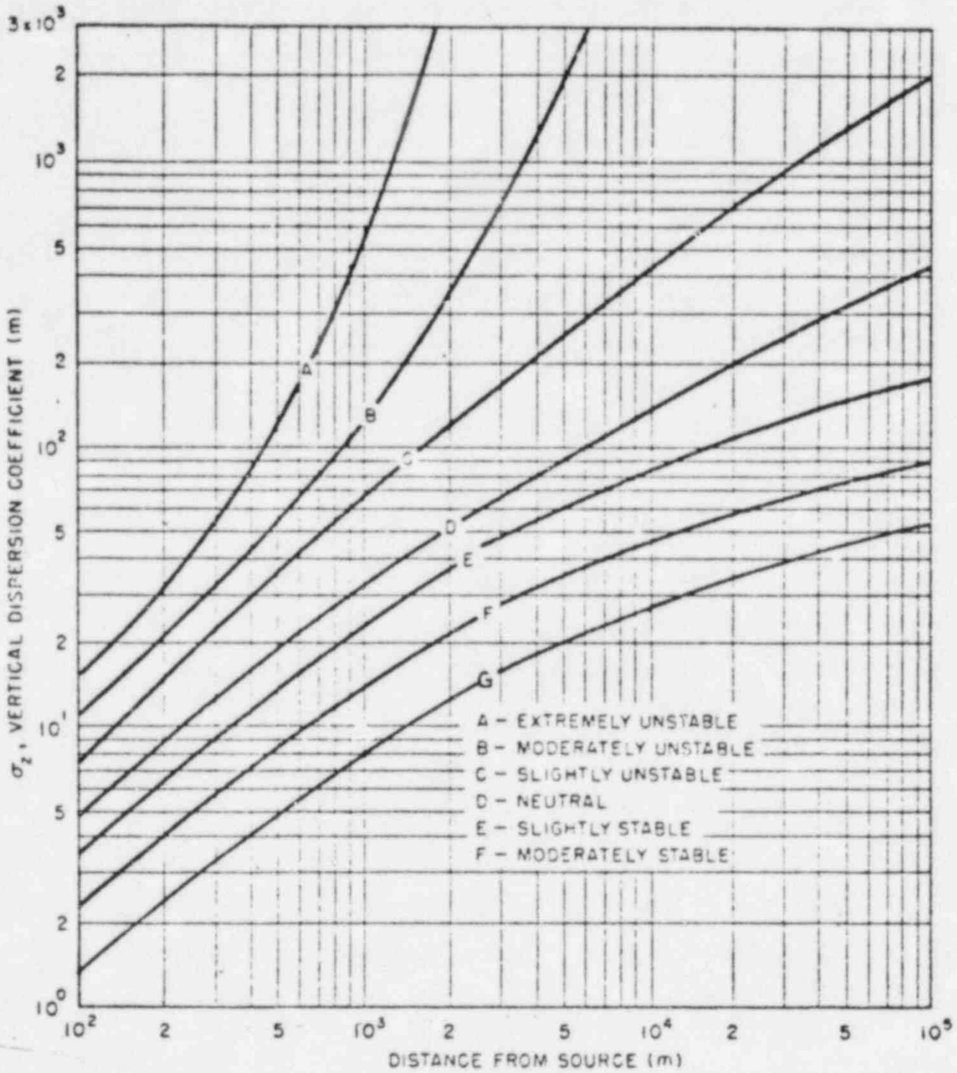


Figure 4: Vertical Dispersion Coefficients

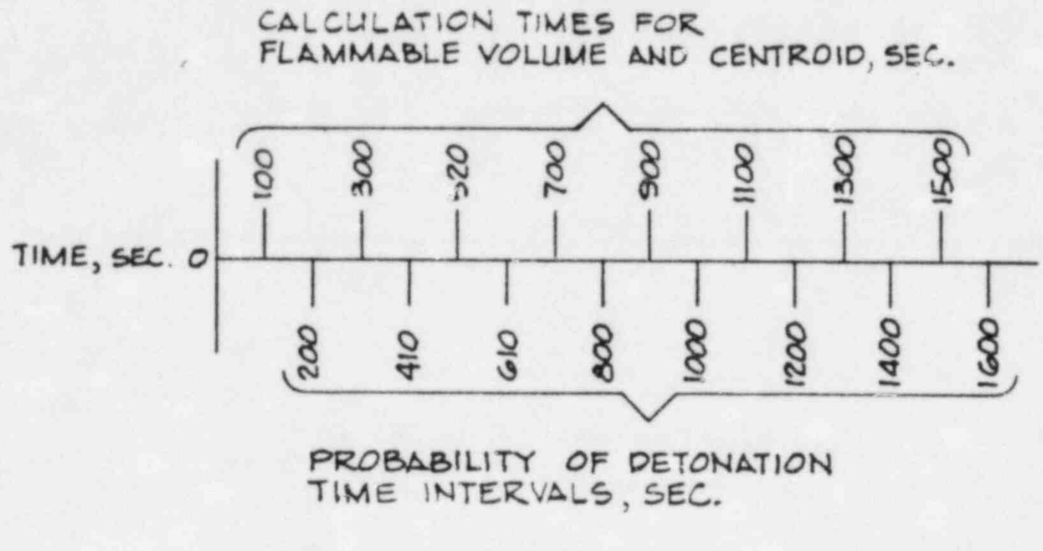


Figure 5: Time After Rupture for Calculation of Flammable Volume and Centroid Location; Time Intervals for Probability of Detonation Calculation, 1600 Second Duration

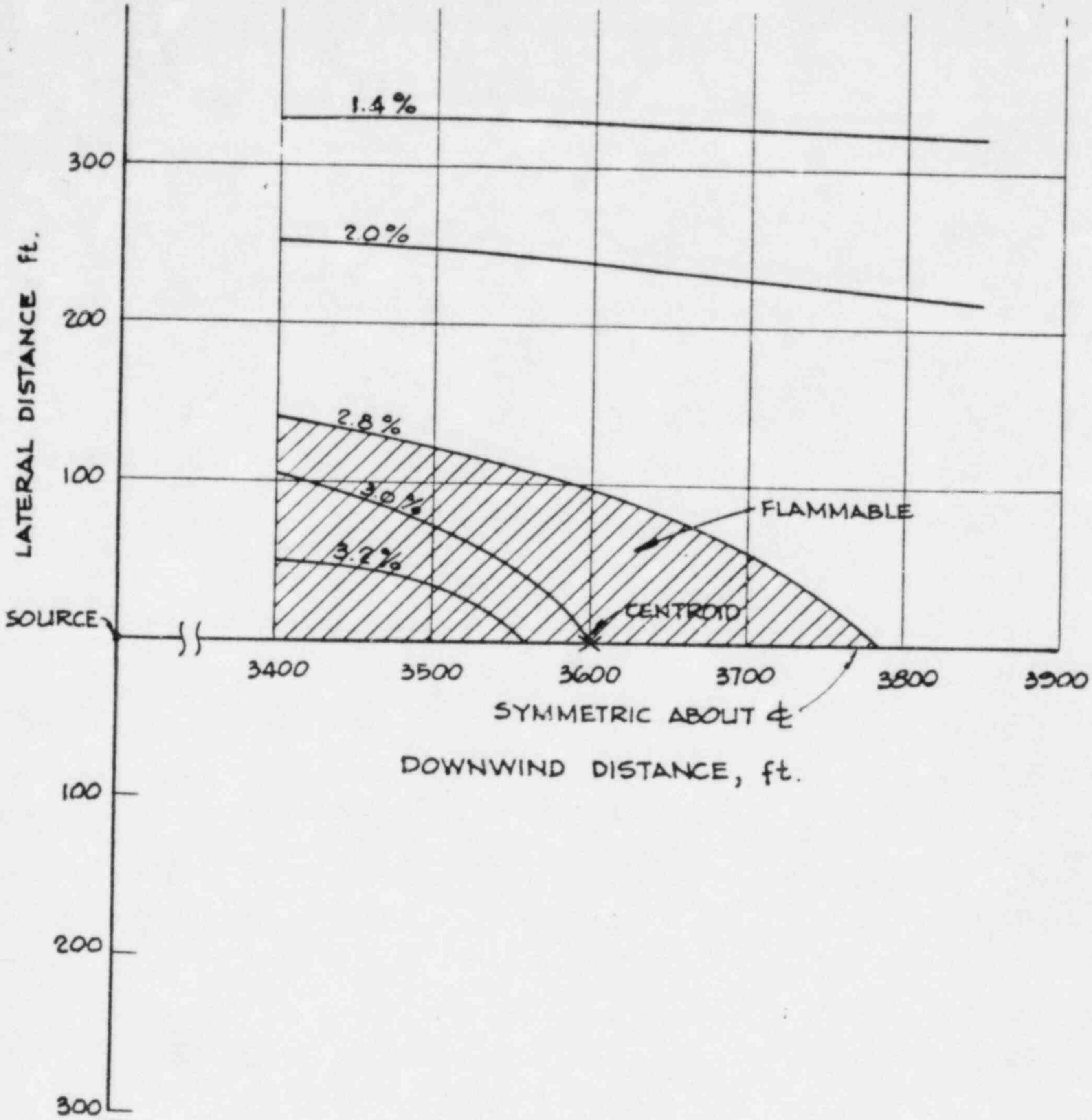
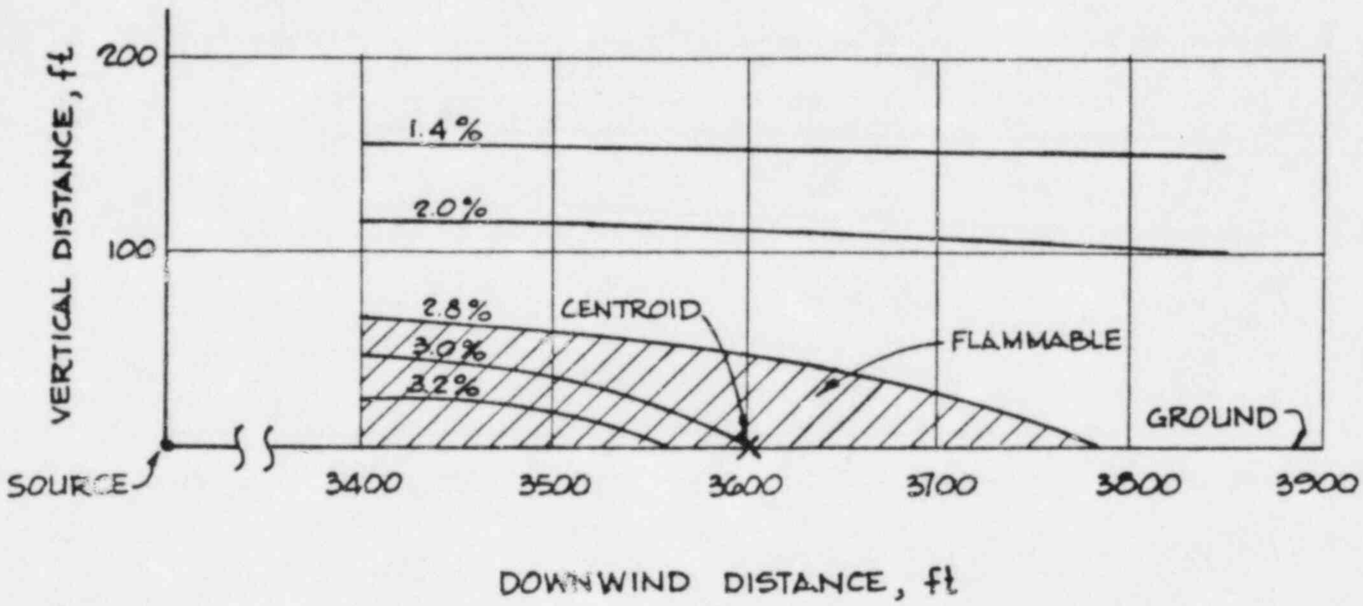
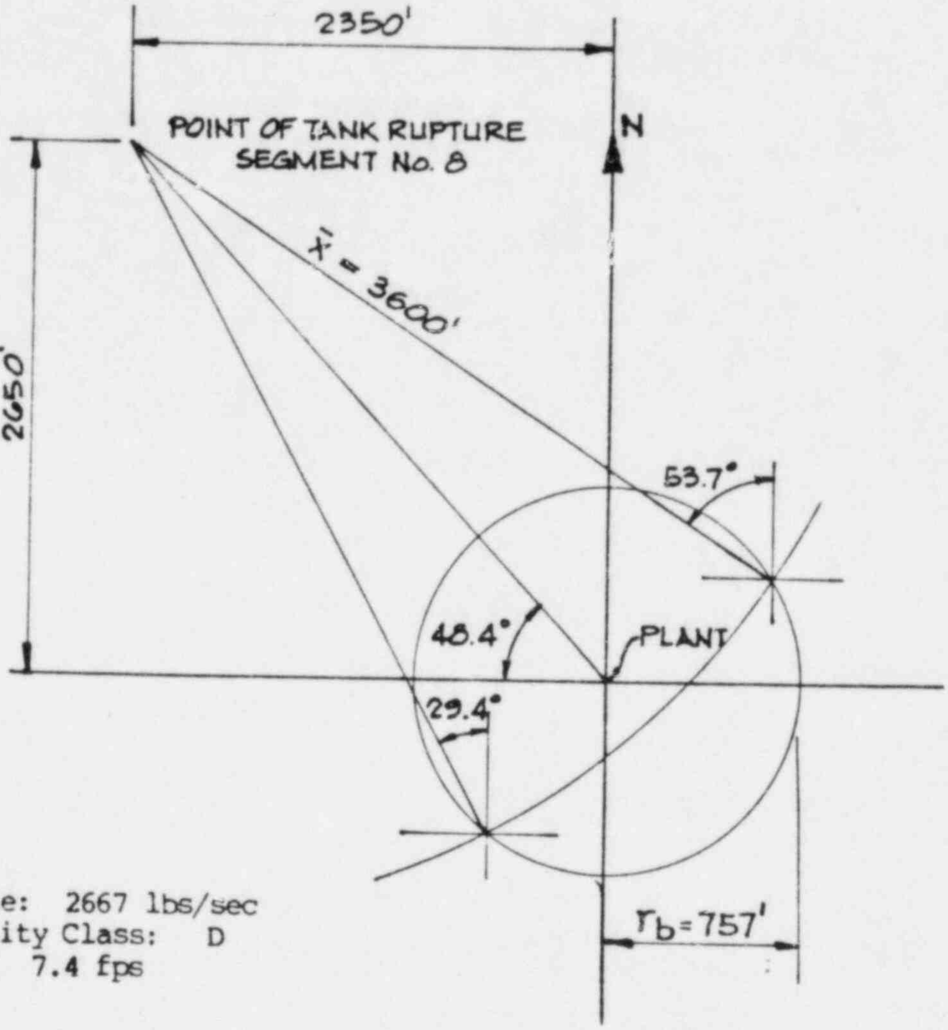


Figure 6: Ground Level Concentration at 520 Seconds After Rupture



Release Rate 2667 lb/sec.
Wind Stability Class: D
Wind Velocity: 7.4 fps

Figure 7: Concentration in Vertical Plane at Centerline of Cloud 520 Seconds After Rupture.



Release Rate: 2667 lbs/sec
Wind Stability Class: D
Wind Speed: 7.4 fps

Figure 8: Geometric Considerations for Unfavorable Wind Direction

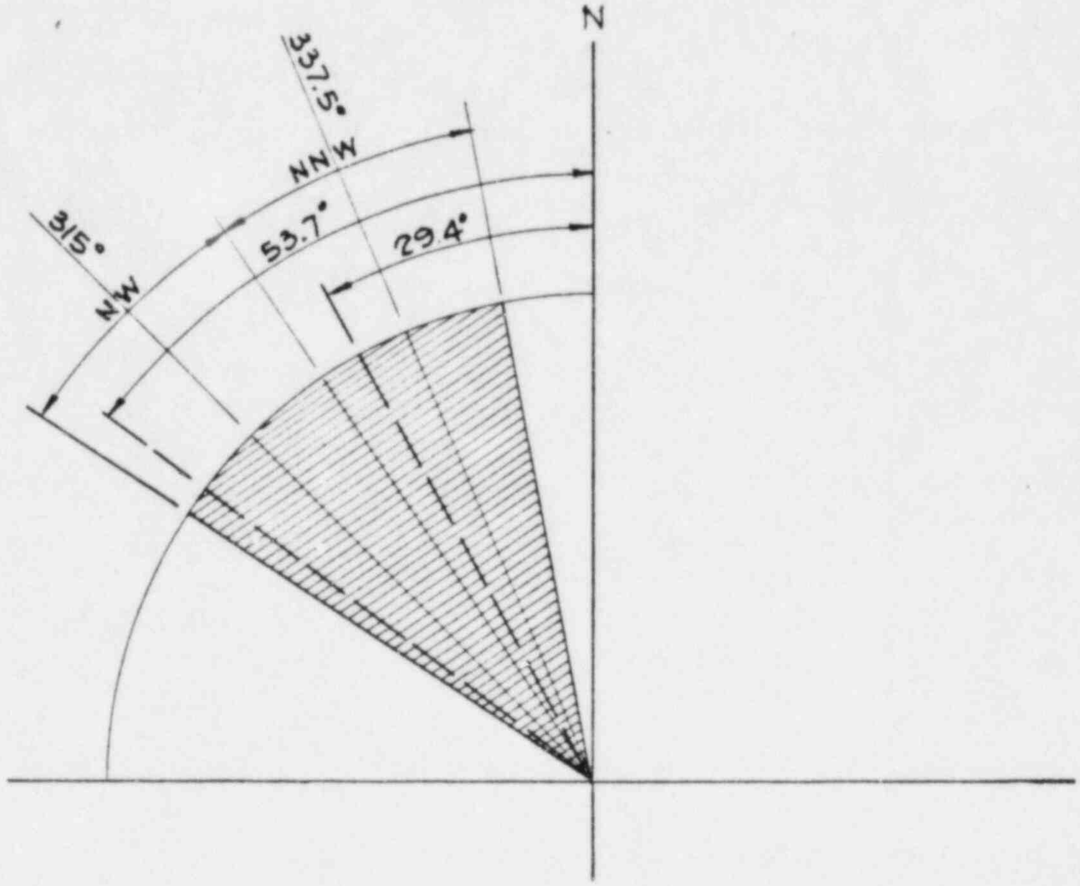


Figure 9: Determination of Applicable Wind Directions. Refer to Figure 8