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EVACUATION AREAS FOR TRANSPORTATION ACCIDENTS INVOLVING PROPELLANT TANK PRESSURE BURSTS

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SUMMARY

Evacuation areas are defined for those transportation accidents where volatile chemical propellant tanks are exposed to fire in the wreckage and eventually explode with consequent risks from fragments in surrounding populated areas. An evacuation area with a minimum radius of 600 m (2000 ft) is recommended to limit the statistical probability of fatality to one in 100 such accidents. The result of this study was made possible by the derivation of a distribution function of distances reached by fragments from bursting chemical car tanks. Data concerning fragments was obtained from reports of tank car pressure bursts between 1958 and 1971.

INTRODUCTION

Between 1958 and July 1, 1971, there were 98 railway accidents that involved spills of flammable liquid chemicals with high vapor pressure at ambient conditions (ref. 1). Of these accidents, 44 involved explosions of 84 chemical car tanks. In many of these accidents, train derailment caused puncture of chemical car tanks, spillage and ignition of thier volatile contents, and eventual pressure rupture of other upset tanks exposed to the fire in the wreckage. Fragments from such accidents, mostly large portions of tanks, were thrown or rocketed hundreds of meters and their impact in surrounding communities often caused casualties and extensive property damage. The frequency and severity of such accidents peaked in 1969 when 33 chemical car tanks exploded in 12 derailments.

The catastrophic proportions of these accidents, especially in 1969, became a subject of concern to many organizations within government and industry and as a result several studies have been underway to find means by which their severity might be decreased. One such study by the Association of American Railroads (AAR) proposes various concepts by which the likelihood of tank puncture and fragment rocketing might be decreased.

Another study by the Naval Ordnance Laboratory (NOL), sponsored by AAR, is investigating thermal insulating materials and applications that might increase tank exposure time to fire before rupture (ref. 2). Even if the results of these studies prove the proposed design concepts feasible, a considerable lead time would be required to modify a great number of tank cars in the railroad inventory.

Railroad companies also have been working to prevent spills by improving equipment, track and train operations. In addition, they have developed emergency action plans for handling hazardous material incidents (ref. 3). These efforts may have helped reduce such accidents, yet spills, fire and explosions continue as more ton-miles of volatile chemicals are logged each year.

In the majority of train accidents that involved explosions, tanks contained either LPG or liquid propane. This suggests that similar catastophic results would be expected in derailments which involve bulk quantity shipments of volatile chemical propellants such as liquid hydrogen, liquid methane, anhydrous ammonia and ethylene oxide. Thus, the consequent risk to the public also becomes a subject of concern to those government agencies which ship or have consigned to them these types of chemical propellants.

Documented data from such accidents that occurred between 1958 and 1971 show that tanks exploded from 3 min to 48 hr after their exposure to fire. Therefore, it appears that in many cases there is enough time to make evacuation of adjacent populated areas a feasible procedure as the fires are being controlled and exposed tanks are being cooled to forestall their pressure rupture. Rocketing could be considerably reduced by a structural provision that would maintain a physical tie between two large parts of a tank that would be formed by any circumferencial rupture of the shell. Such provision on future tank cars would decrease the required areas of evacuation. Improved thermal insulation would increase tank exposure time to fire making evacuation feasible for the majority of these accidents in the future.

At the present time, there is little, if any, quantitative information available to local emergency forces at the scene of such accidents that would help them evacuate reasonable areas consistent with an acceptable risk to people from the impact of fragments (ref. 4, pp. 38 to 40). As a consequence, fire fighters in some cases may be exposed to extreme hazards at hose stream distances for longer periods than should be necessary while larger-than-required areas are being evacuated; conversely, a smaller-than-required evacuation area would result in higher-than-acceptable risk in adjacent communities.

In order to determine an acceptable level of risk to people at various distances from these bursting chemical car tanks, it was necessary to study fragment sizes and distributions. From the results of these studies and assumptions concerning the number of people per unit-area exposed to these fragments, conclusions were drawn as to a reasonable radius of an evacuation area that would limit the statistical probability of fatality to one per 100 such accidents. This limit is considered reasonable since accidents of this kind have occurred on the average of 3 per year for the past several years with a peak of 12 in 1969.

Guidelines for evacuation areas developed on such a basis in this study, are recommended to the Joint Army, Navy, NASA, Air Force (JANNAF) Safety and Environmental Protection Group for their proposed Propellant Spill Cards, which describe emergency procedures. The intended wide distribution of these cards to municipal fire and police departments should help them establish proper and reasonable evacuation areas for those transportation accidents where volatile chemical propellant containers are exposed to fire. Evacuation areas for toxic propellant spills based on Ref. 5 have already been included on these cards.

It should be emphasized that this guideline applies to hazards from fragments only. It does not apply to that small fraction of accidents where a rapid release of volatile, flammable chemical forms a huge plume of fuel-air mixture, when later ignited, burns with extraordinary speed forming strong and damaging pressure waves (ref. 6). Current studies of fuel-air explosions and their effects may indicate a course of action to prevent ignition sources and facilitate evacuation of people from hazards.

SUMMARY AND ANALYSIS OF DATA

Data from accident reports (ref. 1) as summarized in Fig. 1, show that 64 fragments impacted and came to rest at distances ranging from tens of meters to 1500 m (4900 ft) from the origin. Although a total of 84 tanks exploded, apparently not all of the fragments were forcibly propelled and there is evidence that some impacted within the wreckage of the train. Of the 64 fragments that did leave the scene, 50 percent came to rest beyond a distance of 150 m (490 ft) and 20 percent were found beyond 300 m (980 ft). As to size of these fragments, 20 percent were classified as small and the majority of these were found to be within a distance of 150 m (500 ft). Only four small pieces traveled beyond this distance. This implies that if there were sufficient time to evacuate people from an area with a 500 ft radius, the primary hazard would be from the impact of large portions of tank rather than from the shrapnel affect of small high velocity pieces. Of the total fragments, 50 ranged in size from tank ends to 4/5 of a tank. The predominance of large pieces seems to be typical of these container pressure bursts.

APPROACH TO ASSESSMENT OF RISK FROM FRAGMENTS

The approach taken to arrive at some estimate of risk to people from fragments of exploding tanks is based on the statistical probability of their being within the impact areas. Thus, it is desirable to find the best fit of data on distances reached by fragments (ref. 1) to some equation representing a distribution function. Once the distribution function is derived it can be used with assumptions concerning the number of people per unit area exposed to the average fragment impact area to predict risks. Assuming that all people within the impact area are killed, the statistical probability of fatality per accident is expressed as a function of an established radius of an evacuation area as given in Eq. (1):

$$P = \rho_E F_A A_F \left[1 - \varphi(R)\right] \tag{1}$$

where

ρ_E = number of people per unit area exposed to fragments

F_A = average number of fragments per accident

A_F = average impact area per fragment

$\varphi(R)$ = distribution function of fragments within radius R

Distribution Function of Distances Reached by Fragments

Fragment data from Fig. 1, as plotted on probability paper (fig. 2), shows good confidence in the log normal form of distribution as a function of frament travel distances where the mean of the natural log arithm of the radius, $\mu = 6.16$ and the standard deviation of the natural log arithm of the radius $\sigma = 1.00$. The distribution function of distances reached by tank car fragments, $\varphi(R)$, as derived from Fig. 2, is shown in Eq. (2):

$$\varphi(R) = 0.001314 \int_0^R \exp\left[-\frac{1}{2}(\ln R - 5.16)^2\right] dR \tag{2}$$

Estimate of Fragment Impact Areas

The behavior of large portions of tank upon their impact is difficult to predict. In Crescent City, Illinois, the explosion of a tank car (SOEX 3252) occurred 2-1/2 hr after its exposure to the fire in the wreck. A 30 ft long section of tank rocketed striking the roof of a two story building 100 m away and flew 230 m before impacting the ground. After the initial impact with the ground, it apparently skipped and traveled another 290 m before it came to rest at a total distance of 520 m (1600 ft) from the scene of the explosion. The launch angle was estimated to be approximately 11 degrees (ref. 7). Other fragments such as tub sections less than 20 ft in length or larger portions with attached trucks have a tendency to tumble in flight with relatively high aerodynamic drag. If fragments of this type have small launch angles, they may travel over relatively shorter distances with considerable tumbling subsequent to their impact. Without the quantitative data that would allow a realistic estimate of these fragment impact areas caused by skipping and tumbling, it becomes necessary to make some arbitrary assumptions. The conservative assumptions made were as follows:

(a) An intact tank is 60 ft long by 9 ft in diam

(b) Tank ends (fig. 1) were grouped with 1/4 tank portions

(c) The average length, $\bar{L}$, of the 51 large portions of tank were determined and multiplied by the 9 ft diam

(d) The average length times the diameter or the effective imprint area of the large fragments were also applied to the 13 small pieces

(e) All fragments leave the scene of the tank explosion at small angles to the ground surface, resulting in one skip, an impact and a slide distance equal to the average length of tank before they come to rest

On the basis of these rather conservative assumptions, the averaged impact area per fragment A_F was estimated to be $3(18.4 \times 9)$ or 498 ft^2 (47.5 m^2).

The average number of fragments per accident is 1.5. Therefore, the impact area of fragments per accident = $1.5 \times 47.5 = 71.5\ m^2$.

Estimate of Number of People per Unit Area Exposed to Fragment Impact Area

Although one might assume that the highest number of derailments which involve spillage of hazardous materials occurs at high speed, such is not the case according to Ref. 1. Thus, the explosion of chemical car tanks could occur in switching and humping operatings in close proximity to highly populated areas as well as on main lines in sparsely populated areas.

A survey of world population densities, Ref. 8, divides the earth's surface into 740 equal area cells. Fourteen of these cells cover the United States and the highest populated cell was found to be the Northern portion of the Eastern Seaboard with a density of 166 people/km^2. This cell population density, ρ_c, was used as an average rural/urban population density in arriving at the estimated probability of fatality from fragments of bursting chemical car tanks. However, as is the case with most spectacular accidents, curiosity causes a considerable number of people to gather at the perimeter of the evacuated area for such accidents. Thus, the number of people gathered at the perimeter is taken into account to predict the probability of fatality from fragment impacts.

Figure 3 describes the populated areas surrounding a train derailment with an established evaluation area. Using Fig. 3, the following assumptions are made concerning population densities that are exposed to the total fragment impact per accident, 71.5 m^2:

(a) All evacuated people gather in the perimeter area.

(b) A percentage of the cell population density, 166.5 people/km^2 in the outlying area with a radius of R_o = 5000 m are attracted to the perimeter area.

(c) The perimeter area is occupied by evacuated people and attracted people to a crowd density $\rho\Delta$ of one person/10 m^2.

(d) The decrease of the population density in outlying areas by the number of people attracted to the perimeter area is neglected.

DEFINITION OF REQUIRED EVACUATION AREA

Probability of Fatality Versus Radii of Evacuation Areas

The overall probability of fatality from fragments of bursting chemical car tanks would be strongly influenced by the number of people gathered at the perimeter of an established evacuation area. Thus, it is necessary to define the size of the perimeter area in terms of an incremental distance ΔR so that the distribution of fragment impacts in this area of high population density is taken into consideration. Based on the somewhat arbitrary assumptions concerning population density exposed to these fragments, the width of the perimeter area ΔR is expressed in Eq. (4).

$$\Delta R = \left[\frac{\sqrt{R^2 \left[\rho_\Delta^2 + (1 - z)(\rho_c \rho_\Delta)\right] + z\,(R_o)^2 (\rho_c \rho_\Delta)}}{\rho_\Delta} \right] - R \qquad (4)$$

where

z = fraction of the cell population density, ρ_c, attracted from the outlying areas to the perimeter area

R_o = radius from the site of the accident to the extremity of the outlying area, 5000 m

R = radius of the established evacuation area

The overall probability of fatality from fragment impacts in the perimeter area where the crowd is gathered and the areas beyond can now be expressed in terms of radii of evacuation areas as given in Eq. (5).

$$P_o = P_{\Delta R} + P_{R+\Delta R} - P_{\Delta R} P_{R+\Delta R} \qquad (5)$$

where $P_{\Delta R} = \rho_\Delta F_A A_F \left\{ \left[1 - \varphi(R)\right] - \left[1 - \varphi(R + \Delta R)\right] \right\}$ is the probability of fatality within the perimeter area and $P_{R+\Delta R} = \rho_c F_A A_F \left[1 - \varphi(R + \Delta R)\right]$

is the probability of fatality in the outlying area beyond the perimeter area.

With the use of Eq. (5), a family of curves was developed showing the overall probability of fatality from fragment impacts per accident versus radii of evaluation areas for fractions of the cell population density, $z\rho_c$, attracted to the perimeter (fig. 4). It is obvious from this plot that for a given radius of an evacuation area the overall probability of fatality, P_o, increases with increasing fractions of cell population density, ρ_c, attracted to the perimeter.

Choice of Suitable Limit on Probability of Fatality

In the past 30 years, the railroads have experienced a fatality rate of 1.1 persons/yr from accidents involving hazardous materials and during that time period millions of tons of hazardous materials were shipped each year. During the 1960's the fatality rate from spills of hazardous materials was 1.1 persons/yr even with the spectacular tank car explosions in 1968 and 1969 (ref. 3). These explosion-type accidents have averaged about 4/yr from 1958 through July 1, 1971. On the basis of these statistics, it would appear that a limit of one fatality per 100 such accidents would cause fatalities due to this type of accident to be minor in comparison with all fatalities due to hazardous materials. It can be seen from Fig. 4 that using the 1/100 limit would mean that some radius of an evacuation area from 300 m (980 ft) to 800 m (2600 ft) would be required depending on the fraction of the population density attracted to the scene of the accident. Areas of evacuation for the 1/100 limit are considered small enough to make evacuation a feasibly procedure within the first 60 min after the accident.

Recommended Evacuation Area and Procedure

Experience has shown that spectacular accidents attract crowds of such numbers that it is difficult to bring in additional emergency equipment. In discussions with local fire and police officials, they indicate a wide range of estimates concerning the numbers of people that have gathered in such accidents within the first 60 min. Conclusions were drawn from these discussions that from 10 to 40 percent of the surrounding population density, ρ_c, would be attracted while an evacuation area is being established.

Accordingly, it was decided to accept a certain degree of uncertainty in the probability of fatality for the initial evacuation area. On this basis, a 600 m radius (approximately 2000 ft) was chosen where the probability of fatality from fragment impact would range from 8/1000 to 2/100 accidents. After the initial evacuation area is established, an estimate of crowd size should be made for possible increases in the area to hold the probability of fatality limit to 1/100 such accidents as shown in Fig. 5 and summarized in table I.

CONCLUDING REMARKS

For those transportation accidents in which tanks of volatile chemicals are exposed to fire, an initial minimum radius of an evacuation area of 600 m (2000 ft) should be established as quickly as possible to limit the probability of fatality from the impact of large tank fragments to 1/100 such accidents. This limit is thought to be reasonable based on the frequency of these accidents over the past 13 yrs. The initial evacuation area should be subsequently increased, if necessary, depending on the estimated number of spectators gathered at its perimeter.

Even though it was possible to derive the distribution function for distances traveled by fragments for accidents involving pressure burst of tanks, two sources of uncertainty were encountered which required the use of rather arbitrary assumptions in order to predict probability of fatality from the impact of tank fragments. The first source of uncertainty is the behavior of these large fragments subsequent to their impact and consequetly the estimated size of the total fragment impact areas. It is thought that this problem was dealt with in a conservative manner by arbitrarily increasing the average fragment impact area by a factor of three. This assumption allows for skipping, sliding, and tumbling.

The other problem is the estimated number of spectators that would be expected to gather while a reasonable evacuation area is being established. The factors which cause people to gather are not predictable; however, based on conversations with emergency-service personnel, a good guess is from 10 to 40 percent of the population density from 3 mi away would be attracted to the scene of a spectacular accident. This forces acceptance of some uncertainty in the probability of fatality for the initially established evacuation area, which is recommended to have a 600 m (2000 ft) radius. However, once this area is established, an estimate of crowd size on the perimeter would indicate additional increases to the initial area to meet the desired probability limit of one fatality per 100 accidents.

More work is needed in both cases to reduce the uncertainty in establishing evacuation area guidelines to protect people from the impact of fragments caused by the pressure burst of chemical tanks. Perhaps the most pressing need is to understand fragment trajectories and the behavior of these fragments subsequent to their impact.

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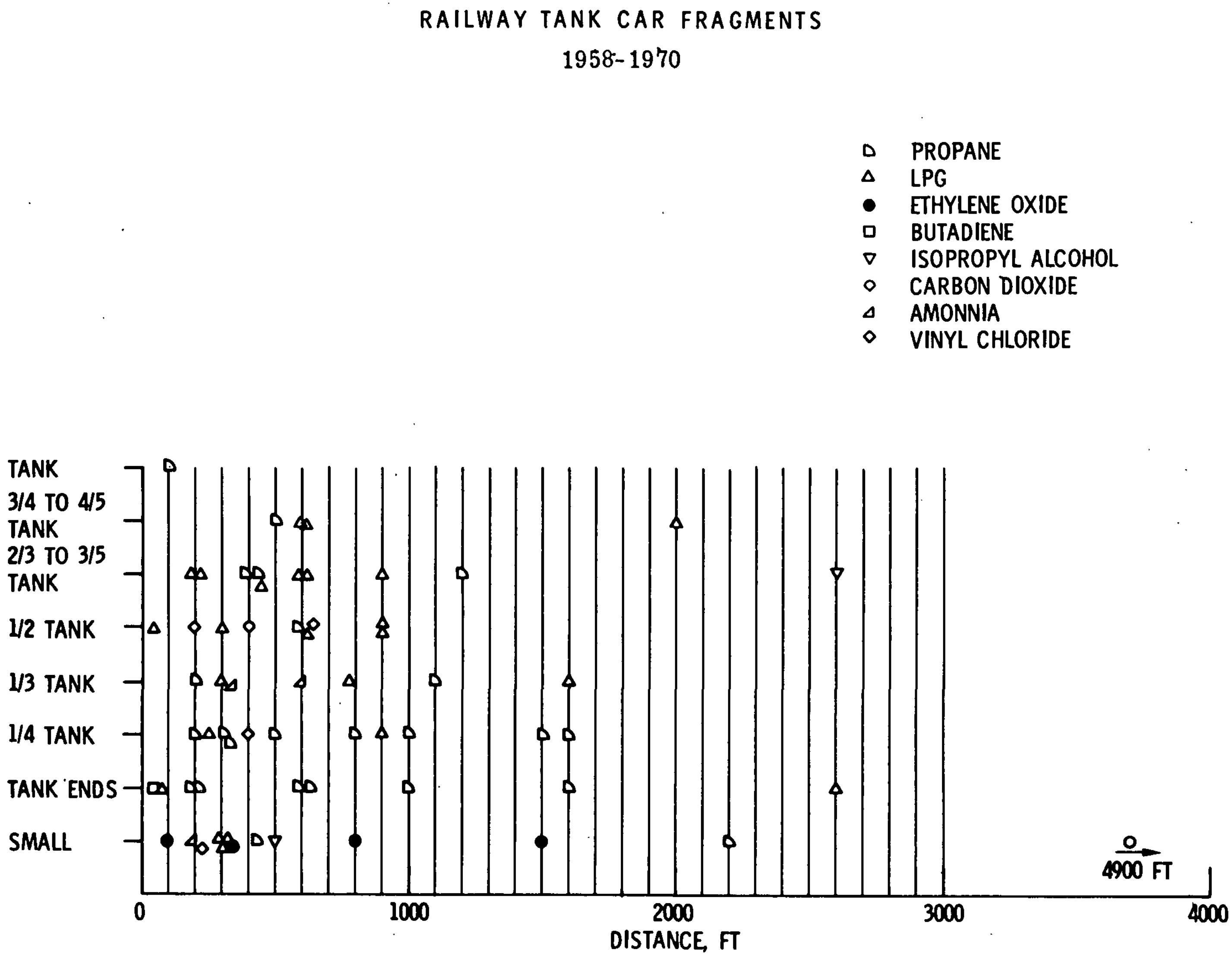
TABLE I. - PEOPLE AT PERIMETER VERSUS REQUIRED RADII OF EVACUATION AREAS FOR A PROBABILITY OF FATALITY LIMIT OF ONE PERSON PER 100 ACCIDENTS

Radius of evacuation areas m (ft, approx.)	People gathered at perimeter
400 (1300)	500
440 (1450)	750
520 (1700)	1250
560 (1850)	1550
[a]600 (1950)	1950
640 (2100)	2400
680 (2250)	3250
720 (2375)	3900
760 (2500)	4800
800 (2625)	5900
840 (2750)	7350
880 (2850)	8500
920 (2950)	9550

[a]Minimum radius of evacuation area



RAILROAD TANK CAR SAFETY RESEARCH AND TEST PROJECT
PHASE I RA-01-2-7, RP1-AAR PROGRAM 1971

Figure 1.

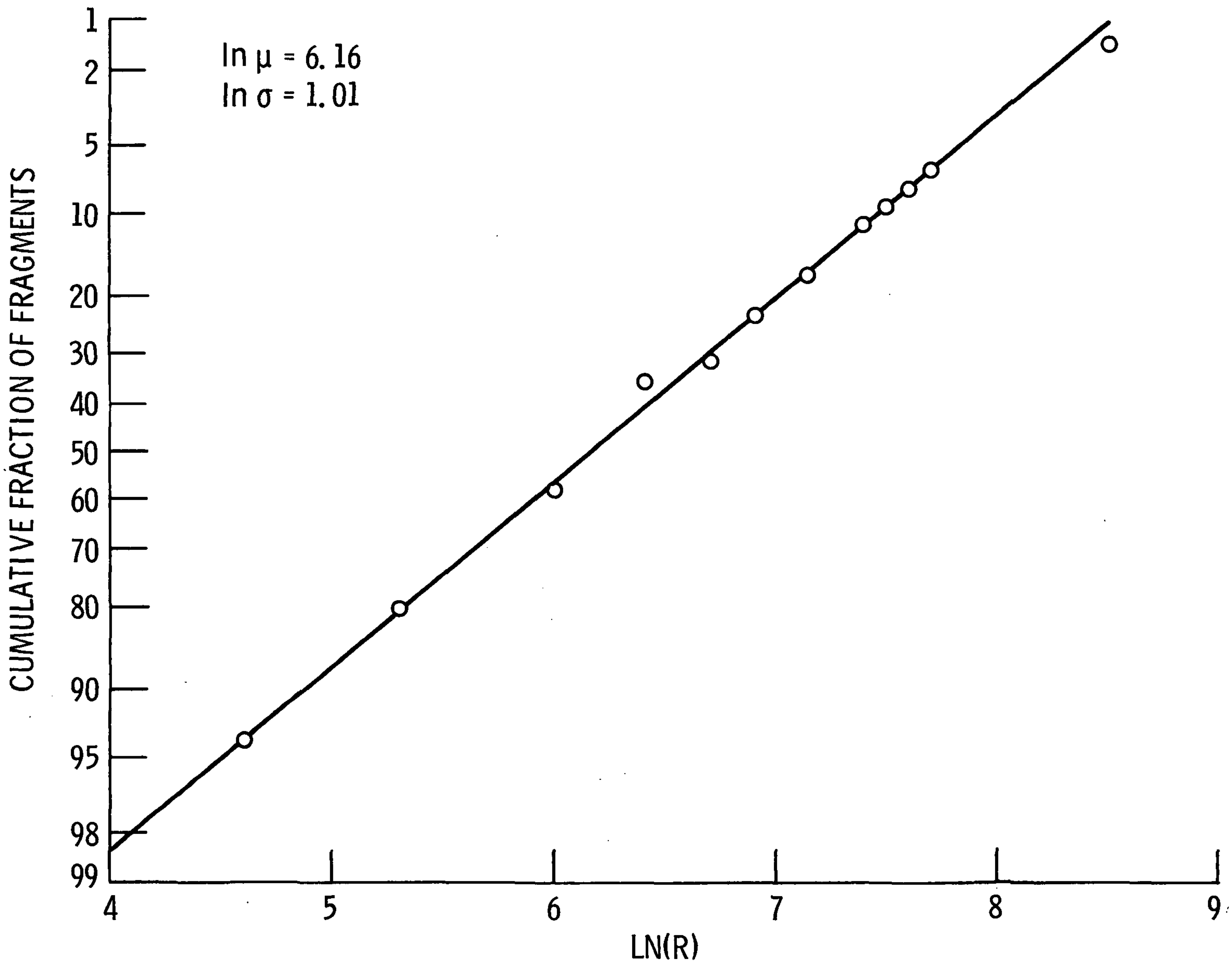
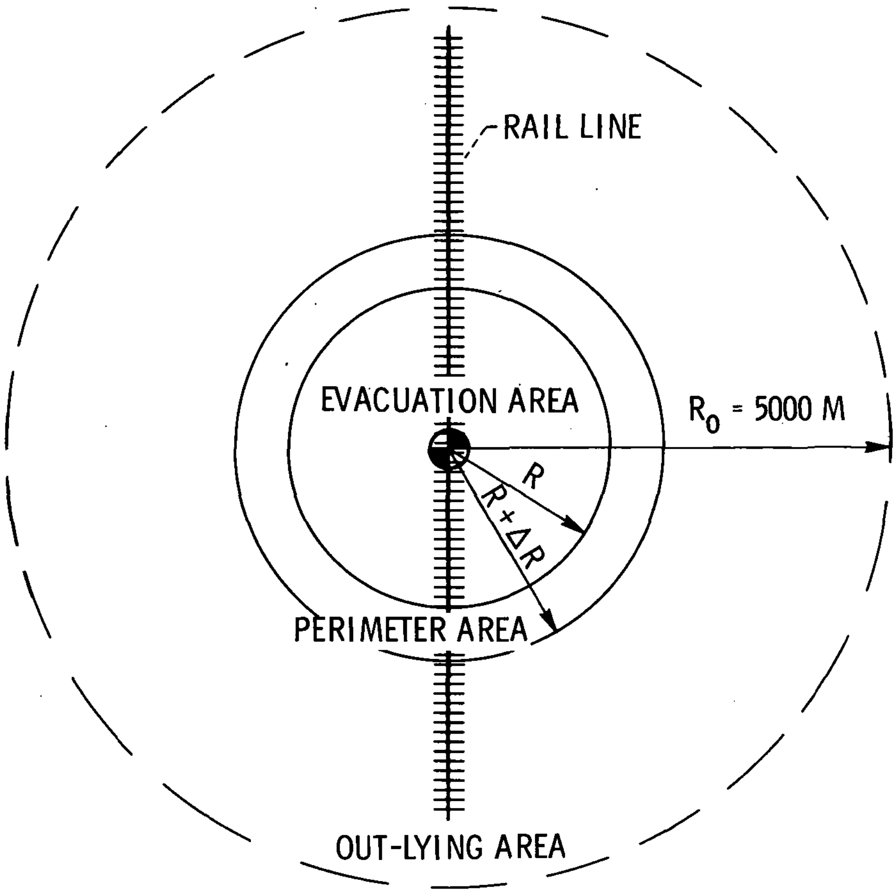
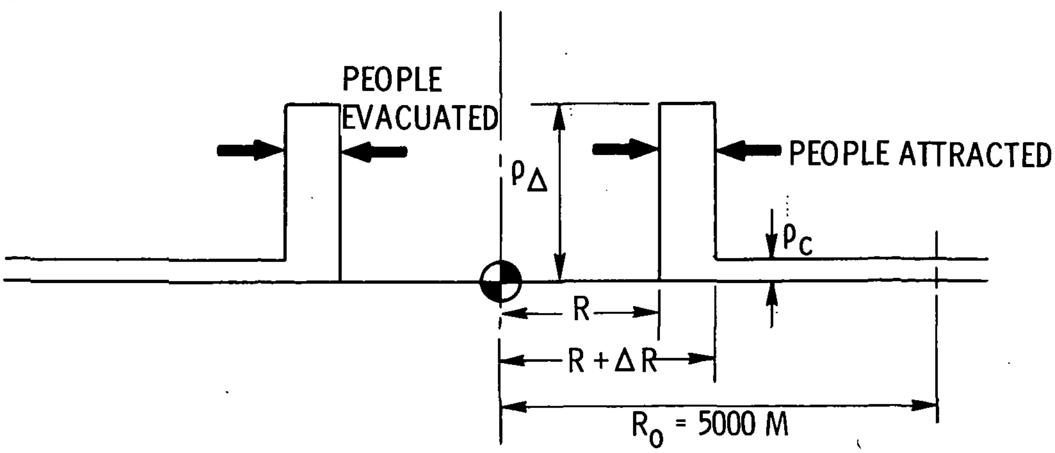


Figure 2. - Density of fragments versus the log of distance R (distance in feet).



(a) DESCRIPTION OF AREAS.



(b) POPULATION DENSITIES.

Figure 3. - Populated areas and population density surrounding an established evacuation area for accidents involving chemical car tank bursts.

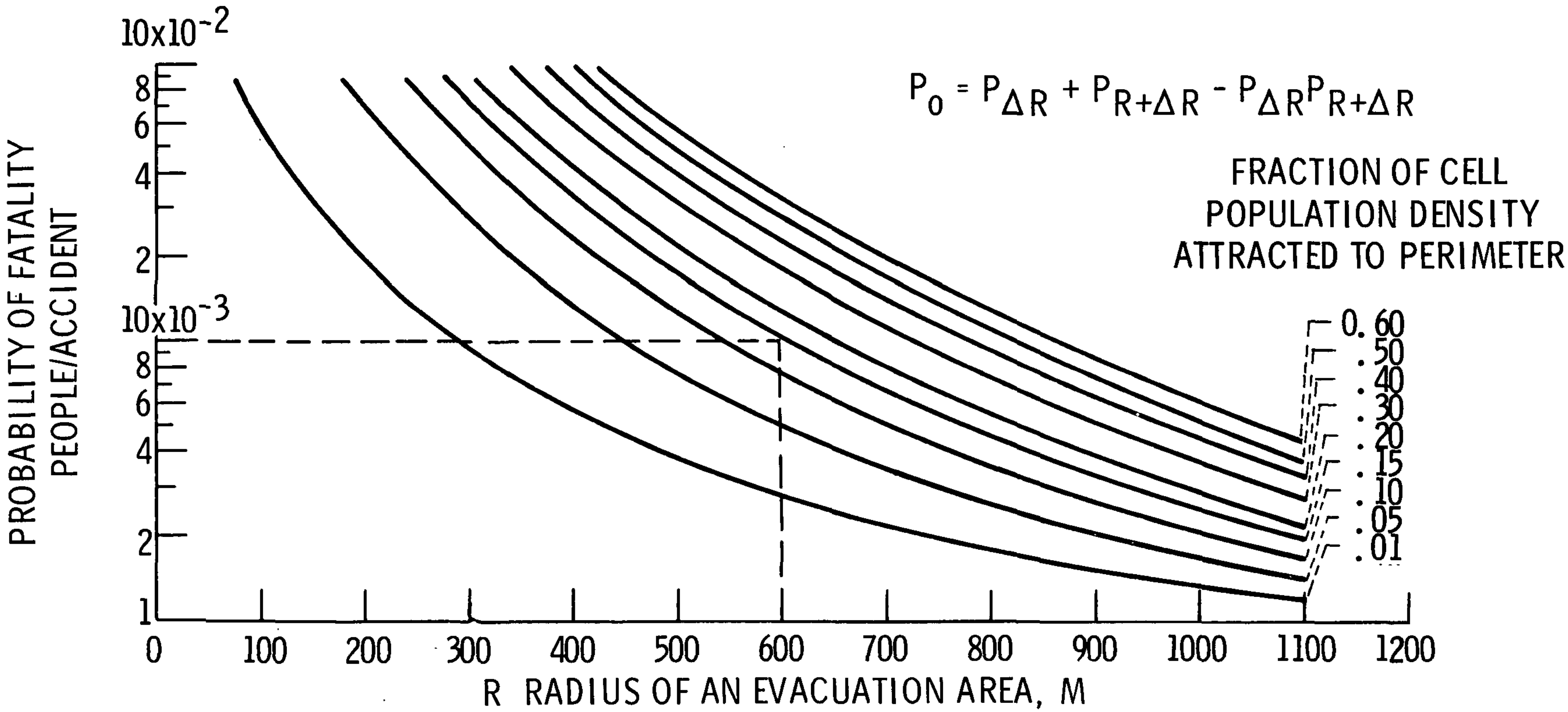


Figure 4. - Probability of fatality per accident versus radius of an evacuation area.

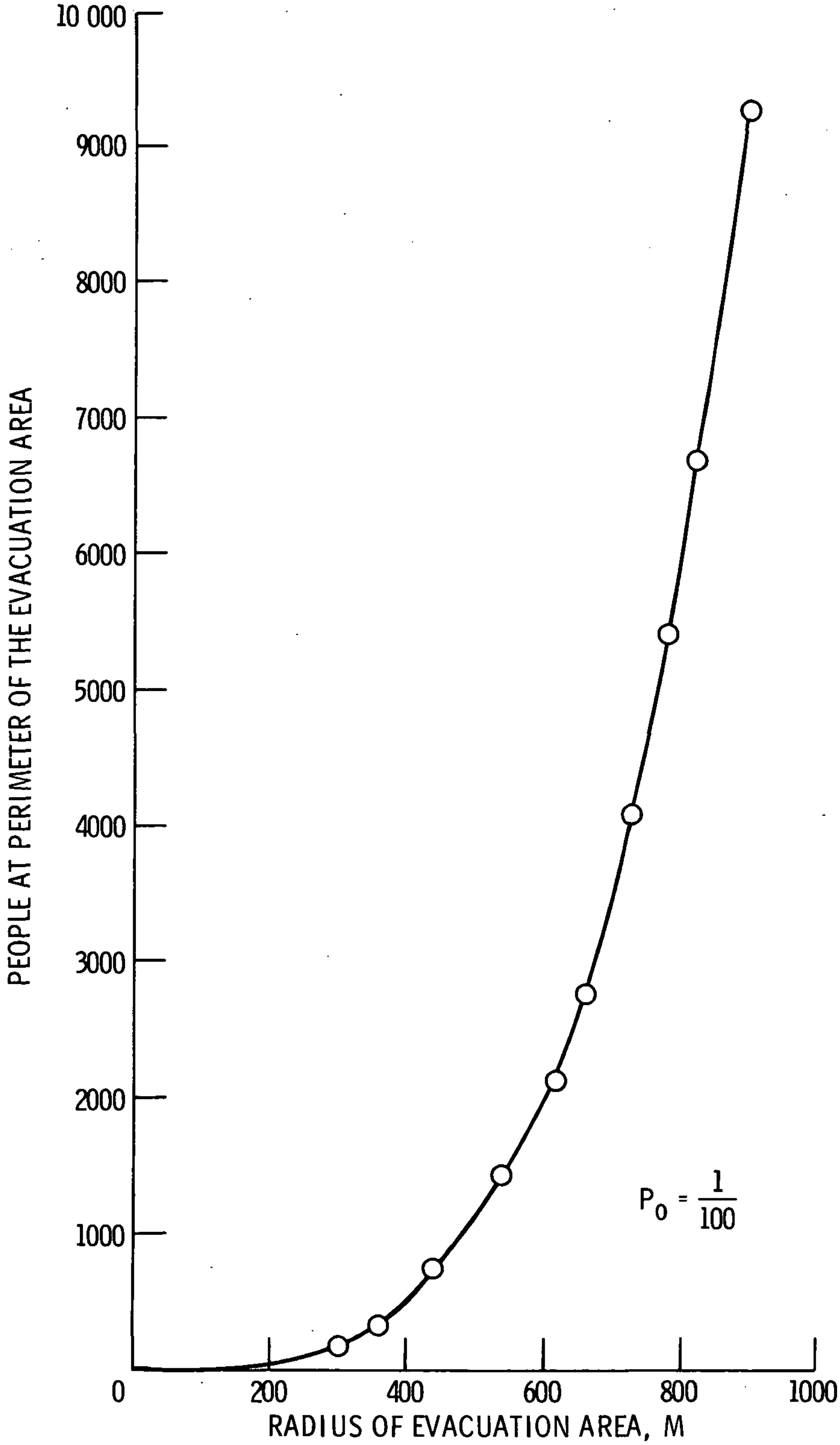


Figure 5. - People at perimeter of an evacuation area versus radius for probability of fatality limit of one per 100 accidents.