DP - 105 (Rev. 2)

Health and Safety

AEC Research and Development Report

ACCIDENTAL DISPERSION OF REACTOR POISONS AND THE CONTROLLED DISTANCE REQUIRED

by

R. L. Menegus and H. F. Ring

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Explosives Department - Atomic Energy Division
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Printed in USA. Price $1.25
Available from the Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

730970 ✓

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(TID-4500, 13th Ed., Rev.)

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Printed by Savannah River Laboratory for
The United States Atomic Energy Commission
Contract AT(07-2)-1

ABSTRACT

The aftermath of a serious reactor incident could be radiological injury to the populace living in the vicinity of the plant site. Methods of estimating and eliminating the hazard are presented in this report. Also given is a calculation of the plant size needed to reduce the expectation number of deaths below any arbitrary figure.

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INTRODUCTION

As more nuclear reactors are constructed, and especially if nuclear power should become economical, the problem of locating the reactors will assume increasing importance. An economical plant designed to produce energy is preferably located in or near the market. Under some circumstances the installation of such a power reactor could endanger the people living in the area around it. The hazard might in fact be deemed so high that reactors might never be built in certain locations where electrical power is needed; and operation of the nuclear reactors installed in ships and submarines might, on the same basis, be forbidden when the craft approach populous seaports.

In determining the size of the plant site for reactors, a formula* has been suggested that relates power level to the distance between the reactor and the inhabitants living closest to the plant. According to this formula, a reactor operating at a high power level requires a large controlled distance. It was possible to locate early reactors in regions where large tracts of land were available and where relatively few people had to be displaced. Consequently, the cost of the tract was of relatively small moment in the total plant cost concerned. But, if power reactors are to be proposed for location in regions of high population density, where the land is much more valuable, the cost of the tract might well make the reactor uneconomical. The present report attempts to show what practical factors besides power level are of importance in choosing the location of a reactor plant site and its size. Much of it was done at the suggestion of the Advisory Committee on Reactor Safequards.

SUMMARY

Two types of hypothetical reactor catastrophe are considered. In the first of these, the "Boiling Accident," it is assumed that a fraction of the radioactive material in a reactor is released to the atmosphere at a steady rate over a period of hours. In the second, the "Puff Accident," it is assumed that the release of the radioactive material takes place "instantaneously." Either type of accident can release enough poison to endanger the populace. We use the following concepts as measures of the hazard existing outside the controlled plant area: "Danger Distance," defined as that distance beyond which the fission product cloud becomes so dilute that it cannot cause death; "Probability of Death per Capita per Accident," which is a measure of the hazard to any individual; and "Expectation Number of Deaths per Accident," which is a statistical measure of the hazard to the entire off-site populace.

Three mechanisms for each type of catastrophe have been considered in our evaluation of the magnitudes of the hazards. These are: direct irradiation from the fission product cloud, inhalation of the air in the cloud, and rainout from the cloud followed by irradiation from the ground. In this report fallout is not considered, for it requires that a very energetic explosion be assumed.

It is concluded that the size of the plant should be set by the hazard of irradiation from the low-lying poison cloud produced in the boiling accident, because this mechanism is the most hazardous at short distances from the reactor. A formula is proposed that permits the calculation of the controlled area that should exist around any reactor.

Inversion and average meteorology are analyzed in terms of their effect on off-site hazard. If the expectation number of deaths is used as a criterion for measuring hazard, average meteorology is sometimes more dangerous than inversion meteorology. However, the low dispersion that is characteristic of inversion conditions can result in very great danger distances; e.g., there is a very small but finite chance of death, for people situated at distances greater than 1000 miles from the reactor site, by rainout following the puff accident.

* Controlled distance, miles = $0.32(\text{Reactor Power in MW})^{0.5}$

Reactors are not the only hazardous pieces of equipment in the country. A large tank of stored poisonous gas, hydrogen sulfide or sulfur dioxide or chlorine, for instance, might be fully as hazardous an installation. The same theory, utilizing the concepts of the probability of death and the expectation number of deaths, is useful in estimating the hazard in the event the tank ruptures, releasing to the atmosphere great quantities of gaseous poison. This problem is treated briefly at the end of the report. It is estimated that the escape of 1.4 million pounds of unignited hydrogen sulfide over a period of half an hour is equivalent in hazard to a 1000-MW reactor that runs away and releases a cloud of fission products in which the decay heat is 2 MW.

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ACKNOWLEDGMENT

The writers are indebted to Professor J. A. Wheeler of Princeton University, to Professor E. Teller of the University of California, and to J. W. Langhaar of the du Pont Company.

DISCUSSION

It is well to state at the outset that the location and size of a reactor area are always based on the postulated occurrence of reactor incidents that have no precedent and that one hopes will never happen. It is nevertheless true that large amounts of radioactive poisons could be liberated, and that these poisons, if liberated, could be transported by wind and water toward regions of habitation. In order to reduce the concentration of the airborne or waterborne poisons to a tolerable level, a certain dispersion distance is needed between the reactor and the off-site inhabitants, and this distance depends in part on the amount of radioactive matter liberated from the reactor at the time of the postulated accident. This dispersion distance is then the radius of the plant site - the controlled distance.

The present methods of preventing the liberation of large amounts of reactor fission products are not discussed in this report. It is assumed that continuing effort in this sphere will further reduce the possibility of a release of radioactivity.

However, if one presumes that some fraction of the fission products, and perhaps radioisotopes, produced in the reactor could be liberated to the environment, the problem is to place the evaluation of all reactor locations on an equal footing insofar as hazard to the populace is concerned. In short, one would like to choose and design reactor plant sites such that each site presents about the same low hazard to the people living nearby. The acceptable magnitude of this hazard is for the time being open to argument, and we shall work without necessarily setting the allowable hazard. Any chosen magnitude of hazard can be inserted in the formulation derived in this report.

Quantitatively, the arbitrary hazard may be measured by the probable number of people that would meet death in the unlikely event that the reactor experienced a nuclear runaway or in some other way liberated a large fraction of its radioactive poisons. In calculating the expectation number of deaths, the concept of probability of death is used. As defined herein, the expectation number of deaths in an incremental area is the product of the probability of death per capita per reactor incident and the number of people living in that area. This product is integrated over the whole area in which the probability of death is greater than zero.

It will be observed that the expectation number of deaths is an average figure for a large number of accidents, an implied state of affairs that is intolerable, of course. No one will meet death for most postulated accidents, while in a few cases a large number of people will be killed. The number of deaths per postulated accident cannot, in principle, be a relatively invariant quantity such as the number of people killed per year by lightning.

While the expectation number of deaths is a negative rating, it can be used as an arbitrary but reasonable concept in evaluating plant sites. It takes into account the reactor power level, the population density outside the plant, the climatology of the area, the susceptibility of man to death by radiations, the size of the plant controlled area, and the dispatch with which people can be evacuated from the path of the poison cloud. It will be shown later that it would be possible to eliminate the danger if the populace downwind of the reactor could be moved out soon after the occurrence of a serious accident, if it were ever to occur. It is not at all unreasonable to state that no deaths whatever should result if the proper precautions are taken.

Nevertheless, if one chooses to say that the populace living in a sector downwind of the scene of the incident will not be moved out promptly, the calculated expectation number of deaths will be a finite number. This number can be reduced as much as one wishes by increasing the size of the controlled area around the reactor.

Therefore, if one chooses the allowable expectation number of deaths, the controlled distance can be specified for any reactor in any location.

If large quantities of radioactive material are released to the atmosphere in a reactor incident, people can be endangered by several mechanisms: breathing of the airborne poisons, radiation from the airborne poisons surrounding the receptor, and rainout of the airborne poisons followed by radiation from the ground. Ingestion of fission products that have settled on the ground and in the water is not considered herein, because it could certainly be controlled by a comparatively leisurely evacuation of the populace. The other three mechanisms are more dangerous because more rapid action is necessary to obviate the hazard. However, the prevention of ingestion of settled fission products could be an expensive operation.

In this report, these three mechanisms have been analyzed for two types of accident: sudden and gradual release of fission products from the reactor. It has been determined that for distances of 0 to 10 miles around a reactor, the most dangerous mechanism is radiation from the airborne poisons surrounding an unshielded person, a result that has been pointed out previously by E. Teller and that is the basis of the formula that has been suggested by calculating the controlled distance around a reactor. It has been found, also, that for greater distances from a reactor one should consider the rainout mechanism as a possible hazard.

It is found that the controlled distance is usually larger when calculated by the mechanism that involves radiation from the cloud than it is by the mechanism that involves rainout. This occurs mainly because the probability of death is higher in the case of radiation from the cloud, for death by this mechanism can occur if the poison cloud merely sweeps by a receptor, without the coincident occurrence of rain that is necessary to cause death by the mechanism of rainout from the cloud.

Hence, the required controlled distance can be specified for most practical cases by a proposed formula, which has been plotted in Figure 7. The formula is derived on the basis of radiation from the airborne poisons.

The required controlled distance depends primarily on the size of the postulated accident; and the size of the accident is measured conveniently by the fission product decay heat in the poison cloud resulting from the accident. Numerically, the size of the accident is

$$\text{Size} = \frac{pfat}{T} \text{ MW of fission product heat in the cloud}$$

The symbols are explained in the Nomenclature.

The reactor power in MW, p, is definite in any situation. But the fraction of the fission products liberated, f, is a quantity that has caused considerable argument. Figures from 0.01 to 0.5 have been guessed for this quantity, and there is no way to put down a definite number, since no large accidents have occurred. For purposes of specifying the controlled distance, the writers choose

$$\frac{fat}{T} = 0.002$$

which is equivalent to saying that f is in the range of 0.1 to 0.2. In other words, if the reactor power is 1000 MW, then the writers estimate the size of a large accident as 2 MW of fission product decay heat in the poison cloud.

In addition to the size of the accident, one must know the population density, N, in the region surrounding the reactor plant site. Also, it is helpful to know if the wind blows preferentially in certain directions, $P(\theta)$, compared with the average around the full arc of the horizon. And, finally, some decision must be made concerning the allowable number of deaths per accident. The writers choose $\chi = 1$ death per accident. These parameters are grouped as follows:

$$\frac{N\,P(\theta)}{\chi} \quad \frac{\text{people}}{\text{mile}^2 - \text{death}}$$

If N and $P(\theta)$ are larger in certain directions than in others, the controlled distance is logically made larger in those directions. $P(\theta)$ averages unity around the full arc of the horizon, while N may be anything.

With these assumptions, the required controlled distance might be shown in tabular form on the following page.

FIGURES IN THE TABLE MEASURE
CONTROLLED DISTANCE IN MILES

N P(θ) people/mile² \ Reactor power - MW	30	100	300	1000	3000
10	0	0	0	0.88	3.64
30	0	0	0.34	1.86	7.0
60*	0	0	0.63	2.85	11.3
100	0	0.20	0.89	3.87	15.0
300	0.09	0.45	1.76	7.7	--
1000	0.21	0.95	3.70	16.0	--
3000	0.42	1.90	7.1	--	--
10000	0.88	3.90	15.0	--	--

* U. S. Average

It is observed that if the statistical hazard to the populace is to be 1 death per accident for every site, it is impractical to place high power reactors in regions of high population density, where the cost of land is high.

It should be mentioned that the formula has been derived more accurately than is warranted by our present understanding of dispersion by the fickle atmosphere. Moreover, the reader is cautioned that a theory involving probabilities has limitations, and the formula perhaps implies an exactitude that does not exist in fact. Nevertheless, if the formula is used to compare various proposed sites, it will be useful. It does involve a rational approach to the location problem in reactor siting.

One deduces from the formula for expectation number of deaths, Equation (59 P), that a plant site with a number of small reactors should have a smaller controlled distance than a site with one large reactor, if the total plant power is fixed. Quantitatively, the plant land area is about inversely proportional to the number of reactors, when the total plant power is constant and the reactors are placed in a group near the center of the site.

DETAILS

RADIOACTIVITY AT THE AXIS OR CENTER OF THE CLOUD

Boiling Accident

The boiling accident is visualized as a gradual release of some fraction of the fission products contained in the reactor by a series of events that cause uncontrolled boiling of the liquid moderator. The fuel sheaths rupture and fission products are released to the moderator, and from there they are liberated with the vapor. It is postulated that the fission products are liberated from the reactor building at a uniform rate of Q/T particles per hour. Sutton's equation for the concentration of particles in the atmosphere from such a source located close to the ground is as follows:

$$\text{Concentration} = \frac{2Q}{\pi C^2 v D^{2-n} T} \exp\left[\frac{-y^2-z^2}{C^2 D^{2-n}}\right] \text{particles/meter}^3 \qquad (1)$$

where

Q = total number of particles emitted
v = wind velocity, meters/hr
D = distance from the source, meters
T = time over which the particles are emitted, hr
C = dispersion coefficient, meters$^{n/2}$
n = turbulence index
y = crosswind distance from the axis of the cloud, meters
z = vertical distance from the axis of the cloud, meters

In the above equation, it is assumed that the axis of the cloud lies along the level ground.

Breathing of the Cloud

The hazard attending the release of the fission products in the reactor can be estimated by letting Q in Equation (1) be the number of curies of radioactivity released.

If one assumes that 50% of the heat energy in the cloud is due to β-particles, that the average energy of the β-particles is 0.3 Mev, and the γ-energy released in the body is 20% as dangerous as the equivalent β-energy, Q can be converted to more useful units as follows:

$$Q' = (\text{pfa MW})(0.5)(1.2)(6.24 \times 10^{18} \frac{\text{Mev}}{\text{MW-sec}})$$

$$\left[\frac{1}{0.3}\ \frac{\beta}{\text{Mev}}\right] \left[\frac{1}{3.7 \times 10^{10}}\ \frac{\text{curie-sec}}{\beta}\right]$$

$$Q' = 3.37 \times 10^8 \text{ pfa curies of equivalent } \beta\text{'s} \qquad (2)$$

where p = reactor power level, MW
f = fraction of the reactor fission products rendered airborne
a = afterheat fraction of full power due to fission product decay

Then, for the present purpose Equation (1) can be written

$$\text{Concentration} = \frac{2.15 \times 10^8 \text{ pfa}}{C^2 v D^{2-n} T} \exp\left[\frac{-y^2-z^2}{C^2 D^{2-n}}\right] \text{curies/meter}^3 \qquad (3)$$

Note that the concentration in curies/meter^3 is numerically the same as if it were expressed in microcuries/cm^3.

By letting y and z be zero, one calculates the concentration at the axis of the cloud. Average dispersion conditions in the atmosphere are represented by Sutton $C = 0.19$ meters$^{1/8}$ and $n = 0.25$. Inversion conditions are represented as: $C = 0.04$ meters$^{1/4}$ and $n = 0.5$. Equation (3) yields the following equations for the concentration of fission products on the axis of the cloud formed by a gradual liberation of the radioactivity.

$$\text{Concentration of equivalent } \beta\text{, microcuries/cm}^3 = \underbrace{\frac{9.02\ pfa}{vD^{1.75}T}}_{\text{Average}} \text{ or } \underbrace{\frac{1300\ pfa}{vD^{1.5}T}}_{\text{Inversion}} \qquad (4) \quad (5)$$

(p in MW, v in miles/hr, D in miles, and T in hours)

In any reactor location the wind velocity, v, can take a wide range of values, of course. If one chooses a low value to insert in Equations (4) and (5), the hazard will be as high as one chooses to make it. A reasonable way to look at the hazard is to consider first the probability of having any wind velocity, v, or less.

Data obtained at one plant site in the U.S.A. for low level and high level winds are plotted in Figure 1. From these data the following are taken:

TABLE I

Probability that the wind velocity will be v miles/hr, or less	Low level wind velocity v miles/hr
0.85	14.2
0.50	8.23
0.05	2.50

The quantity, a, the afterheat of fission product decay is tabulated below for a reactor that has been operating for a month or more.

TABLE II

Time After Shutdown	Afterheat of Fission Products
1 hour	0.0160
6	0.0105
12	0.0087
24	0.0074
100	0.0046

From the above table one can choose a value of a, knowing the wind velocity and the distance of the receptor (thus getting the time of transport). For purposes of explanation, a figure of 1/80 will be chosen. The quantity f is unknown, and only a guess as to its value can be made; f will be taken as 1/2.

The wind velocity probability data of Table I were used in the calculations. These data are derived from a large number of measurements, and should be reliable for average meteorological conditions. One would expect, however, that the data underestimate the probability of occurrence of low velocity winds during inversions. Unfortunately, there is little quantitative information on the connection between wind velocity and dispersion parameters. At some later date it may be possible to reduce this gap in our knowledge. For the moment, we are forced to use Table I as representative of both average and inversion meteorological conditions in the United States.

In Equations (4) and (5) we have chosen two sets of values - average and inversion - for the dispersion parameter, and we can let the wind velocity take the three values of Table I for the three chosen values of the wind velocity probability. Qualitatively, the result of a strong correspondence between low wind velocity and inversion conditions may be stated simply. If such a correspondence does exist, then Equation (5) underestimates the concentration of fission products on the axis of the cloud, for any given wind velocity probability.

In order to correlate the concentration of fission products in the atmosphere with hazard, one should know first of all the probability of death with different amounts of fission products inhaled. Such data have been supplied by K. Z. Morgan of ORNL in the form of a graph, Figure 2.

Note from Figure 2 that the lower threshold for death (probability is zero) is 0.13 microcurie/cm^3 breathed for 24 hours at the average man's breathing rate of 2×10^7 cm^3/24 hours, a total of 2.6 curies.

The "danger distances," or radii of the areas in which death could occur, can be calculated with the help of Equations (4) and (5).

By multiplying the concentration by the average man's breathing rate and by the time that he breathes the cloud, one obtains the total intake, which for death is 2.6 curies, or more. From this equation, the danger distance based on the inhalation mechanism is solved for below.

$$\text{Danger Distance in miles} \approx \underbrace{\left[\frac{2.89\ pfat}{vT}\right]^{0.571}}_{\text{Average (6)}} \text{ or } \underbrace{\left[\frac{413\ pfat}{vT}\right]^{0.667}}_{\text{Inversion (7)}}$$

For instance, if p = 600 MW, f = 1/2, a = 1/80, t = 6 hours, v = 8.23 miles/hr, and T = 6 hours, the danger distance is computed to be 1.07 miles for average conditions and 33.5 miles for inversion conditions.

One may associate the hazard attending the inhalation of fission products not with death, as has been done above, but with an arbitrary figure that describes the allowable emergency concentration in the air if no long term physiological damage is to be done. K. Z. Morgan of ORNL sets this allowable emergency concentration as 10^{-6} microcurie/cm^3 of air, and danger distances calculated with this figure as a basis are much greater than those noted above.

Radiation from the Cloud

When the cloud of radioactive fission products surrounds the receptor, which is at the level of the ground, the γ-rays - not the β-particles - are of importance, since the β's have a short range in air. So, as before, we assume that 50% of the heat energy in the cloud is due to γ-rays. Then Q in Equation (1) can be converted to more useful units as follows:

$$Q' = (\text{pfa MW})(0.5)\left[6.24 \times 10^{18}\ \frac{\text{Mev}}{\text{MW-sec}}\right]\left[\frac{1}{6 \times 10^5}\ \frac{\text{sec-cm}^2}{\text{Mev}}\ \frac{\text{r}}{\text{hr}}\right]\left[\frac{1}{100}\ \frac{\text{meters}}{\text{cm}}\right]^{2**}$$

$$Q' = 5.2 \times 10^8 \text{ pfa } \frac{\text{r-meter}^2}{\text{hr}} \tag{8}$$

Then combining Equations (1) and (8), one calculates a "concentration" in units of r/hr-meter. Call this "concentration" S, for the moment.

A receptor on the ground, surrounded by a cloud in which the "concentration" of radioactivity is S*, is bombarded by γ-rays from elements of volume in the shape of hemispherical shells having a radius ρ and a thickness $d\rho$. The γ-rays from these shells are attenuated by air with a coefficient, μ. Then the total bombardment rate of the receptor is r/t, below:

$$\frac{r}{t} = \int_0^\infty S\ \frac{e^{-\mu\rho}}{4\pi\rho^2}\ 2\pi\rho^2 d\rho = \frac{S}{2\mu} \text{ roentgens/hr} \tag{9}$$

$1/\mu$ is about 330 meters for the average γ-ray in the cloud. Therefore, combining Equations (1), (8), and (9), one gets

$$r = \frac{5.46 \times 10^{10} \text{ pfat}}{C^2 v D^{2-n} T} \exp\left[\frac{-y^2-z^2}{C^2 D^{2-n}}\right] \text{ roentgens} \tag{10}$$

As before, by letting y and z be zero, substituting $C = 0.19$ meters$^{1/8}$ and $n = 0.25$ for average conditions, and $C = 0.04$ meters$^{1/4}$ and $n = 0.5$ for inversion conditions, and converting to length units of miles from meters, equations are obtained for the total exposure from the cloud received by a receptor on the axis of the cloud formed by a gradual liberation of the radioactivity.

	Average		Inversion	
$r =$	$\frac{2270 \text{ pfat}}{vD^{1.75}T}$	or	$\frac{324000 \text{ pfat}}{vD^{1.5}T}$	roentgens of γ
	(11)		(12)	

(p in MW, v in miles/hr, D in miles, T and t in hours)

The probability of death from exposure to γ-rays has been obtained from K. Z. Morgan of ORNL and plotted in Figure 3. Note from this curve that the lower threshold for death is 150 roentgens.

* S is assumed to be constant in a hemisphere of radius $1/\mu$. This will hold for long distances from the reactor. See Note at the end of the report.

** It is convenient in shielding work and in this problem to use a rule-of-thumb definition for the roentgen. The roentgen is herein defined as a certain gamma energy per unit of surface on the receptor. Actually, the roentgen is defined according to the amount of ionization produced by the radiation.

A danger distance based on radiation from the cloud can be computed from Equations (11) and (12) by solving for D with r = 150 roentgens.

$$\text{Danger Distance, miles} = \underset{\text{Average}}{\left[\frac{15.1\ pfat}{vT}\right]^{0.571}} \quad (13) \quad \text{or} \quad \underset{\text{Inversion}}{\left[\frac{2160\ pfat}{vT}\right]^{0.6667}} \quad (14)$$

For instance, if p = 600 MW, f = 1/2, a = 1/80, t = 6 hours, v = 8.23 miles/hr, and T = 6 hours, the danger distance is computed to be 3.01 miles for average conditions and 100 miles for inversion conditions.

It is pertinent to mention here that the formula derived previously by J. A. Wheeler for computing the controlled area of a plant site, was based on this same mechanism of radiation from the cloud surrounding the receptor, although some of the parameters chosen by Wheeler were different from those chosen here. That formula is

$$\text{Controlled Distance} = 0.32\sqrt{p}\ \text{miles} \qquad (15)$$

Thus, for p = 600 MW, the controlled distance would be 7.8 miles.

Rainout from the Cloud

Large amounts of radioactivity could be deposited on the ground beneath a radioactive cloud by heavy rains. It is assumed that some fraction, c, of the particulate and gaseous fission products contained in an imaginary vertical tube of unit cross sectional area through the cloud is brought straight down by the rain and deposited on the ground over the unit area. Part of this deposited radioactivity, the fraction, g, is near or on the surface of the ground, while the rest percolates into the earth. Also, the factor g could take into account the shielding by structures and the rough ground.

Therefore, on this framework of assumptions, one integrates Equation (1) from 0 to ∞ with respect to z, the vertical distance. Then the resulting formula is multiplied by cg giving

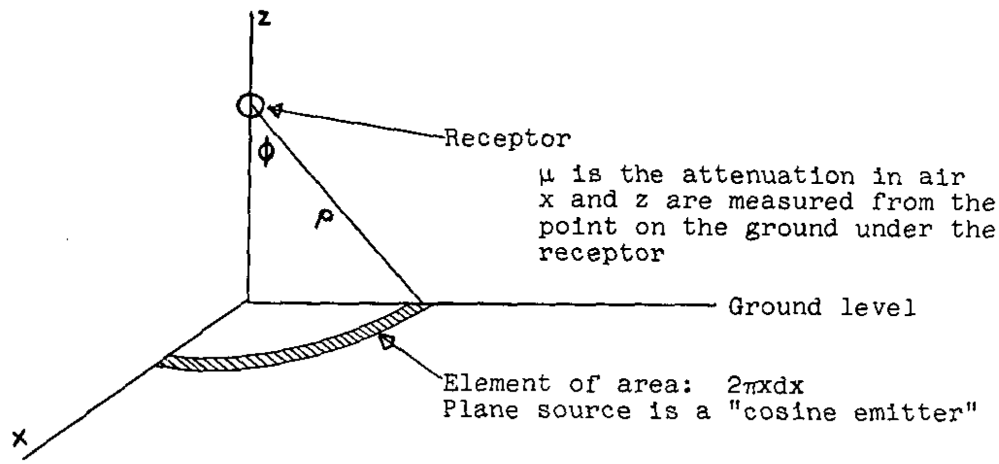
$$\text{Deposit} = \frac{Qcg}{\sqrt{\pi}\ CvD^{(2-n)/2}T} \exp\left[\frac{-y^2}{C^2D^{2-n}}\right] \text{particles/meters}^2 \qquad (16)$$

As before, it is assumed that 50% of the energy of the cloud is due to γ-rays. Then Q, expressed as the number of particles, is converted to more useful units as follows:

$$Q = (\text{pfa MW})(0.50)(\text{geom. factor})(6.25 \times 10^{18}\ \frac{\text{Mev}}{\text{MW-sec}})$$

$$\left[\frac{1}{6 \times 10^5}\ \frac{\text{cm}^2\text{-sec}}{\text{Mev}}\ \frac{\text{r}}{\text{hr}}\right]\left[\frac{1}{100}\ \frac{\text{meters}}{\text{cm}}\right]^2$$

The (geom. factor) above is the fraction of the γ-rays emanating from a unit area of ground that strikes a receptor of unit area said to be 1 meter off the ground. This factor is computed as follows:



$$\text{(geom. factor)} = \int_0^\infty \frac{e^{-\mu\rho}}{4\pi\rho^2} 2\pi x dx \cos\Phi$$

From the diagram $x^2 + z^2 = \rho^2$

where z is constant in this case

$$2xdx = 2\rho d\rho$$

and $$\cos\Phi = \frac{z}{\rho}$$

Then, if $\mu = 0.003$ meters^{-1} and $z = 1$ meter (not important quantities)

$$\text{(geom. factor)} = \frac{\mu z}{2} \int_{\mu z}^\infty \frac{e^{-\mu\rho}}{(\mu\rho)^2} d(\mu\rho) = 0.49$$

Thus:

$$Q' = 2.55 \times 10^8 \text{ pfa } \frac{\text{r-meters}^2}{\text{hr}} \tag{17}$$

where p = reactor power level, MW
f = fraction of the reactor fission products rendered airborne
a = afterheat fraction of full power due to fission product decay

Now, r = (Deposit)(t), where t in hours is the time that a person remains at the scene of the rainout.

Then for the present purpose Equation (16) can be written:

$$r = \frac{1.44 \times 10^8 \text{ pfacgt}}{CvD^{(2-n)/2}T} \exp\left[\frac{-y^2}{C^2D^{2-n}}\right] \text{ roentgens} \tag{18}$$

If one uses diffusion parameters for average and inversion conditions, and converts units, the following equations are obtained for the rainout deposit under a cloud formed by gradual emission of the radioactivity:

For average conditions:

$$r = \frac{735 \text{ pfacgt}}{vD^{0.875}T} \exp\left[-\frac{13.3y}{D^{0.875}}\right]^2 \text{ roentgens of } \gamma \tag{19}$$

For inversion conditions:

$$r = \frac{8790\ \text{pfacgt}}{vD^{0.75}T} \exp\left[-\frac{155y}{D^{0.75}}\right]^2 \text{ roentgens of } \gamma \tag{20}$$

(p in MW, t in hours, v in miles/hr, D in miles, and T in hours)

The product cg is later taken pessimistically as unity, but there is very little knowledge to draw from in making this choice. Along with the great uncertainty in f, the uncertainty in cg is one of the least satisfactory aspects of the whole rainout problem.

The danger distance on the basis of rainout from the cloud may be computed by solving for D with y = 0 and r = 150 roentgens (the lower threshold for death).

$$\text{Danger Distance, miles} = \underbrace{\left[\frac{4.9\ \text{pfacgt}}{vT}\right]^{1.14}}_{\text{Average (21)}} \text{ or } \underbrace{\left[\frac{58.5\ \text{pfacgt}}{vT}\right]^{1.33}}_{\text{Inversion (22)}}$$

For instance, if p = 600 MW, f =1/2, a = 1/80, cg = 1, t = 6 hours, v = 8.23 miles/hr, and T = 6 hours, the danger distance is computed to be 2.49 miles for average conditions and 76 miles for inversion conditions.

Puff Accident

Rainout from the Cloud

The puff accident is visualized as a sudden release of some fraction of the fission products in the reactor - by a nuclear runaway, for instance. The increasing rate of heat liberation suddenly ruptures the fuel elements and destroys their geometry, releasing to the atmosphere fission products in the form of noble gases and particulate matter. The size of the particles is of course very difficult to estimate, as is the fraction of the fission products liberated.

A further complication arises in estimating how high the cloud will rise initially, due to the great heat liberation. Estimates of this height place the figure at about 6000 feet for a reactor operating at 600 MW. On this basis, the breathing hazard and radiation from the cloud are negligible in comparison with the rainout hazard. Therefore, in the case of the puff accident, we will confine our attention to the rainout mechanism.

Sutton's equation for the concentration of particles in the atmosphere from a source that is located far above the ground is

$$\text{Concentration} = \frac{Q}{\pi^{3/2}C^3D^{3(2-n)/2}} \exp\left[\frac{-x^2-y^2-z^2}{C^2D^{2-n}}\right] \text{ particles/meters}^3 \tag{23}$$

Q = total number of particles emitted
C = dispersion coefficient, meters$^{n/2}$
D = distance from the source, meters
n = turbulence index
x = distance from the center of the spherical cloud measured in the wind direction, meters
y = crosswind distance from the center of the cloud, meters
z = vertical distance from the center of the cloud, meters

As before, the problem of rainout is attacked by first integrating with respect to the vertical distance. Since the cloud is elevated, in this case, Equation (23) is integrated from $-\infty$ to ∞ with respect to z; and the result is multiplied by cg to find the deposit

$$\text{Deposit} = \frac{Qcg}{\pi C^2 D^{2-n}} \exp\left[\frac{-x^2-y^2}{C^2 D^{2-n}}\right] \text{particles/meter}^2 \quad (24)$$

Q has in Equation (24) the same meaning as in Equation (16); thus Q is defined by Equation (17). Also, $x^2 + y^2 = R^2$. If we combine this knowledge, Equation (24) becomes

$$r = \frac{8.13 \times 10^7 \text{ pfacgt}}{C^2 D^{2-n}} \exp\left[\frac{-R^2}{C^2 D^{2-n}}\right] \text{roentgens} \quad (25)$$

It should be noted that D in Equations (23), (24), and (25) can be corrected to account for any initial explosion of the cloud. If the initial size of the cloud can be estimated, it is possible to solve for an apparent initial D from Equation (23); then this fictitious distance can be added to the actual distance traveled by the cloud to get D in Equation (25). For instance, in the case of a reactor operating at 600 MW, we estimate that this "virtual source distance" will be about 8 miles when average dispersion parameters are used in Equation (23), and a violent explosion is assumed. For the purposes of this analysis, however, the virtual source distance will be neglected, on the assumption that a very minor explosion of the reactor liberates the fission products.

One further qualification should be mentioned. The workers at Los Alamos are of the opinion that at high altitudes the effect of shearing winds greatly increases the lateral dispersion; thus Equation (25) gives a high value on this account. Perhaps the conservativism could be lessened if one knew the value of C that would account for wind shear.

Many of the uncertain quantitative aspects of this problem could be eliminated, at least in principle, with the help of Equation (25), by analyzing a rainout from the atom bomb tests. It is possible to get from these tests a value for the unknown group

$$\frac{fcg}{C^2}$$

by guessing that n will be perhaps 0.25 at high altitude. C and n are so related theoretically that an error in estimating n is partially compensated for, when Equation (25) is used, by a resultant error in C. Other errors are almost certain to exceed the errors accumulated by making dispersion calculations. For instance, the atom bomb is certain to release particles of smaller size than the particles released in a reactor runaway.

At present, the best that can be done is to substitute average and inversion dispersion parameters in Equation (25), although it is difficult to justify the use of inversion dispersion parameters for high altitudes. The length units can, as before, be converted to miles from meters. Then the following equations are obtained for ground radioactivity following a rainout of the puff cloud formed by a sudden emission of the radioactivity.

For average conditions

$$r = \frac{5460 \text{ pfacgt}}{D^{1.75}} \exp - \left[\frac{13.3R}{D^{0.875}}\right]^2 \text{roentgens of } \gamma \quad (26)$$

For inversion conditions

$$r = \frac{781000 \text{ pfacgt}}{D^{1.50}} \exp - \left[\frac{155R}{D^{0.75}}\right]^2 \text{roentgens of } \gamma \quad (27)$$

(p in MW, t in hours, D in miles, and R in miles)

A danger distance can be computed from Equations (26) and (27) by solving for D with r = 150 roentgens (the lower threshold for death) and R = 0

	Average		Inversion
Danger Distance, miles =	$(36.4 \text{ pfacgt})^{0.571}$	or	$(5200 \text{ pfacgt})^{0.667}$
	(28)		(29)

For instance, if p = 600 MW, f = 1/2, a = 1/80, cg = 1, and t = 6 hours, the danger distance is computed to be 46 miles for average conditions and 2400 miles for inversion conditions.

The equations derived for the maximum values of the exposure (at the center of the cloud) have been plotted in Figure 4 with a uniform set of assumptions. The values taken for the parameters are as follows:

p = 600 MW
f = 0.5
a = 0.0125
cg = 1
t = 6 hours
v = 8.25 miles/hr (average)
T = 6 hours
R = 0 (center of rainout)
y = 0 (axis of cloud)
Average dispersion parameters

Note from Figure 4 that in point of magnitude of the possible hazard, the rainout of the puff cloud is the most dangerous.

We note further that from the standpoint of danger distance, rainout from a puff cloud is also the most dangerous mechanism so far considered. Furthermore, if one postulates that any reactor can suddenly liberate a sizable fraction of its radioactivity, then all reactors operating at the same power level are equally hazardous, again on the basis of danger distance, regardless of the climatology and plant location. This is also the implication of Wheeler's equation [Equation (15)] for the controlled distance around a reactor.

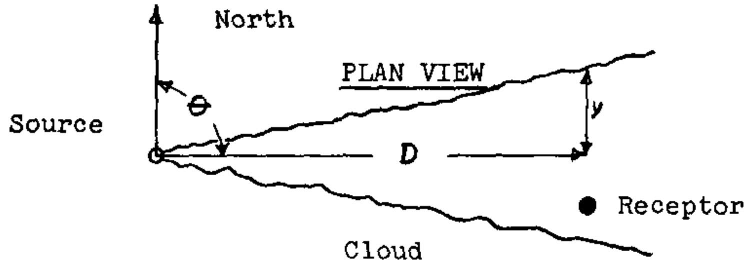
If we are to differentiate rationally among various sites available for reactor location, we cannot rely on danger distances or maximum possible hazards, since these are, as indicated above, functions mainly of reactor power. We need an additional boundary condition, and this additional condition is afforded by the concept of probability. In the next section, we consider probabilities as applied to the hazard problem.

PROBABILITY OF GETTING A CERTAIN DOSAGE

Judging from Figure 4, one concludes that the breathing mechanism cannot result in a hazard exceeding that of radiation from the cloud. Therefore, it will suffice to analyze the three other lines on the chart from the viewpoint of probability. First, the two rainout cases and then the radiation case will be analyzed.

Boiling Accident - Rainout

In order for a receptor to be exposed, the cloud must first of all pass directly over it. The chance that this will occur is shown as follows:



Chance that the cloud will sweep over the receptor at D $\cong \frac{2y}{2\pi D} P(\theta)$

where $P(\theta)$ is the relative probability that the wind, persistent in direction and velocity, will blow between the angles θ and $\theta + d\theta$ as compared with unity if all wind directions were equally probable. Ordinarily, $P(\theta)$ will vary from 0.5 to 3.0 for low-level winds.

The chance that a rain will occur while the cloud is over the receptor is equal to the quotient of the time spent by the cloud over the receptor and the time between rains. A rain, for this purpose, is considered to be an incident that occurs over any receptor with the frequency $(1/\tau)$ hours^{-1}. In general, τ could be a function of both wind velocity, v, and wind direction, θ.

Then

Chance that a rain will occur while the cloud is overhead $= \frac{T}{\tau} \epsilon$

where ϵ is some undetermined function of the persistence of the wind direction and velocity. It is assumed that $\epsilon = 1$ (persistent wind), which is equivalent to saying that if the fission products are liberated over a period of 6 hours, then the cloud will pass over certain receptors for the same period of time.

But if the cloud should experience a rain before reaching the receptor, it seems likely that a great fraction of the radioactivity contained in the cloud will be washed out before the cloud passes over the receptor. This effect can be accounted for in a very approximate way by multiplying the chance that a rain will occur over any given receptor by $(1-\alpha)$, where α is the fraction of the time that any receptor experiences rain. This formulation is good only if the time between local and general rains is long compared with the time of passage of the cloud between the source and receptor. α is ordinarily a small number; in most places in the U. S. it is less than 0.1. Hence, the quantity $(1-\alpha)$ is close to unity; and it is not important in its effect on the probability of rainout.

Combining these chances, one finds the probability of rainout, P(c), at the distance D miles from the receptor, if the cloud is defined to be y miles wide.

$$P(c) \cong \frac{yT}{\pi D\tau} (1-\alpha)\, P(\theta) \qquad (30)$$

Equations (19) and (20) may be solved for y. The y so obtained defines an envelope within which the point radioactivity is everywhere (r/t) roentgens/hr, or higher.

For average conditions

$$y = \frac{D^{0.875}}{13.3} \left[\ln \frac{735\ pfacgt}{rvD^{0.875}T} \right]^{0.5} \qquad (19a)$$

For inversion conditions

$$y = \frac{D^{0.75}}{155}\left[\ln \frac{8790\ \text{pfacgt}}{rvD^{0.75}T}\right]^{0.5} \tag{20a}$$

Note that as r increases, y decreases; that is, if one chooses to set a high value of r, the cloud becomes narrow - hence the probability of rainout becomes small.

It is convenient to define a new velocity, v*, which reduces y to 0 [see Equations (19a) and (20a) at any chosen value of r, when p,f,a,c,g,t,D and T have been fixed]. Then,

$$v^* = \underset{\text{(31)}}{\underset{\text{Average}}{\frac{735\ \text{pfacgt}}{rD^{0.875}T}}} \text{ or } \underset{\text{(32)}}{\underset{\text{Inversion}}{\frac{8790\ \text{pfacgt}}{rD^{0.75}T}}}$$

Now we arrive at the problem of finding the integrated probability that any receptor will get r, or more, roentgens exposure in the land area surrounding a reactor. This probability is

$$\int\int dP(c)\ dP(v) \tag{33}$$

where P(c), the probability of a rainout from a cloud, is defined by Equation (30) and P(v) is the probability of the wind speed being v miles/hr or less.

In order to evaluate this integral properly, it must be realized that P(c) is a function of C (the dispersion coefficient - which may or may not be a function of v), of v (the wind velocity), of τ (the time between rains - which is almost certain to be a function of v and θ), and of θ (the direction of the receptor). P(v), the probability of experiencing a certain wind velocity or less, is $0.0085\ v^2$ for low-level winds, according to the data of Figure 1.

The data of climatology do not at present allow the integral to be evaluated accurately. Therefore, we approximate the probability by choosing two values of C(average and inversion conditions), and by choosing the average value of τ independent of v, which is equivalent to saying that rain is equally probable no matter how hard the wind blows. Then P(c) is a function of only one variable v, and the integral of Equation (33) is approximately true. Hence we work as follows:

$$\text{Probability of rainout of r roentgens or more} = \int_0^1\int_0^{P(c)} dP(c)\ dP(v) = \int_0^1 P(c)\ dP(v) \tag{34}$$

Figure 1 allows one to perform the integration in Equation (34) over the whole range of P(v) from 0 to 1. But, alternately, it will be accurate to within several per cent to evaluate Equation (34) with the approximation

$$dP(v) = 2(0.0085)\ v\ dv \tag{35}$$

from v = 0 to v = v*. Now, it is seen that the highest value v* can take is the wind velocity, V, that will make P(v) = 1. Above that value of v*, the approximation made (i.e., that $P(v) = 0.0085v^2$) will not hold - for it is obvious that P(v) cannot be greater than unity. Accordingly, we can calculate the probability of a rainout of r roentgens or more for average conditions by substituting Equations (30), (19a), (31), and (35) in Equation (34); and the following is obtained:

$$\begin{array}{l}\text{Probability of rainout} \\ \text{of r roentgens or more}\end{array} = \left[\frac{(2)(0.0085)}{(13.3)(\pi)} \frac{Tv^{*2}(1-\alpha)\ P(\theta)}{\tau D^{0.125}}\right] \int_0^1 \left(\frac{v}{v^*}\right) \left(\ln \frac{v^*}{v}\right)^{0.5} d\left(\frac{v}{v^*}\right) \quad (36)$$

where v* is defined by Equation (31), subject to the limitation above, and

$$\int_0^1 \left[\frac{v}{v^*}\right] \left[\ln \frac{v^*}{v}\right]^{0.5} d\left[\frac{v}{v^*}\right] = \frac{\Gamma(1.5)}{2^{1.5}} = 0.313 \quad (37)$$

where Γ signifies the gamma function.

The same procedure is followed in deriving a similar expression for inversion conditions.

The resulting equations give the probability of a rainout that will expose any receptor at a distance of D miles to r roentgens, or higher, following a gradual emission of fission products from the reactor

For average conditions

$$\begin{array}{l}\text{Probability of rainout} \\ \text{of r roentgens or more}\end{array} = \frac{69(1-\alpha)\ P(\theta)}{TD^{1.875}\tau} \left[\frac{pfacgt}{r}\right]^2 \quad (38)$$

For inversion conditions

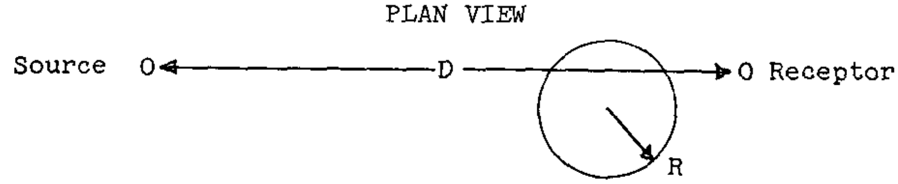
$$\begin{array}{l}\text{Probability of rainout} \\ \text{of r roentgens or more}\end{array} = \frac{825(1-\alpha)\ P(\theta)}{TD^{1.75}\tau} \left[\frac{pfacgt}{r}\right]^2 \quad (39)$$

(p in MW, t in hours, T in hours, τ in hours, D in miles, and r in roentgens)

Puff Accident - Rainout

The chance that a spherical cloud of radius R, formed by a sudden emission of radioactivity, will sweep over a receptor at a distance D is found by a method analogous to that used in the case of the long cloud, formed by gradual emission of the radioactivity.

PLAN VIEW



$$\begin{array}{l}\text{Chance that the cloud will} \\ \text{sweep over the receptor at D}\end{array} \cong \frac{2R}{2\pi D}\ P(\theta)$$

The chance that a rain will occur while the cloud is directly over the receptor is

$$\frac{2R}{v\tau} \cdot \frac{\pi}{4}$$

Thus, by the same reasoning used to get Equation (30)

$$P(c) \cong \frac{R^2}{2v\tau D}(1-\alpha)\ P(\theta) \quad (40)$$

In this case of the spherical cloud and circular rainout envelope, R^2 can be obtained from Equations (26) and (27) as

For average conditions

$$R^2 = \frac{D^{1.75}}{177}\left[\ln \frac{5460 \text{ pfacgt}}{rD^{1.75}}\right] \tag{26a}$$

For inversion conditions

$$R^2 = \frac{D^{1.50}}{24000}\left[\ln \frac{781000 \text{ pfacgt}}{rD^{1.50}}\right] \tag{27a}$$

It is convenient, as before, to define for later work a new exposure, r*, as follows:

$$\begin{array}{ccc} & \underline{\text{Average}} & & \underline{\text{Inversion}} \\ r^* = & \dfrac{5460 \text{ pfacgt}}{D^{1.75}} & \text{or} & \dfrac{781000 \text{ pfacgt}}{D^{1.50}} \\ & (41) & & (42) \end{array}$$

In this case of the spherical puff cloud (which is the result of a sudden emission of the fission products), we make the same approximations as for the case of the long cloud (which is the result of gradual emission of the fission products) and work as follows:

$$\text{Probability of rainout of r roentgens or more} = \int_0^1 P(c)\, dP(v) \tag{43}$$

dP(v) for high level winds is found from Figure 1 to be:

$$P(v) = 0.003\ v^2 \tag{44}$$

$$dP(v) = (2)(0.003)\ v\ dv \tag{44a}$$

Combining Equations (40), (43), and (44a), and integrating from v = 0 to v = V, we obtain

$$\text{Probability of rainout of r roentgens or more} = \int_0^V \frac{R^2(1-\alpha)\ P(\theta)}{2v\tau D}(2)(0.003)\ v\ dv = \frac{0.003\ R^2 V(1-\alpha)\ P(\theta)}{\tau D} \tag{45}$$

V is the extrapolated value of the wind velocity, in miles/hr, that makes P(v) = 1. Hence, from Equation (44), V = 18.2 miles/hr. R^2 is obtained from Equations (26a) and (27a).

Then the following equations are obtained for the probability of a rainout that will expose any receptor at a distance of D miles to r roentgens, or higher, following a sudden emission of fission products from the reactor

For average conditions

$$\text{Probability of rainout of r roentgens or more} = \frac{3.08 \times 10^{-4}(1-\alpha)\ D^{0.75}\ P(\theta)}{\tau}\left[\ln \frac{5460 \text{ pfacgt}}{rD^{1.75}}\right] \tag{46}$$

For inversion conditions

$$\text{Probability of rainout of r roentgens or more} = \frac{2.15 \times 10^{-6}(1-\alpha)\ D^{0.50}\ P(\theta)}{\tau}\left[\ln \frac{781000 \text{ pfacgt}}{rD^{1.50}}\right] \tag{47}$$

(p in MW, τ in hours, t in hours, D in miles, and r in roentgens)

Boiling Accident - Radiation from the Cloud

As in the case of the rainout, the chance that a cloud will pass over and around a receptor is

$$P(c) = \frac{2y}{2\pi D} P(\theta)$$

The width of the cloud y is obtained from Equations (10) and (11) with z = 0 (receptor on the ground) as

$$y = \frac{D^{0.875}}{13.3} \left[\ln \frac{v^{**}}{v}\right]^{0.5} \tag{10a}$$

$$\text{where } v^{**} = \frac{2270 \text{ pfat}}{rD^{1.75}T} \tag{48}$$

for average conditions.

For inversion conditions, the coefficients 13.3 and 2270 are altered to 155 and 329000 respectively, and the powers of D from 0.875 and 1.75 to 0.75 and 1.5 respectively.

Then the probability of exposure to r roentgens or higher is found by a calculation similar to that described by Equation (34).

$$\begin{matrix}\text{Probability of exposure} \\ \text{of r roentgens or more}\end{matrix} = \int_0^1 P(c)\, dP(v) \tag{34a}$$

Equation (35) gives dP(v) in the above equation, and the integration is similar to that shown in Equations (36) and (37). Then for average conditions

$$\begin{matrix}\text{Probability of exposure} \\ \text{of r roentgens or more}\end{matrix} = \frac{(2)(0.0085)(0.313)\ P(\theta)\ v^{**2}}{(\pi)(13.3)\ D^{0.125}} = 1.273 \times 10^{-4} \frac{v^{**2}}{D^{0.125}} P(\theta) \tag{49}$$

where v** is defined by Equation (48) and cannot exceed 10.6 miles/hr for reasons outlined earlier (see Equation 35).

For inversion conditions

$$\begin{matrix}\text{Probability of exposure} \\ \text{of r roentgens or more}\end{matrix} = 1.064 \times 10^{-5} \frac{v^{**2}}{D^{0.25}} P(\theta) \tag{50}$$

$$\text{where } v^{**} = \frac{324000 \text{ pfat}}{rD^{1.5}T} \tag{51}$$

and v** cannot exceed 10.6 miles/hr, no matter what values of the parameters are chosen.

(p in MW, T and t in hours, D in miles, and r in roentgens)

Now it will be obvious upon inspecting Equations (36) and (49)* that, unless $\tau < T$, which is highly unlikely in the temperate zone, the rainout probability is less than the radiation probability. Both of these equations apply to the boiling accident. Therefore, from this point on we can confine our attention to the following two cases (see Figure 4):

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* When Equation (36) = Equation (49):

$$\tau = \frac{(1-\alpha)\ D^{1.75}(cg)^2 T}{9.6}$$

1) Puff Accident - rainout
2) Boiling Accident - radiation from the cloud

In the next section, the concept of the probability of death will be used to find the expectation number of deaths by these two mechanisms when average climatology is assumed.

EXPECTATION NUMBER OF DEATHS FOLLOWING A REACTOR INCIDENT, AND THE CONTROLLED DISTANCE

Puff Accident - Rainout

Should a large amount of radioactive fission products be suddenly liberated to the atmosphere, the inhabitants living in the surroundings would be subjected to a low probability of death. According to our definition and approximations, this probability, P(d), is as follows:

$$P(d) = \int \left[\int P(r)\ dP(c) \right] \quad dP(v) \tag{52}$$

P(r) is the chance that a person will die if exposed to r roentgens of γ-rays emitted by fission products deposited on the ground by a rainout. This relation has been supplied to us by K. Z. Morgan of ORNL, and it is plotted in Figure 3. dP(v) has been defined for high level winds in Equation (44a). dP(c) is found as a function of r from Equations (40) and (26a) for average climatology as follows:

$$dP(c) = \frac{2RdR(1-\alpha)\ P(\theta)}{2v\tau D} \tag{40a}$$

$$2RdR = -\frac{D^{1.75}}{177}\frac{dr}{r} \tag{26b}$$

Then

$$P(d) = \int_0^{v*} \left[\int_{r*}^{0} - \frac{(1-\alpha)\ D^{0.75}\ P(\theta)\ P(r)\ dr}{(2)(177)\ v\tau r} \right] (0.006)\ vdv \tag{53}$$

Note that the lower limit on the integration inside the brackets corresponds to the condition that P(c) = 0. Such a condition comes about by letting R = 0 in Equation (26a); and for R to be zero, r must be r*. v* has been found from Equation (44) to be 18.2 miles/hr. The integration inside the brackets, with sign changed and limits reversed

$$\int_0^{r*} \frac{P(r)dr}{r}$$

is given in Figure 5 as a function of r*. The graph is plotted for values of r* less than 10^5 roentgens. If r* should be greater than 10^5, the integral has the value

$$5.50 + \ln \frac{r*}{10^5}$$

since P(r) is very close to unity (a person will surely meet death) for such high values of γ-exposure.

Then, the following equations are obtained for the probability of death by rainout per capita per reactor incident that suddenly releases fission products to the atmosphere.

For average conditions

$$\text{Probability of death} = \frac{3.08 \times 10^{-4}(1-\alpha)\ D^{0.75}\ P(\theta)}{\tau} \int_0^{r*} \frac{P(r)dr}{r} \tag{54}$$

$$\text{where:}\quad r* = \frac{5460\ pfacgt}{D^{1.75}} \tag{41}$$

For inversion conditions

$$\text{Probability of death} = \frac{2.15 \times 10^{-6}(1-\alpha)\, D^{0.50}\, P(\theta)}{\tau} \int_{0}^{r^*} \frac{P(r)dr}{r} \qquad (55)$$

$$\text{where: } r^* = \frac{781000 \text{ pfacgt}}{D^{1.50}} \qquad (42)$$

(p in MW, t in hours, D in miles, and τ in hours)

Perhaps the only absolute rating that can be placed on a reactor plant site is the number of deaths to be expected if the reactor should fail with the liberation of some fraction of its fission products. While this is a negative rating, and the actual number of deaths per reactor incident cannot in principle be a relatively invariant quantity (such as the number of people killed by lightning per year) it is a useful concept. It takes into account the frequency of rainfall, the population density outside the plant site, the reactor power level, the prevailing wind direction, the susceptibility of man to injury by exposure to radiations, and the size of the plant site. The use of the concept demands, however, that one assume that people remain in a polluted area for some arbitrary period of time.

In truth, it is entirely conceivable that the danger of death could be eliminated by arranging to evacuate the populace soon after a rainout occurs, if it occurs at all. For instance, if people live 10 miles from a reactor operating at 600 MW, one can estimate how soon they must be evacuated after a rainout from a puff accident in order to eliminate the chance of death. Equation (26) is useful for this purpose. From it we obtain

$$t = \frac{rD^{1.75}}{5460 \text{ pfacg}} \text{ hours, with } R = 0 \text{ (center of rainout)}$$

Now with r = 150 roentgens (lower threshold for death)
D = 10 miles
p = 600 MW
fcg = 1/2 (very pessimistic)
a = 0.02 (see Table II)

t, the time a person can remain at the scene of the rainout before he is in danger of losing his life, is found to be 0.26 hour.

It is perhaps more reasonable to guess that fcg = 0.1, or even lower, so that t = 1.3 hours, or more.

Since the average wind velocity at high altitude is about 16 miles/hr it would probably take an additional 10/16 hour for the cloud to reach a settlement 10 miles from the reactor. A warning is certainly possible. Hence, it is not unreasonable to state that no deaths whatever should result if certain precautions were taken, even in the event of a reactor disaster that has no precedent.

Nevertheless, if one chooses to say that people will remain at the scene of a rainout for say 6 hours (or some such arbitrary figure set by the authorities for the purpose only of rating various plant sites), one can calculate the expectation number of deaths as follows:

1. Divide up the area surrounding the reactor into small segments on polar coordinates, each at a distance D miles from the reactor and at angle θ from the north.

2. Note the number of people living in each one of these segments. Call this number N_i.

3. Determine from the climatology of the plant site how frequently heavy rains occur. Arbitrarily, a heavy rain is one over 0.5 in. Call this frequency (1/τ) hours^{-1}.

4. Determine from the climatology of the plant site the relative probability that the wind will blow toward each of the segments of area. Call this relative probability $P(\theta)$ (the average segment has $P(\theta) = 1$).

5. Estimate a, the afterheat due to fission product decay, for each segment from Table II. (a may be deduced if one knows the average wind velocity at high altitudes and the distance from the reactor of each segment.)

6. Arbitrarily, set fcgt at 3 hours (fcg = 1/2, t = 6 hours).

7. Calculate the number of deaths per reactor incident to be expected in each segment of area on the assumption of average climatology, as follows:

$$\text{Deaths in Segment 1} = N_1 P(d) = \frac{3.08 \times 10^{-4} N_1 (1-\alpha)\, D^{0.75}\, P(\theta)}{\tau} \int_0^{r^*} \frac{P(r)dr}{r} \qquad (56)$$

(N_1 in persons, D in miles, and τ in hours)

The value of the integral above is found from Figure 5 with

$$r^* = \frac{5460\ pa(fcgt)}{D^{1.75}} \qquad (41)$$

(p in MW, D in miles)

8. Sum the expectation deaths in each segment of area, arriving at the figure for the expectation number of deaths.

The above calculation is general for an area in which the population density is highly variant. If the population is assumed to be more uniformly distributed in the surroundings, one can calculate the controlled distance in a similar manner by arbitrarily choosing the allowable number of deaths and using average dispersion parameters.

$$\text{Expectation Deaths} = \chi = \frac{(2\pi)(3.08 \times 10^{-4})\ N(1-\alpha)\ P(\theta)}{\tau} \int_{D1}^{D2} D^{1.75} \left[\int_0^{r^*} \frac{P(r)dr}{r} \right] dD \qquad (57)$$

where D_2 = danger distance by Equation (28) miles

D_1 = controlled distance miles

r^* = upper limit of exposure from Equation (41) roentgens

The controlled distance has been solved for in the above equation, and the results have been plotted in Figure 6. With this graph, one enters on the ordinate and abscissa with the known parameters to find the controlled distance. Or if a controlled distance is known, the allowable power level, for instance, may be found. The basis for Figure 6 is the mechanism of rainout from a cloud formed by a puff accident. Note that for large accidents, the existence of a controlled zone is of small help.

Boiling Accident - Radiation from the Cloud

In this section direct radiation from the low-lying poison cloud is considered as a mechanism that can result in a number of deaths.

This mechanism is the one that is found to set the controlled distance for most practical cases. In order to find this controlled distance for any number of probable deaths per accident, it is necessary to write an equation for the number of deaths in terms of the controlled distance, D_1. In general, the expectation number of deaths per accident, χ, is written as follows:

$$\chi = \int_0^{\Delta\theta} \int_0^{\infty} \int_0^{\infty} \int_{D_1}^{\infty} NDdDP(r) \left[\frac{\partial P(c)}{\partial r}\right] dr \left[\frac{\partial P(v)}{\partial v}\right] dv d\theta \qquad (58)$$

Equation (58) is written with the assumption that the atmospheric dispersion parameters are fixed (average values), and the only meteorological variable is the wind velocity, v. The wind velocity is assumed to be independent of the dispersion parameters and angle, θ. In the region of low wind velocities, which are most important in this problem, the wind velocity probability is found to be of the form

$$P(v) = Kv^2 \text{ (see Figure 1)}$$

By this formula, the upper limit on the wind velocity is $V = K^{-0.5}$, for then $P(v) = 1$. It will be sufficiently accurate to use this upper limit on v when integrating Equation (58), since high wind velocities do not contribute much to the integral.

Then

$$\frac{\partial P(v)}{\partial v} = 2Kv$$

If N is independent of distance, D, integration with respect to θ may be carried out immediately to obtain the number of deaths, χ^*, in the sector $\Delta\theta$ radians wide.

$$\chi^* = N(\Delta\theta) \int_0^\infty \int_0^\infty \int_{D_1}^\infty DdDP(r) \left[\frac{\partial P(c)}{\partial r}\right] dr \left[\frac{\partial P(v)}{\partial v}\right] dv \tag{59}$$

P(r) is defined in Figure 3.

$P(c) = \frac{2yP(\theta)}{2\pi D}$ = the chance that the cloud will sweep over the receptor at the distance D, which is greater than the controlled distance D_1.

$$y = \frac{\text{cloud width}}{2} = \frac{D^{0.875}}{13.3} \left[\ln \frac{G}{vrD^{1.75}}\right]^{0.5} \tag{10a}$$

In Equation (10a), average dispersion parameters have been used, and the same applies to G, which is

$$G = \frac{2270 \text{ pfat}}{T} \text{ roentgens - miles}^{2.75}/\text{hr} \tag{48a}$$

Then

$$\frac{\partial P(c)}{\partial r} = - \frac{D^{0.875} P(\theta)}{26.6\pi Dr} \left[\ln \frac{G}{vrD^{1.75}}\right]^{-0.5} \tag{60}$$

In order to integrate Equation (59), it will be convenient to define new variables as follows:

$$v = s$$

$$r = z$$

$$\frac{G}{vrD^{1.75}} = u$$

Then

$$\frac{\partial(v,\ r,\ D)}{\partial(s,\ z,\ u)} = \begin{vmatrix} \frac{\partial v}{\partial s} & \frac{\partial r}{\partial s} & \frac{\partial D}{\partial s} \\ \frac{\partial v}{\partial z} & \frac{\partial r}{\partial z} & \frac{\partial D}{\partial z} \\ \frac{\partial v}{\partial u} & \frac{\partial r}{\partial u} & \frac{\partial D}{\partial u} \end{vmatrix} = \begin{vmatrix} 1 & 0 & \frac{\partial D}{\partial s} \\ 0 & 1 & \frac{\partial D}{\partial z} \\ 0 & 0 & \frac{\partial D}{\partial u} \end{vmatrix} = \frac{\partial D}{\partial u} = \left| \frac{4}{7} \left(\frac{G}{rv}\right)^{4/7} \frac{1}{u^{11/7}} \right|$$

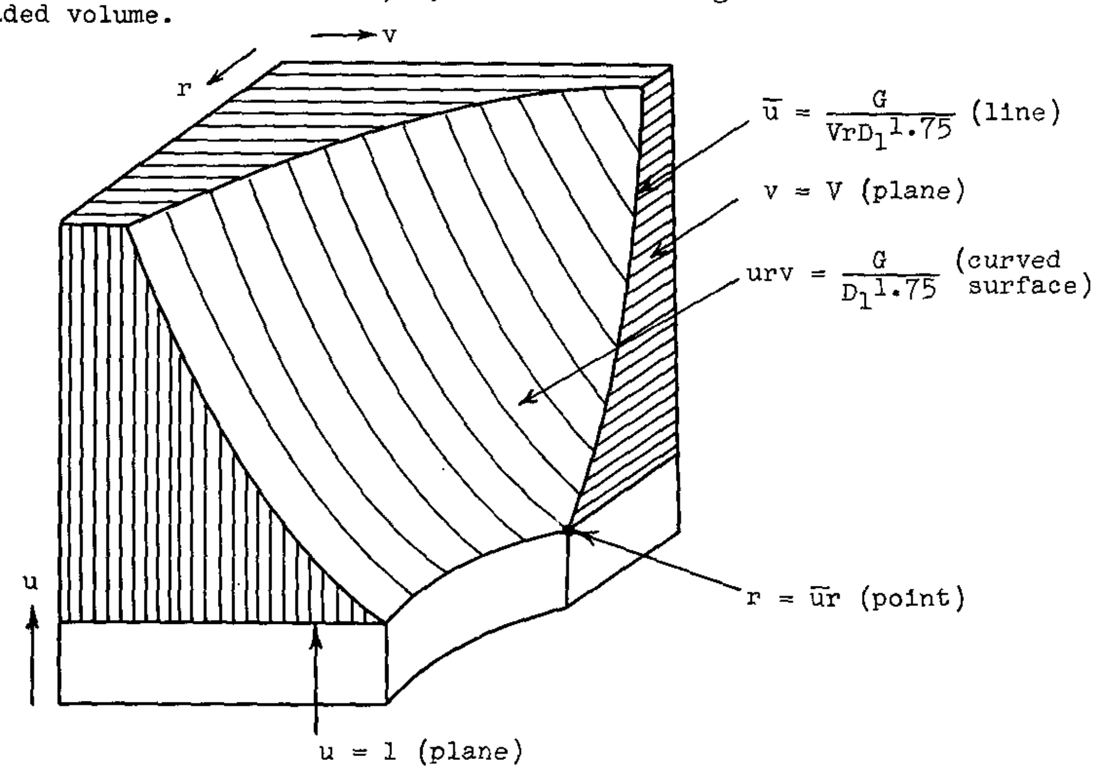
Equation (59) may be rewritten as follows:

$$\chi^* = \frac{N(\Delta\theta)(2K)\ P(\theta)}{(26.6)(\pi)} \int \frac{P(r)dr}{r} \iint \frac{D^{0.875} v dv dD}{(\ln u)^{0.5}}$$

$$= \frac{N(\Delta\theta)(2K)\ P(\theta)}{(26.6)(\pi)} \int \frac{P(r)dr}{r} \iint \left(\frac{G}{rvu}\right)^{0.5} \frac{v}{(\ln u)^{0.5}} \cdot \frac{4}{7} \left(\frac{G}{rv}\right)^{4/7} \frac{dvdu}{u^{11/7}}$$

$$= \frac{N(4)(\Delta\theta)(2K)\ P(\theta)}{(7)(26.6)(\pi)} G^{15/14} \int \frac{P(r)dr}{r^{29/14}} \iint \frac{dvdu}{v^{1/14} u^{29/14} (\ln u)^{0.5}}$$

The new limits of integration are deduced from the following diagram, in which the coordinates are v, u, and r. The integration is carried out over the shaded volume.



$$\chi = \int_0^{\infty} \int_1^{\infty} \int_0^{\frac{G}{D_1^{1.75} ur}} f(v,u,r) dvdudr - \int_0^{\bar{u}r} \int_1^{\bar{u}} \int_V^{\frac{G}{D_1^{1.75} ur}} f(v,u,r) dvdudr$$

The next integration is with respect to v, and the following is obtained:

$$\chi^* = \frac{(14)(4)(N)(\theta)(2K)\ P(\theta)}{(13)(7)(26.6)(\pi)}\ G^{15/14}\ W \tag{59 A}$$

where

$$W = \left(\frac{G}{D_1{}^{1.75}}\right)^{13/14}\left[\int_0^\infty\int_1^\infty \frac{du}{u^3(\ln u)^{0.5}}\frac{P(r)dr}{r^3} - \int_0^{\bar{u}r}\int_1^{\bar{u}} \frac{du}{u^3(\ln u)^{0.5}}\frac{P(r)dr}{r^3}\right] + V^{13/14}\int_0^{\bar{u}r}\int_1^{\bar{u}} \frac{du}{u^{29/14}(\ln u)^{0.5}}\frac{P(r)dr}{r^{29/14}}$$

The next integration is with respect to u, and one notes that

$$\int_1^\infty \frac{du}{u^3(\ln u)^{0.5}} = \sqrt{\frac{\pi}{2}}\ \text{erf}\ (2\ \ln \infty)^{0.5} = \sqrt{\frac{\pi}{2}} \tag{61}$$

$$\int_1^{\bar{u}} \frac{du}{u^3(\ln u)^{0.5}} = \sqrt{\frac{\pi}{2}}\ \text{erf}\ (2\ \ln \bar{u})^{0.5} \tag{62}$$

$$\int_1^{\bar{u}} \frac{du}{u^{29/14}(\ln u)^{0.5}} = \sqrt{\frac{14\pi}{15}}\ \text{erf}\ \left(\frac{15}{14}\ \ln \bar{u}\right)^{0.5} \tag{63}$$

Thus, the integrated form of Equation (59) becomes

$$\frac{(13)(7)(26.6)(\pi)}{(14)(4)(N)(\Delta\theta)(2K)\ P(\theta)}\chi^* = \sqrt{\frac{\pi}{2}}\frac{G^2}{D_1{}^{13/8}}\int_0^\infty \frac{P(r)dr}{r^3} - \sqrt{\frac{\pi}{2}}\frac{G^2}{D_1{}^{13/8}}\int_0^{\bar{u}r} \text{erf}\ (2\ \ln \bar{u})^{0.5}\ \frac{P(r)dr}{r^3} + \sqrt{\frac{14\pi}{15}}\ \frac{G^{15/14}}{K^{13/28}}\int_0^{\bar{u}r} \text{erf}\ \left(\frac{15}{14}\ \ln \bar{u}\right)^{0.5}\frac{P(r)dr}{r^{29/14}} = \frac{67.9\chi^*}{N(\Delta\theta)K\ P(\theta)} \tag{59 I}$$

where

$$\bar{u} = \frac{G}{D_1{}^{1.75}Vr} = \frac{GK^{0.5}}{D_1{}^{1.75}r} \tag{64}$$

This cannot be integrated analytically any further since P(r) is an empirical function. The integrals have been evaluated by graphical means.

It will be observed that if $D_1 = 0$ (no controlled distance) $\bar{u} = \infty$, erf $(\infty) = 1$, and the first two terms cancel leaving only the third term.

In the region where $\bar{u} = 1$, the second and third terms are both zero, since erf $(0) = 0$. If $\bar{u} = 1$, then

$$r = \frac{GK^{0.5}}{D_1{}^{1.75}} \tag{64a}$$

In order for the first term to hold, r must be greater than 150 roentgens, for this is the lower threshold for death (see Figure 3). Therefore, the second and third terms drop out and the first terms holds if

$$150 < \frac{GK^{0.5}}{D_1^{1.75}} \text{ or } D_1^{1.75} > \frac{GK^{0.5}}{150} \qquad (64b)$$

K from Figure 1 is 0.0085 $hr^2/mile^2$ for a typical site. Then

$$D_1^{1.75} > \frac{1.43 \text{ pfat}}{T} \quad \text{(The region where only the first term is needed)} \qquad (64b)$$

One additional fact from Equation (59 I) may be deduced. If the quantity $\chi^*/\Delta\theta$ is not to be a function of θ, that is, if the distribution of deaths with angle is constant, then D_1 must be a function of $P(\theta)$. The controlled distance should be greater at angles where $P(\theta)$ is high. That is, the plant should have a larger buffer zone in the direction that the wind blows more often.

If $\chi^*/\Delta\theta$ is constant, for the above reason, then χ can represent the total expectation number of deaths per accident when $\Delta\theta = 2\pi$. Equation (59 I) then becomes

$$\frac{\chi}{N\,P(\theta)} = \frac{5060}{D_1^{13/8}} \left[\frac{\text{pfat}}{T}\right]^2 \int_0^\infty \frac{P(r)dr}{r^3} - \frac{5060}{D_1^{13/8}} \left[\frac{\text{pfat}}{T}\right]^2 \int_0^{\bar{u}r} \text{erf } (2 \ln \bar{u})^{0.5} \frac{P(r)dr}{r^3}$$

$$+ 47.8 \left[\frac{\text{pfat}}{T}\right]^{15/14} \int_0^{\bar{u}r} \text{erf } \left(\frac{15}{14} \ln \bar{u}\right)^{0.5} \frac{P(r)dr}{r^{29/14}} \qquad (59\ P)$$

where

$$\int_0^\infty \frac{P(r)dr}{r^3} = 4.5 \times 10^{-6} \text{ roentgens}^{-2} \text{ from Figure 3}$$

$$\int_0^\infty \frac{P(r)dr}{r^{29/14}} = 1.71 \times 10^{-3} \text{ roentgens}^{-15/14} \text{ from Figure 3}$$

$\bar{u}$ is defined in Equation 64.

Equation (59 P) has been plotted in Figure 7 with pfat/T on the ordinate. This is the size of the accident measured by the fission product decay heat in the whole cloud in MW. On the abscissa is $N\,P(\theta)/\chi$, the number of people per square mile times the wind direction probability divided by the expectation number of deaths per accident. Lines of constant controlled distance then connect the size of the accident with the number of deaths.

Equation (59 I) is general in that it need not be used only for calculating the number of deaths; it may also be used to find the number of people who will receive r roentgens, or more, following an accident. For instance, suppose a plant has zero controlled distance and an accident occurs that puts up a cloud of 2 MW. It is required to find the number of people who will receive one roentgen, or more, if the population density is N = 15 people per square mile. The meteorology of the area is such that K = 0.01.

Since $D_1 = 0$, $\bar{u} = \infty$, and only the third term remains in Equation (59 I). P(r) is 0 from r = 0 to r = 1. P(r) is 1 from r = 1 to r = ∞. G = 4540, since pfat/T = 2.0 MW.

$$\frac{67.9\chi^*}{(\Delta\theta)N\ P(\theta)} = \sqrt{\frac{14\pi}{15}}\, G^{15/14} K^{15/28} \int_1^\infty \frac{dr}{r^{29/14}} \qquad (59\ I^*)$$

$$\frac{\chi^*}{(\Delta\theta)\ P(\theta)} = \sqrt{\frac{14\pi}{15}}\, \frac{(15)}{(67.9)}\, (0.01)^{15/28} (4540)^{15/14} \left[\frac{14}{15}\right] \left[\frac{1}{1} - \frac{1}{\infty}\right]$$

$$= 240 \text{ people per radian}$$

Hence, a total of 1500 people in the surroundings will receive 1 roentgen or more by direct radiation from the cloud.

ACCIDENTAL RELEASE OF OTHER POISONOUS GASES

Equation (59 I) may be used to calculate the hazard to people living near any stored or released poisonous gases. For instance, if a large amount of H_2S were to be released over a period of hours, the number of people who would be likely to breathe any given concentration of this gas, or more, can be calculated with Equation (59 I.)

In this case it will be necessary to redefine G. A convenient set of units for the concentration of poisonous gas would be: parts per million by volume, and r would be the concentration in parts per million.

The atmospheric dispersion equation, with average dispersion parameters, becomes

$$r = \frac{P}{1330vTD^{1.75}}\, e^{-\left[\frac{13.3\ y}{D^{0.875}}\right]^2} \quad \text{ppm at ground level}$$

$$G = \frac{P}{1330\ T}$$

r = concentration of gas in the atmosphere, ppm by volume
P = amount of gas released, cubic feet measured at the conditions of the ambient atmosphere
T = time, hours over which the gas is released
v = wind velocity, miles per hour
D = distance, miles downwind of the point of release
y = crosswind distance in miles from the axis of the cloud

In order to illustrate the calculation of hazards due to the release of gases, the following problem is mentioned:

An industrial concern is required to build a scrubber to remove hydrogen sulfide from a large flow of waste air. The concentration of the gas in the scrubbed air has an important bearing on the size of the scrubbing tower. The flow of air has been fixed at 1.5×10^6 cubic feet per hour. Therefore, the problem is to determine the permissible average rate of release of hydrogen sulfide, and from this the concentration of the gas in the scrubbed air is easily computed. The stack is considered to be at ground level, for all practical purposes.

The concern in question is situated in an area in which the population density is 10,000 people per square mile, and it is impractical to maintain a controlled zone around the plant. It is judged that relations with the townspeople will be satisfactory if, on the average, 10 people can detect hydrogen sulfide in the atmosphere while the tower is in operation. The lower limit for detection of hydrogen sulfide is 1 ppm by volume. The meteorology of the region is such that K is $0.01\ hr^2/mile^2$.

The fact that the hydrogen sulfide is released to the atmosphere of the town diluted with 1.5×10^6 cubic feet per hour of air is of small help, for the wind passing over the plant makes this flow insignificant. One can consider the poison being released as a pure gas, and this is to be diluted by dispersion in the wind, as far as the populace is concerned. Done in this fashion, the calculation is only slightly conservative.

In this case the controlled distance is zero. Therefore, $\bar{u}$ is infinity, and only the third term in Equation(59 I) is retained.

$$\frac{67.9\chi^*}{(\Delta\theta)N\ P(\theta)} = \sqrt{\frac{14\pi}{15}}\ K^{15/28} G^{15/14} \int_0^\infty \frac{P(r)dr}{r^{29/14}} \qquad (59\ I^*)$$

$\Delta\theta$ is 2π, since the whole arc on the azimuth is considered.

N is 10,000.

$P(\theta)$ is 1, since the whole arc on the azimuth is considered.

χ^* is 10.

K is 0.01.

G is to be determined.

P(r) is zero in the range of r from 0 to 1.

P(r) is 1 in the range of r from 1 to infinity.

$$\int_0^\infty \frac{P(r)dr}{r^{29/14}} = \int_1^\infty \frac{dr}{r^{29/14}} = \frac{14}{15}$$

Hence, G is found to be 0.156 = P/1330 T. P/T is then 208 cubic feet per hour of pure hydrogen sulfide. The concentration of hydrogen sulfide in the air from the tower is 138 ppm by volume.

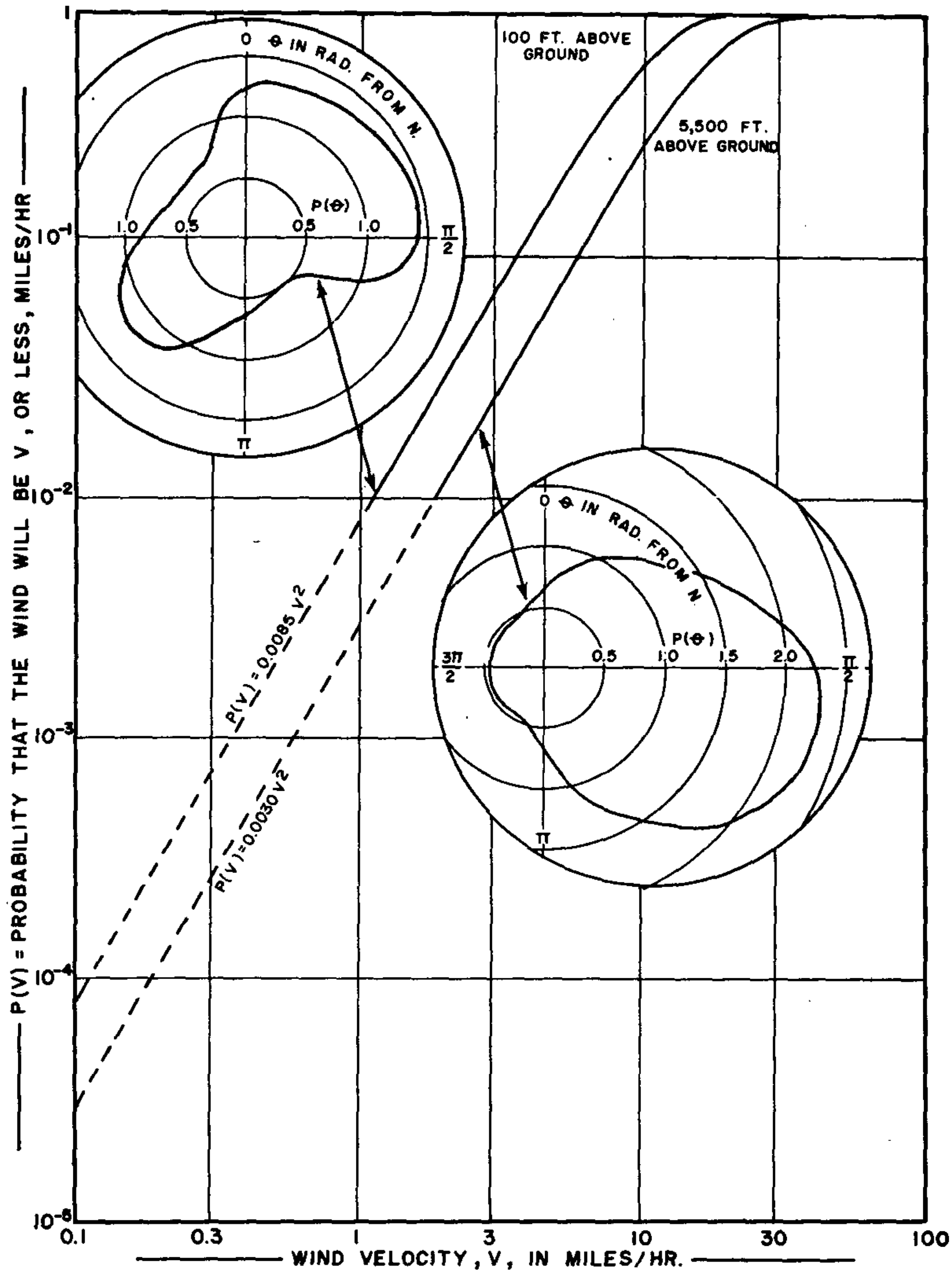
Thus, we note that the atmosphere dilutes the poison from the tower by a factor of 138, and it is perfectly reasonable to neglect the 1.5×10^6 cubic feet per hour of air flowing from the tower.

The hazard due to the possible release of a large quantity of poisonous hydrogen sulfide is treated in the same fashion as the hazard due to release of radioactivity. For this calculation, P(r) vs. r defines the probability of death when gas is inhaled. In this case, P(r) = 0.5 (see Figure 3) when r = 600 ppm and the inhalation time is 0.5 hr. With such a function, Equation(59 I) is evaluated to obtain a graph similar to Figure 7. On this basis, if 15×10^6 ft^3 of H_2S (1.4×10^6 lb) is released over a period of 0.5 hr, the hazard is equivalent to a 2-MW accident (reactor power = 1000 MW) in point of the expectation number of deaths, when the controlled distance is zero. The expectation number of deaths in both these accidents is N/6, about 10 in the average location in the U. S.

NOMENCLATURE

C	=	dispersion coefficient in the atmosphere, meters$^{n/2}$
D	=	distance from the reactor, meters, or miles where so stated
N	=	population density, people/mile^2
N_i	=	number of people living in a small area i, bounded by D and D + ΔD and θ and θ + Δθ
P(b)	=	probability that a person will die if he breathes b microcuries of airborne fission products
P(c)	=	probability that exposure will occur from the fission product cloud for a receptor located at distance D from the reactor and at a distance of either R or y from the center of the rainout or from the center of the cloud
P(d)	=	probability of death per capita per reactor incident
P(r)	=	probability that a person will die if exposed to r roentgens of γ's
P(v)	=	probability that the wind velocity will be less than v
P(θ)	=	relative probability that the wind direction will be between θ and θ + dθ. P(θ) is the probability of the wind's blowing in a given direction divided by the probability if there were an equal chance of blowing in any direction
Q	=	total number of particles liberated to the atmosphere, where they are dispersed
R	=	distance from the center of the puff cloud, meters, or miles where so stated
T	=	time over which the fission products are liberated to the atmosphere, hours
a	=	afterheat fraction of full reactor power level due to the decay of fission products - β and γ heats are included
b	=	the total radioactivity inhaled by a receptor over the period of time t, microcuries
c	=	fraction of the airborne fission products that is brought down from the cloud by falling rain
f	=	fraction of the reactor fission products that is rendered airborne by the reactor incident
g	=	fraction of the fission product γ radioactivity that remains on or near the surface of the ground
n	=	turbulence index for dispersion in the atmosphere
p	=	reactor power level, MW
r	=	the γ exposure received by the receptor over a period of time t, roentgens
r*	=	the upper limit of integration, having the same definition as r
t	=	time that the receptor (a living creature) is bombarded by γ-rays or breathes radioactivity at the location of the rainout or fission product cloud, hours
v	=	wind velocity, meters/hr, or miles/hr where so stated
v*	=	wind velocity defined by Equations (31) and (32)
v**	=	wind velocity defined by Equations (48) and (51)
V	=	extrapolated upper limit of the wind velocity, miles/hr, at which P(v) = 1, when P(v) is of the form, $(K)(v^2)$, for low values of v
x	=	distance downwind from the center of the puff cloud, meters, or miles where so stated
y	=	distance crosswind from the axis of the long cloud or crosswind from the center of the puff cloud, meters, or miles where so stated
z	=	vertical distance from the axis of the long cloud or from the center of the puff cloud, meters, or miles where so stated
α	=	fraction of the time that any spot in the vicinity of the reactor experiences rainfall
θ	=	azimuthal angle, radians measured clockwise from north - after the method of the mariners (It is applied to both wind direction and location of the receptor with respect to the source.)
τ	=	time between rain incidents at the location of the reactor, hours (For instance, if 93 rains occur every year on the average, τ = 94 hours.)
χ	=	expected number of deaths per reactor incident

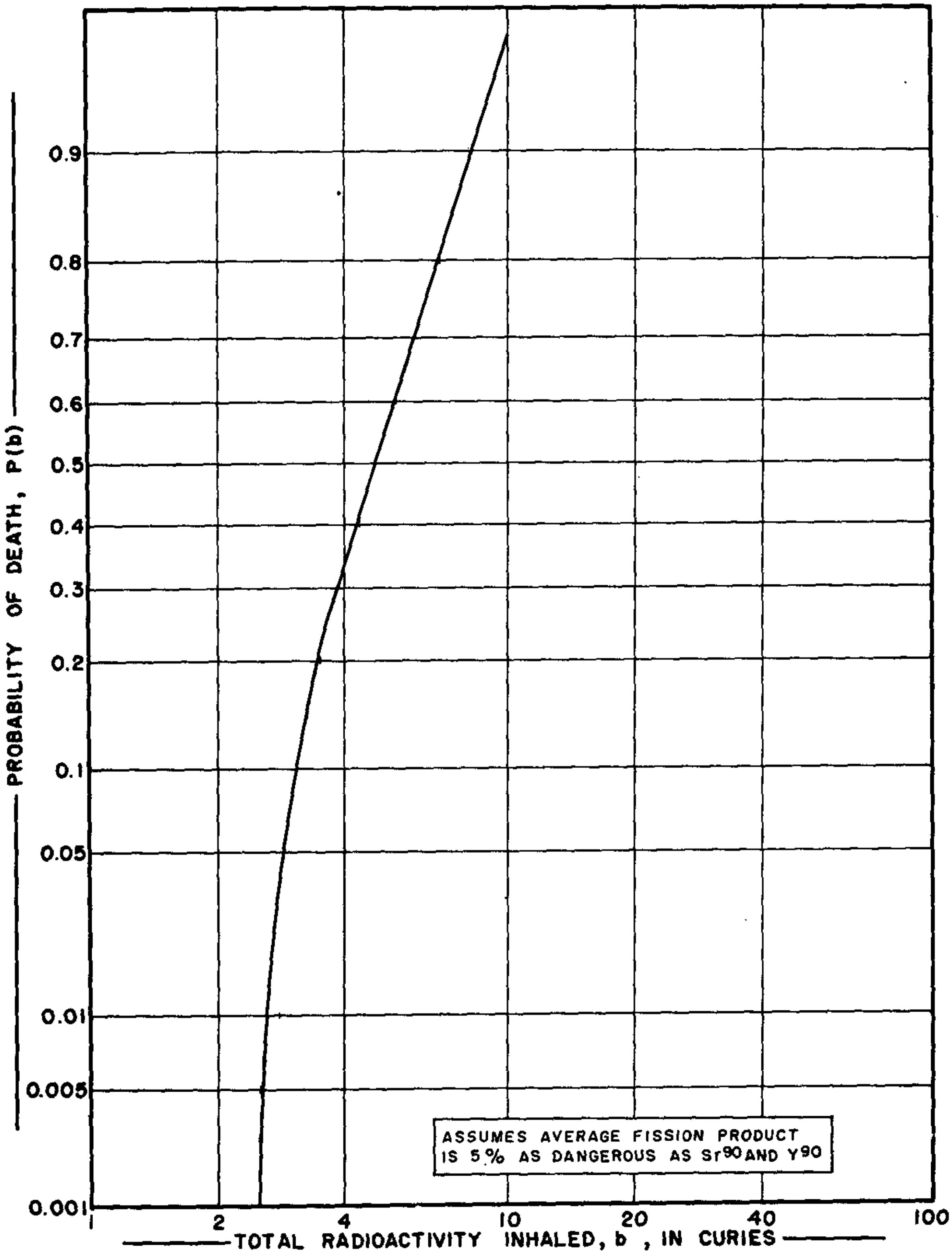
FIGURE 1



WIND VELOCITY PROBABILITY, P(v) and WIND DIRECTION PROBABILITY, P(θ)

FOR HIGH AND LOW LEVEL WINDS. θ = ANGLE TOWARD WHICH WIND BLOWS

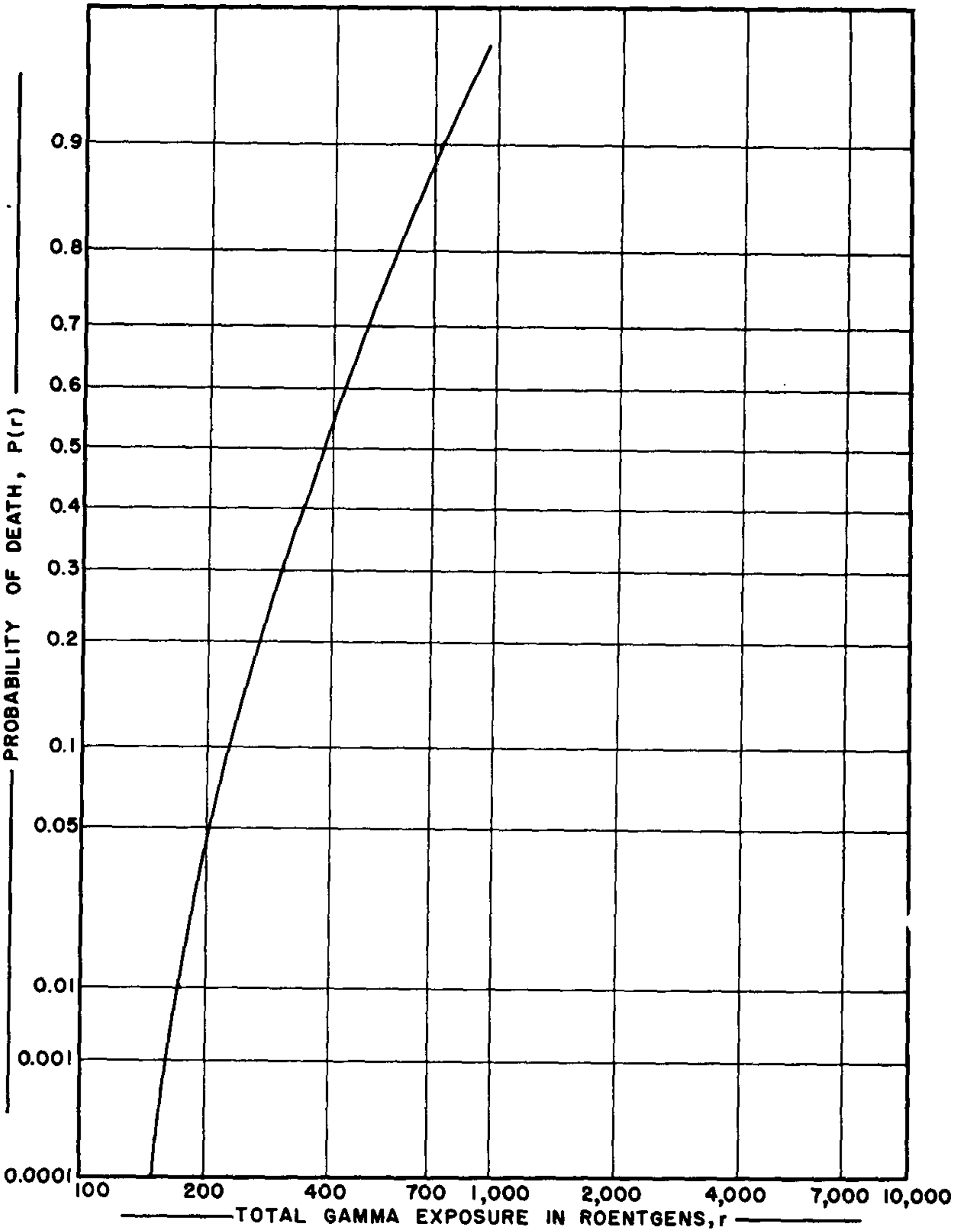
FIGURE 2.



PROBABILITY OF DEATH

IF A PERSON BREATHES FISSION PRODUCTS. DATA OF K.Z. MORGAN (ORNL)

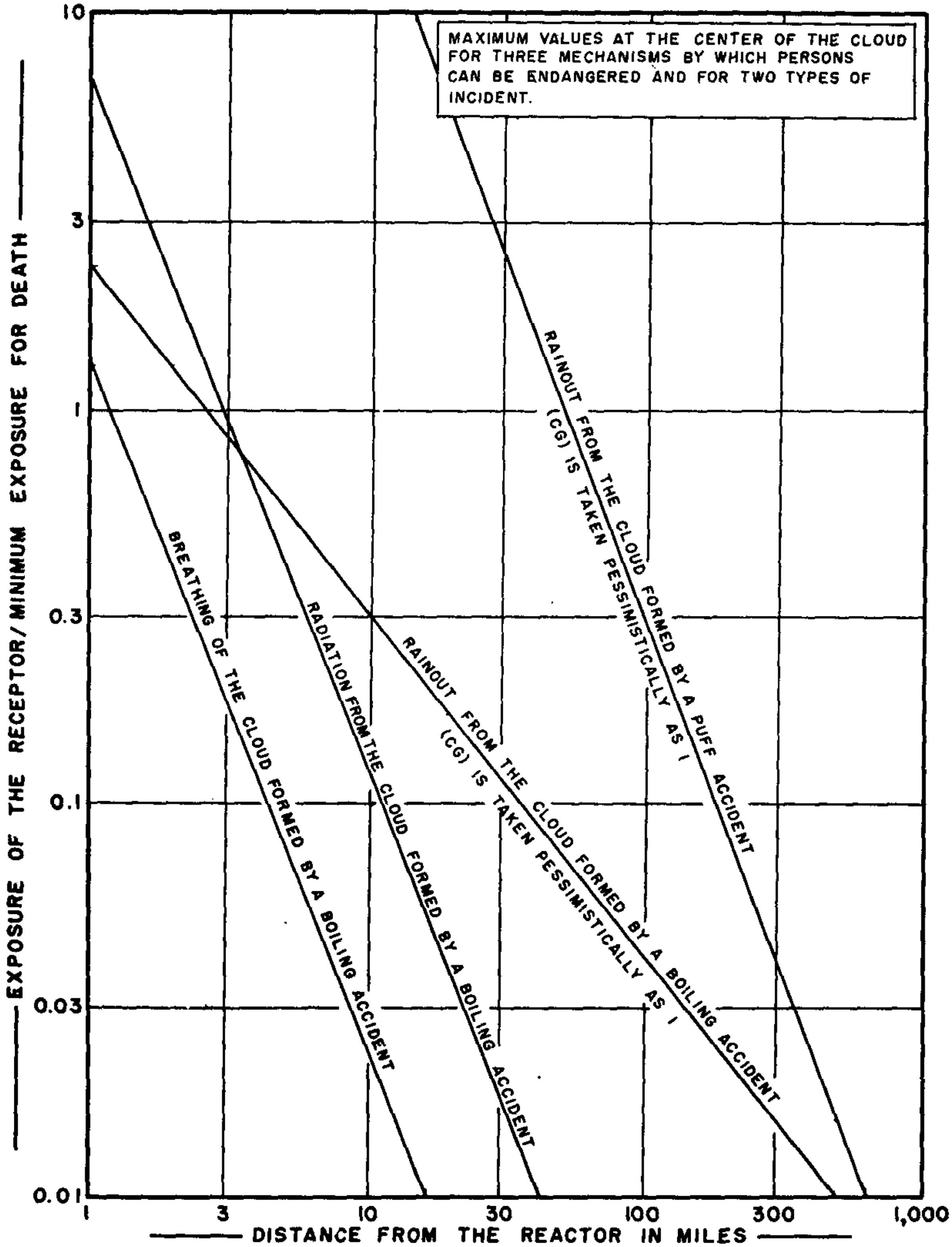
FIGURE 3



PROBABILITY OF DEATH

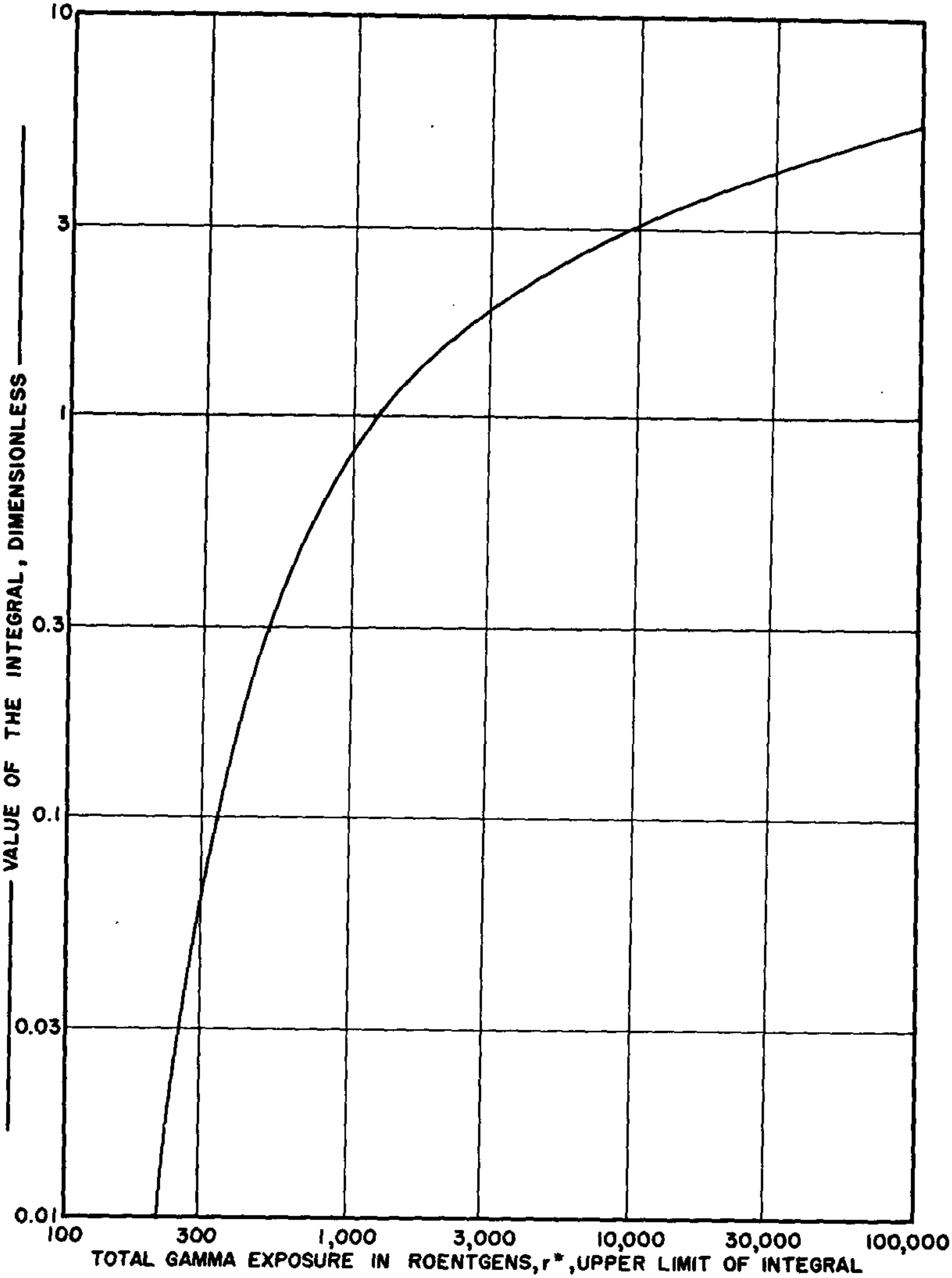
IF A PERSON IS EXPOSED TO GAMMAS. DATA OF K.Z. MORGAN (ORNL)

FIGURE 4



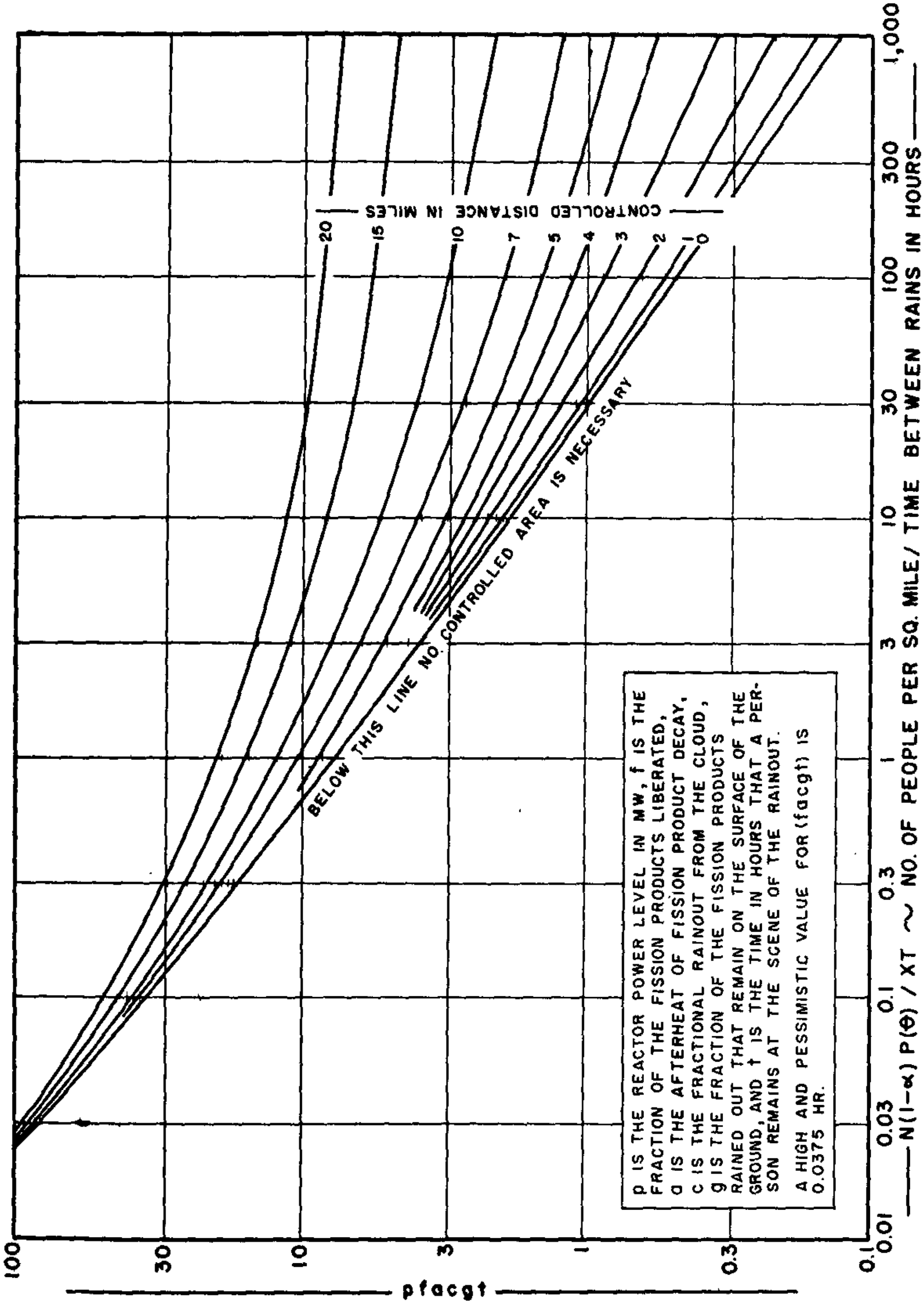
HAZARD IN THE SURROUNDINGS

FIGURE 5



$$\int_{150}^{r^*} \frac{P(r)}{r}\, dr \text{ vs. } r^*$$

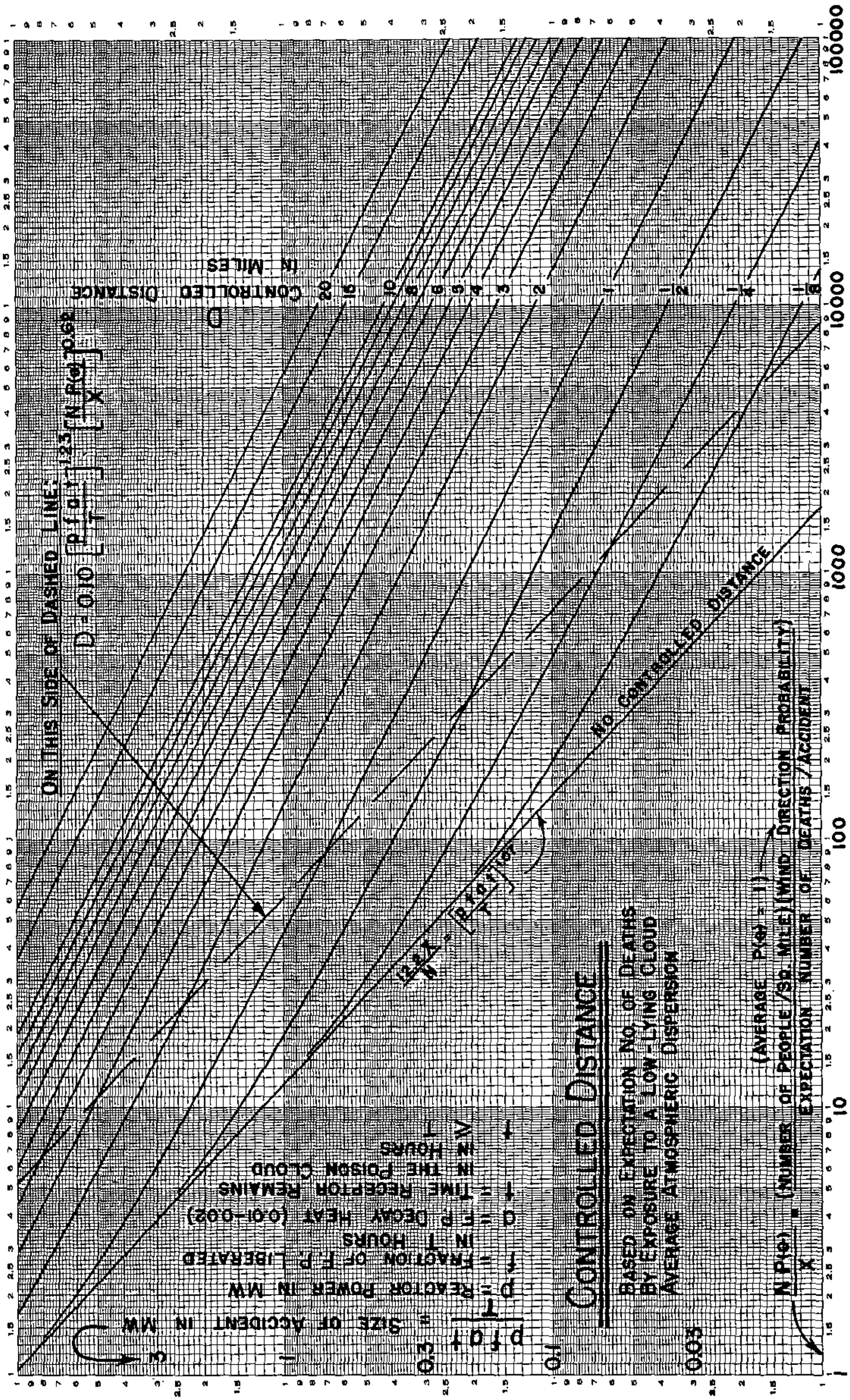
<u>FIGURE 6</u>



<u>CONTROLLED DISTANCE</u>

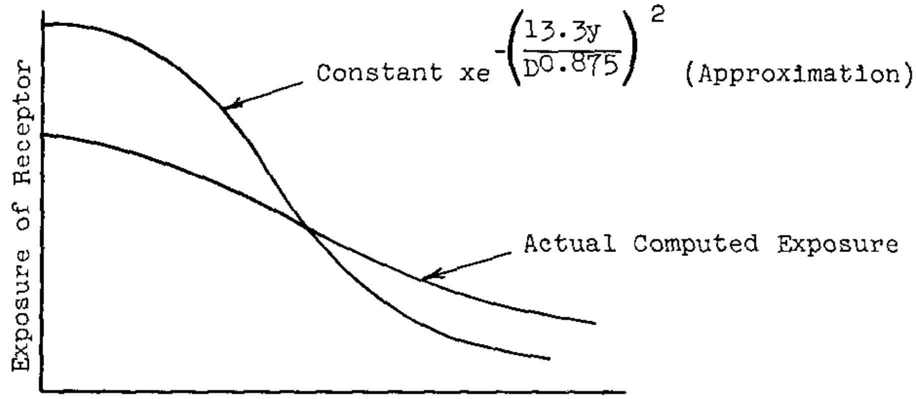
ON THE BASIS OF RAINOUT <u>FROM THE CLOUD FORMED</u> BY A SUDDEN LIBERATION OF THE FISSION PRODUCTS IN THE REACTOR

FIGURE 7


ON THIS SIDE OF DASHED LINE:
D = 0.10 [P f a T / T]^1.25 [N P(θ) / X]^0.62
D CONTROLLED DISTANCE IN MILES
20
15
10
8
6
5
4
3
2
1
1/2
1/4
1/8
NO CONTROLLED DISTANCE
CONTROLLED DISTANCE
BASED ON EXPECTATION NO. OF DEATHS BY EXPOSURE TO A LOW-LYING CLOUD AVERAGE ATMOSPHERIC DISPERSION
(AVERAGE P(θ) = 1)
N P(θ) / X = (NUMBER OF PEOPLE/SQ. MILE)(WIND DIRECTION PROBABILITY) / EXPECTATION NUMBER OF DEATHS/ACCIDENT
P f a T / T = SIZE OF ACCIDENT IN MW
P = REACTOR POWER IN MW
f = FRACTION OF F.P. LIBERATED IN T HOURS
a = F.P. DECAY HEAT (0.01-0.02)
T = TIME RECEPTOR REMAINS IN THE POISON CLOUD IN HOURS
10
100
1000
10000
100000
0.3
0.1
0.05

NOTE: Concerning the derivation of Equation (59 I).

It has been assumed that the cloud is wide, so that the exposure received by a receptor is proportional to the concentration of fission products in the atmosphere. This approximation is valid for long distances from the scene of the accident. Close to the point of release appreciable derivations from this approximation may occur. Qualitatively, the picture looks about as follows in the crosswind direction for points close to the scene of the accident.



Receptors on the axis of the cloud receive less than the approximated exposure, while receptors further from the axis may receive more.

The expectation number of deaths has been calculated for several specific cases by the more accurate calculation. It was found that the dangerous cloud is wider and shorter than the approximation used in this report would indicate. However, the expectation number of deaths is not appreciably different when calculated by the two methods.

In view of the fact that the more accurate calculation cannot be expressed as a general formula, the writers have preferred to use the approximation. One obtains, then, a general formula, Equation (59 I), which may be used for calculating the breathing hazard for both radioactive and poisonous gases, in addition to getting a fairly good estimate of the radiation from the cloud.